MOLTEN WAX SPRAY TREATMENT MAKES ORIENTED STRANDBOARD (OSB) MORE WATER REPELLENT AND REDUCES THICKNESS SWELLING

by

BAREND THERON LOTTER

B.Sc., The University of Stellenbosch, 2007

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTRAL STUDIES

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2014

Abstract

When oriented strandboard (OSB) absorbs moisture its compressed wood strands swell up and recover strains that were induced during hot pressing. Adhesive bonds that hold the strands together rupture and permanent thickness swelling occur. Few post-treatments are able to effectively reduce the thickness swelling of OSB. OSB is porous, with inter-strand voids up to 1.5 mm in diameter. Surface coatings are less effective at restricting moisture ingress into OSB than into solid wood, because of the irregular surface of OSB. Molten wax has a low viscosity and may be able to flow into and block the inter-strand voids of OSB. In this thesis I hypothesize that the water repellency and dimensional stability of OSB may be improved by spraying molten wax onto the hot surface of the board. Furthermore, I hypothesize that polar and low melting point waxes will form more effective water repellent barriers than nonpolar or high melting point waxes. The properties of 13 different waxes and five custom made wax blends were characterized with emphasis on properties likely to influence the water repellency of OSB. Molten waxes were sprayed onto the surface of hot OSB and the water absorption and thickness swelling of the samples were measured. Wax treatments were able to reduce the rate of water absorption and the rate of thickness swelling, but not the extent thickness swelling. I conclude that wax treatments are able to increase the water repellency of OSB and reduce the thickness swelling during short-term periods of exposure to water. Waxes with high melting point temperatures tended to form more effective water-repellent barriers, especially for short-term exposure periods, contrary to my hypothesis. Blends of pure beeswax, which contains polar functional groups, and strongly hydrophobic waxes, such as paraffin wax, formed excellent water-repellent barriers. The results suggest that a combination of polar and nonpolar wax is more effective at reducing the thickness swelling of wax-treated OSB than waxes that contain only hydrophobic components.

Preface

This thesis is original and unpublished work of Barend Theron Lötter. Support and technical assistance from my supervisor, supervisory committee members and colleagues is gratefully acknowledged (pp. xix).

Table of contents

Abstract ii

Preface iii

Table of contents iv

List of tables viii

List of figures ix

List of abbreviations xviii

Acknowledgements xix

Dedication xx

Chapter 1. Introduction 1

- 1.1. General introduction 1
- 1.2. General hypothesis 4
- 1.3. Outline of thesis 5

Chapter 2. Literature review 7

- 2.1. History and current markets 7
  - 2.1.1. A brief history of oriented strandboard 7
  - 2.1.2. Current markets 8
- 2.2. Water absorption and thickness swelling 11
  - 2.2.1. Water absorption 11
  - 2.2.2. Thickness swelling 12
  - 2.2.3. Industry standards for measuring thickness swelling 14
- 2.3. Factors that affect thickness swelling 14
  - 2.3.1. Raw materials 15
    - 2.3.1.1. Wood species 15
    - 2.3.1.2. Strand geometry and orientation 16
    - 2.3.1.3. Resin content 17
    - 2.3.1.4. Wax sizing 18
  - 2.3.2. Board density 18
  - 2.3.3. Porosity 19
- 2.4. Treatments that reduce thickness swelling 21
  - 2.4.1. Thermal modification 22

2.4.2. Chemical treatments 25
2.4.3. Film-forming surface coatings 27
2.4.4. Penetrating water-repellent treatments 29
2.5. Waxes and their properties 30
2.5.1. Origin 31
2.5.2. Chemical composition 31
2.5.3. Water repellency 32
2.5.4. Melting point temperature...35
2.6. Summary 37
Chapter 3. Wax properties that affect the water repellency of wax-treated OSB.......................39
3.1. Introduction 39
3.2. Materials and methods 40
3.2.1. Waxes...40
3.2.2. Contact angle measurements 42
3.2.2.1. Experimental design 42
3.2.2.2. Sample preparation 43
3.2.2.3. Contact angle measurements..44
3.2.3. Surface confocal profilometry 46
3.2.3.1. Surface roughness measurements on pure wax surfaces 46
3.2.3.2. Profilometry image rendering 47
3.2.4. Scanning electron microscopy 47
3.2.5. Melting point temperatures 49
3.2.5.1. Congealing point: ASTM D938 – 12 49
3.2.5.2. Drop melting point: ASTM D127 – 08..50
3.2.6. Viscosity 51
3.2.7. Acid number titration 51
3.2.8. Fourier transform infrared (FTIR) spectroscopy 52
3.2.9. Statistical methods 52
3.3. Results 53
3.3.1. Contact angles 53
3.3.1.1. Glass slides coated with different wax types 53
3.3.1.2. OSB samples treated with different wax types 55

3.3.2. Surface confocal profilometry 57
3.3.2.1. Surface roughness measurements of wax-coated glass slides 57
3.3.2.2. Profilometry images 58
3.3.3. Scanning electron microscopy 61
3.3.4. Melting point temperature 64
3.3.5. Viscosity 65
3.3.6. Acid number titration 66
3.3.7. Relationships between contact angles on pure wax and on wax-treated OSB surfaces 67
3.3.8. Relationships between contact angles and melting point temperatures 69
3.4. Discussion 71
3.5. Conclusion 75
Chapter 4. Effects of wax treatments on thickness swelling 77
4.1. Introduction 77
4.2. Materials and methods 79
4.2.1. Experimental design 79
4.2.2. Waxes 80
4.2.3. Oriented strandboard 81
4.2.4. Sample preparation 81
4.2.5. Wax application 83
4.2.6. Thickness swelling measurement 85
4.3. Results 86
4.3.1. Wax application and physical appearance of wax-treated samples 88
4.3.2. Effect of wax type on total thickness swelling 89
4.3.3. Effect of wax treatment and wax type on the rate of thickness swelling 90
4.3.4. Effect of wax treatment and wax type on thickness swelling 95
4.3.5. Relationship between wax melting point and thickness swelling 98
4.4. Discussion 98
4.5. Conclusion 103
Chapter 5. Effects of wax polarity and melting point temperature on water absorption and thickness swelling 104
5.1. Introduction 104

5.2. Materials and methods 106

5.2.1. Experimental design 106

5.2.2. Waxes 107

5.2.3. Oriented strandboard 107

5.2.4. Sample preparation 108

5.2.5. Wax application 109

5.2.6. Water absorption and thickness swelling measurement 110

5.3. Results 111

5.3.1. Relationship between water absorption and thickness swelling 114

5.3.2. Wax application and physical appearance of wax-treated samples 115

5.3.3. Effect of wax treatments and wax type on water absorption 116

5.3.4. Effect of wax treatments and wax type on thickness swelling 123

5.3.5. Effects of initial moisture content on water repellency, water absorption and thickness swelling 134

5.3.6. Effects of water repellency of wax-treated surfaces on water absorption and thickness swelling 137

5.3.7. Effects of melting point temperatures on water absorption and thickness swelling 139

5.4. Discussion 142

5.5. Conclusion 147

Chapter 6. General discussion, suggestions for further research and conclusions 149

6.1. General discussion 149

6.2. General conclusions 152

6.3. Suggestions for further research 153

Bibliography 156

Appendices 170

Appendix 1 - Chapter 3 170

Appendix 2 - Chapter 4 185

Appendix 3 - Chapter 5 191

List of tables

Table 3.1. The 13 waxes and five wax blends used to treat OSB 42

Table 3.2. Summary of the ANOVA for the initial contact angles of 5 µL water droplets and the time it took droplets to form contact angles of less than 90° (t<90°) on wax-coated slides and wax-treated OSB surfaces (averaged across all wax types) 53

Table 3.3. Melting point temperatures of different waxes measured according to ASTM D938-12 and ASTM D127 08 65

Table 3.4. Apparent viscosity of different waxes according to ASTM D2669-06........................ 66

Table 3.5. Empirical acid number of waxes according to ASTM D1386-10 67

Table 4.1. The origin, melting point tempeatures, and viscosities of seven waxes 80

Table 4.2. Amounts of wax applied to individual samples.. 85

Table 4.3. The effect of wax treatments on the thickness swelling of OSB samples immersed in water (α = 0.05) 87

Table 4.4. The effect of wax on the thickness swelling of OSB samples immersed in water (α = 0.05).. 88

Table 5.1. The names, abbreviations, origin, melting point, and viscosity of 16 waxes........... 107

Table 5.2. Summary of the amount of each wax type applied to seven samples 109

Table 5.3. The effects of wax treatments on the water absorption and thickness swelling of OSB samples, and a comparison between wax-treated samples and “moisture resistant” samples. All samples were floated face down on water for 72 h and measured at 2 h, 24 h, 48 h and 72 h (α = 0.05)... 112

Table 5.4. The effect of individual wax on the water absorption and thickness swelling of OSB samples that were floated face down on water for 2 h, 24 h, 48 h and 72 h, as well as a comparison between wax-treated samples and “moisture resistant” samples 113

Table 5.5. Average water absorption of all OSB samples 116

Table 5.6. Average thickness swelling of all OSB samples 123

List of figures

Figure 2.1. A typical two-story single family home under construction in West Point Grey, Vancouver, Canada. Note the large amount of OSB for wall sheathing 9

Figure 2.2. A multi-storey building under construction on Marine Drive, North Vancouver, Canada. OSB was used for wall sheathing. The ground floor is typically used for commercial real estate and the upper levels are for medium density residential accommodation........................10

Figure 2.3. A single-family home under construction in West Point Grey, Vancouver, Canada (left). The mud and water in the foreground suggests that the building was exposed to rain water. A close up (right) of OSB wall sheathing that was left unprotected in a rain shower, while the building was under construction 10

Figure 2.4. Oven dried OSB (left) and the same OSB sample immersed in water for 18 h (right). Note that the panel edge swelled by almost 4 mm (± 20%) after 18 h 13

Figure 2.5. Three types of inter-strand voids in flakeboard, as classified by Furuno et al. (1983)19

Figure 2.6. Initial contact angle of a 5μL water droplet on a hydrophilic surface (left) and a hydrophobic surface (right). A solid is considered to be hydrophobic when θ > 90° 33

Figure 3.1. Fischer-Tropsch and paraffin waxes as they were received from Sasol Wax, South Africa 42

Figure 3.2. Goniometer equipped with a camera and syringe (left) and CAM 200 software (right), which was able to calculate the geometry of water droplets using a Young-Laplace algorithm..45

Figure 3.3. The white-light non-contact confocal profilometer (Altisurf 500 ®, ALTIMET, France) used to scan the surface profiles of pure wax surfaces 46

Figure 3.4. The 12 mm diameter SEM stub with the five wax-treated OSB samples that were examined using scanning electron microscopy: (A) beeswax; (B) carnuaba wax; (C) Merkur 300; (D) Tekniwax 600; (E) Vaseline. 49

Figure 3.5. Initial contact angle of 5μL water droplets placed on glass slides coated with different wax types (n = 11). Note the large mean initial contact angle of water droplets on stearic acid. Differences larger than the least significant difference (LSD = 3.02°) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for a blend for Sasolwax M3M and ethylene maleic anhydride (M3M+EMA). Refer to Appendix 1 for precise numerical values 54

Figure 3.6. The time it took for 5µL water droplets to form contact angles of less than 90° on glass slides coated with different wax types (n = 11). Differences larger than the least significant difference (LSD = 4.73 min) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for Tekniwax 801 (T801). Refer to Appendix 1 for precise numerical values 55

Figure 3.7. Initial contact angle of 5µL water droplets placed on OSB surfaces treated with different wax types (n = 6). Differences larger than the least significant difference (LSD = 9.4°) are statistically significant at a 5% level. Clear data points are not significantly ($p > 0.05$) different to the data point for Merkur 300. Refer to Appendix 1 for precise numerical values 56

Figure 3.8. The time it took for 5µL water droplets to form contact angles of less than 90° on OSB surfaces treated with different wax types (n = 6). Differences larger than the least significant difference (LSD = 9.22 min) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for a blend of beeswax and Sasolwax C (Bee+Sc). Refer to Appendix 1 for precise numerical values 57

Figure 3.9. Average surface roughness (R_a) of glass slides coated with different wax types (n = 3). Differences larger than the least significant difference (LSD = 2.61 µm) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for lanolin (Lan). Refer to Appendix 1 for precise numerical values...58

Figure 3.10. Profilometry image of the surface of a glass slide coated with stearic acid. The 10 x 10 mm^2 image consists of 1177 profile scans, scanned with x-axis spacing of 8.5 µm and y-axis spacing of 8.5 µm. The gauge resolution for the z-axis was 0.333 nm (Head No.3). The white and brown areas represent large wax crystals, while the black areas represent unmeasured points that were beyond the 3 mm focal plane of the profilometer head 59

Figure 3.11. Profilometry images of the surface of a glass slide coated with carnauba wax. The original 5 x 5 mm^2 image (left) consists of 1251 profile scans with x-axis spacing of 3.5 µm and y-axis spacing of 4 µm. The area within the dashed white square on the original image is magnified on the right. The gauge resolution for the z-axis was 3.333 nm (Head No.2) 60

Figure 3.12. Profilometry images of the surface of a glass slide coated with microcrystalline wax. The original 5 x 5 mm^2 image (left) consists of 1112 profile scans, scanned with x-axis spacing of 3.5 µm and y-axis spacing of 4.5 µm. The gauge resolution for the z-axis was 3.333 nm (Head No.2). The magnified image of the area within the dashed white square (right) shows that the surface of microcrystalline wax formed microscopic peaks (white) and valleys (black), similar to those found on the super-hydrophobic surfaces of the leaves of some plant species (Barthlott and Neinhuis 1997) 60

Figure 3.13. Profilometry images of the surface of a glass slide coated with two different petroleum jellies, Vaseline (left) and Merkur 300 (right). The 1 x 1 mm^2 images consists of 287 profile scans, scanned with x-axis spacing of 3.5 µm and y-axis spacing of 3.5 µm. The gauge resolution for the z-axis was 3.333 nm (Head No.2) 61

Figure 3.14. SEM photomicrographs of an OSB surface coated with beeswax. The lower magnification image (left) shows that wax covered the OSB surface, but that tiny holes were present in the coating. The image on the right showes the area within the dashed white rectangle at a higher magnification 62

Figure 3.15. SEM photomicrographs of an OSB surface coated with carnauba wax. The lower magnification image (left) shows that the wax totally covered the OSB surface and formed a smooth coating with large and small micro cracks at the surface. The image on the right shows the area within the dashed white rectangle at a higher magnification 62

Figure 3.16. SEM photomicrographs of an OSB surface coated with a Fisher-Tropsch wax (Merkur 300). The lower magnification image (left) shows that the surface of Merkur 300 is not as smooth as those of beeswax or carnauba wax. The image on the right shows the area within the dashed white rectangle at a higher magnification. Merkur 300 tended to agglomorate around certain areas 63

Figure 3.17. SEM photomicrographs of an OSB surface coated with a paraffin wax (Tekniwax 600). The lower magnification image (left) shows that the surface of Tekniwax 600 appeared to be relatively rough. The image on the right shows the area within the dashed white rectangle at a higher magnification. Crater-like formations were visible on the surface 63

Figure 3.18. SEM photomicrographs of an OSB surface coated with a Vaseline. The lower magnification image (left) suggests that some Vaseline was absorbed into the hot OSB surface. The image on the right shows the area within the dashed white rectangle at a higher magnification. The surface topography of an area coated with Vaseline was very smooth 64

Figure 3.19. Relationship between (1) the initial contact angle of 5µL water droplets placed on glass slides coated with different wax types and (2) the time it took those droplets to spread and form contact angles of less than 90° on a pure wax surface ($\alpha = 0.05$) 68

Figure 3.20. Relationship between (1) the initial contact angle of 5µL water droplets placed on glass slides coated with different wax types and (2) the time it took water droplets placed on wax-treated OSB surfaces to spread and form contact angles of less than 90° ($\alpha = 0.05$) 69

Figure 3.21. Relationship between (1) the melting point temperatures of the different wax types and (2) the initial contact angles of 5µL water droplets placed on pure wax surfaces (α = 0.05) 70

Figure 3.22. Relationship between (1) the melting point temperatures of the different wax types and (2) the times it took 5µL water droplets to spread and form contact angles of less than 90° on OSB surfaces treated with different wax types (α = 0.05) 71

Figure 4.1. The seven waxes used in this chapter (and one wax that was not included) after dynamic viscosities were measured using a stress-controlled rheometer (Anton Paar MCR 501). (A) Sasolwax M3M; (B) Vaseline; (C) carnauba wax; (D) lanolin; (E) Sasolwax C; (F) Tekniwax 600; (G) beeswax 81

Figure 4.2. An OSB sample prior to application of molten wax 83

Figure 4.3. The Champ 10s pneumatic spray gun used to spray molten wax onto the OSB samples. Solid wax is inserted into the temperature controlled heating chamber at the back of the spray gun (left). The contol panel (right) is used to set the pressure inside the heating chamber and spray pressure at the nozzle tip 84

Figure 4.4. A schematic drawing of the Champ 10s spray gun's nozzle assembly. The spring, the ball and the stopper is housed inside the spray nozzle. The ball and spring is held in place by the stopper, which is screwed into the back of the nozzle. The spray nozzle, with the three parts inside it, is screwed onto the head of the spray gun body. The spray cap is also screwed onto the spray gun body, and it covers the spray-nozzle assembly. Molten wax is forced out of the spray gun when the chamber pressure is high enough to force the ball to compress the spring. A second pneumatic line, at the top of the spray gun body, helps to atomize the molten wax that escapes 84

Figure 4.5. Eight OSB samples mounted in the swellometer tank and immersed in water (left). Each sample had one linear variable differential transducer (LVDT) mounted above it, which measured thickness swelling over time. A close up (right) of a LVDT with its footpad zeroed onto the surface of an OSB sample treated with molten Vaseline 86

Figure 4.6. Close up of the surface of OSB sprayed with approximately 270 g /m^2 of molten carnauba (left) wax and Vaseline (right). Note that the high application rate caused surface coatings to form, even though the OSB samples were hot (170°C) when the waxes were sprayed onto them. Carnauba wax coatings cracked and flaked off when touched, while Vaseline formed a defect-free coating that filled the surface voids 89

Figure 4.7. Effect of wax type on the total thickness swelling of wax-treated OSB samples after 21 days of immersion in water Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant difference (LSD) is 0.45 mm 90

Figure 4.8. The average thickness swelling of untreated and wax-treated OSB samples that were immersed in water for 24 h (n = 7). Refer to attached CD for numerical values 91

Figure 4.9. The average thickness swelling of untreated and wax-treated OSB samples that were immersed in water for 21 days (n = 7). Refer to attached CD for numerical values 92

Figure 4.10. Effect of wax treatments on the time it took OSB to reach 25% and 50% total thickness swelling (TTS). Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant difference (LSD) for 25% TTS is 35.7 h and the LSD for 50% TTS is 47.5 h 93

Figure 4.11. Effect of wax type on the time it took wax-treated OSB samples to reach 25% and 50% of total thickness swelling (TTS). Non-overlap of error bars indicates that means are significantly different at the 5% level. The least significant difference (LSD) for 25% TTS is 47.3 h and the LSD for 50% TTS is 62.8 h 94

Figure 4.12. Effect of wax treatments on the thickness swelling of OSB after 2 h, 24 h, 72 h, and 240 h. Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant differences (LSD) for 2 h, 24 h, 72 h and 240 h are 0.02 mm, 0.13 mm, 0.22 mm, and 0.42 mm, respectively. Note the different y-axis scales for each plot, always starting at zero 96

Figure 4.13. Effect of individual wax types on the thickness swelling of OSB samples after 24 h, 72 h, and 240 h of immersion in water. Also included (bottom right) are the melting point temperatures of the different waxes. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant differences (LSD) for 24 h, 48 h, and 240 h are 0.17 mm, 0.29 mm, and 0.56 mm, respectively 97

Figure 5.1. Samples were floated face down on water for 72 h. The weight and the thickness of each sample was measured after 2 h, 24 h, 48 h, and 72 h 111

Figure 5.2. The relationship between water absorption and thickness swelling of untreated and wax-treated OSB samples that were floated face down on water for 72 h. Moisture resistant samples not included 114

Figure 5.3. Relationships between water absorption and thickness swelling of untreated and wax-treated OSB samples that were floated face down on water for 72 h. Measurements were made after 2 h (top left), 24 h (top right), 48 h (bottom left) and 72 h (bottom right) 115

Figure 5.4. Average water absorption of: (1) untreated OSB (n = 7); (2) all wax-treated samples (n = 112); (3) OSB samples treated with a blend of beeswax and synthetic beeswax (n = 7); and (4) “moisture resistant” OSB (n = 7). All samples were floated on water for 72 h and measurements were taken after 2 h, 24 h, 48 h, and 72 h 116

Figure 5.5. Average effect of wax treatments on the water absorption of OSB samples that were floated face down on water for 2 h (left) and 24 h (right), as well as comparison between the water absorption of these samples and those of “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 2 h and 24 h was 0.66 mL and 2.57 mL, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.69 mL and 2.46 mL, respectively (not drawn)..117

Figure 5.6. Average effect of wax treatments on the water absorption of OSB samples that were floated face down on water for 48 h (left) and 72 h (right), as well as comparison between the water absorption of these samples and those of “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (48 h and 72 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 48 h and 72 h was 4.63 mL and 7.32 mL, respectively (error bars drawn). The LSD between untreated samples and MR samples after 48 h and 72 h was 4.61 mL and 7.4 mL, respectively (not drawn)...118

Figure 5.7. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 2 h, as well as a comparison between the water absorption of these samples and “moisture resistant” (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.91 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.94 mL (not drawn) 120

Figure 5.8. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 24 h, as well as a comparison between the water absorption of these samples and “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 3.53 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 3.37 mL (not drawn) 121

Figure 5.9. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 48 h, as well as a comparison between the water absorption of these samples and “moisture resistant” (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 6.35 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 6.32 mL (not drawn) 122

Figure 5.10. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 72 h. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 10 mL 123

Figure 5.11. Average thickness swelling of: (1) untreated OSB (n = 7); (2) all wax-treated samples (n = 112); (3) OSB samples treated with a blend of beeswax and synthetic beeswax (n = 7): and (4) “moisture resistant” OSB (n = 7). All samples were floated on water for 72 h and measurements were taken after 2 h, 24 h, 48h, and 72 h 124

Figure 5.12. Average effect of wax treatments on the thickness swelling of OSB samples that were floated face down on water for 2 h (left) and 24 h (right), as well as a comparison between the water absorption of these samples and those of “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 2 h and 24 h was 0.04 mm and 0.11 mm, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.04 mm and 0.12 mm, respectively (not drawn)..125

Figure 5.13. Average effect of wax treatments on the thickness swelling of OSB samples that were floated face down on water for 48 h (left) and 72 h (right), as well as a comparison between the water absorption of these samples and those of “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 48 h and 72 h was 0.16 mm and 0.19 mm, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.17 mm and 0.2 mm, respectively (not drawn)..126

Figure 5.14. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 2 h, as well as a comparison between the thickness swelling of these samples and “moisture resistant” (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) for both statistical analyses is 0.06 mm (error bars drawn)..128

Figure 5.15. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 24 h, as well as a comparison between the thickness swelling of these samples and “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.15 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.16 mm (not drawn)..........................129

Figure 5.16. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 48 h, as well as a comparison between the thickness swelling of these samples and “moisture resistant” (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.22 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.23 mm (not drawn)................................130

Figure 5.17. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 72 h, as well as a comparison between the thickness swelling of these samples and “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.27 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.28 mm (not drawn)..........................131

Figure 5.18. The time-delayed thickness swelling of OSB samples treated with different wax types. Measurements were taken after the samples were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two weeks and a maximum of four weeks. Non-overlap of error bars indicates that means are significantly different at a 5% level. All samples from each individual experimental replication were measured at the same time, irrelevant of their conditioning period 133

Figure 5.19. Total thickness swelling of untreated and wax-treated OSB samples after they were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks. Non-overlap of error bars indicates that means are significantly different at a 5% level. All samples from each individual experimental replication were measured at the same time, irrelevant of their conditioning period 134

Figure 5.20. Relationship between (1) the initial moisture content of wax-treated samples that were oven dried, wax treated and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the time it took for 5 µL water droplets to spread over wax-treated OSB surfaces and form contact angles of less than 90° 135

Figure 5.21. Relationships between (1) the initial moisture content of wax-treated samples that were oven dried, wax treated and conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the water absorption of the samples after they were floated face down on water for 2 h (left) and 24 h (right) 136

Figure 5.22. Relationships between (1) the initial moisture content of wax-treated samples that were oven dried, wax-treated and conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the thickness swelling of the samples after they were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)...............137

Figure 5.23. Relationships between (1) the times it took for 5 µL water droplets to spread over wax-treated surfaces and form a contact angles of less than 90° (t<90°), and (2) the water absorption of wax-treated OSB samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)..138

Figure 5.24. Relationships between (1) the times it took for 5µL water droplets to spread over wax-treated surfaces and form a contact angles of less than 90° (t<90°) and (2) the thickness swelling of wax-treated OSB samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)..139

Figure 5.25. Relationships between the melting point temperatures of the waxes sprayed onto OSB surfaces and the water absorption of wax-treated samples that were floated face down on water for 2 h (left) and 24 h (right) 140

Figure 5.26. Relationships between the melting point temperatures of the waxes sprayed onto the surface of OSB and the thickness swelling of wax-treated samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right) 141

Figure 5.27. Relationship between the melting point temperatures of different wax types and the total thickness swelling of wax-treated OSB samples that were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks 142

List of abbreviations

EMC	Equilibrium moisture content
HM	High melting point temperature (> 65°C)
IB	Internal bond strength
LM	Low melting point temperature (< 65°C)
MC	Moisture content
MDF	Medium density fibreboard
MOE	Modulus of elasticity
MOR	Modulus of rupture
MR	Premium-grade “moisture resistant” OSB
OSB	Oriented strandboard
PTS	Permanent thickness swelling (springback)
r.h.	Relative humidity
RTS	Reversible thickness swelling
TS	Thickness swelling
TTS	Total thickness swelling measured (i.e. the last measurement of each experiment)
t<90°	Time it took for water droplets to form contact angles of less than 90°
WA	Water absorption

Acknowledgements

I would like to thank Professor Philip D. Evans for providing me with the opportunity to come to Canada and to pursue innovative research at one of the world's leading forestry research centers. Without his support and guidance this thesis would not have materialized. I will always be grateful for the freedom I was given to explore my hypotheses and to learn from my mistakes, and for his infinite patience. The technical writing skills that Professor Evans taught me will forever be an asset in my life. Finally, I would like to thank Professor Evans for his courage in pursuing scientific research in its truest sense.

I would like to thank Dr. Simon C. Ellis and Professor Reinhard Jetter for being part of my supervisory committee and for providing me with their expert advice and guidance.

I am thankful for the support and friendship of all the members of the Dr. Evans' research group. It was an honour to work with and learn from such an internationally diverse group of people. Special thanks goes to Siti Hazneza for her benevolence and for being our unofficial "lab mummy". George Chan, Wenchang He, and Kenny Cheng also deserve a big thank you for their technical assistance.

I would like to thank the Faculty of Graduate and Postdoctoral Studies at The University of British Columbia for awarding me the Mary and David Macaree Fellowship Award, and for the people in the Graduate student office of the Faculty of Forestry who recommended me for this award and who provided support during my time at the Faculty (Cindy Prescott , Gayle Kosh, Dan Naidu, and Robin Poirier-Vasic). I would also like to thank the technical and administrative staff at the Center for Advanced Wood Processing for their support (Neeta Hundle, Ivy Fung, Genny Go, Lawrence Gunther, Vincent Leung, Diana Hastings, and Winfield Liu)

I would like to acknowledge Kevin Blau of Tolko Industries Ltd. for supplying me with OSB panels and Sidney Subramony of Sasolwax (South Africa) for supplying some of the waxes.

My warmest thanks go to Lorien Nesbitt for her encouragement, advice and, most of all, her faith in me. Finally, I would like to thank all my family members for keeping me at home while I was far away.

Dedication

To my parents,

who’s unwavering love and support is the greatest blessing in my life.

Chapter 1. Introduction

1.1 General introduction

Oriented strand board (OSB) is a low-cost wood composite, extensively used as a structural panel for residential and commercial construction (Howard and McKeever 2012). In 2010, OSB accounted for 60% of the U.S. structural panel market (Howard and McKeever 2012). In 2012, production of OSB in North America reached 15.5 million m^3 and European production exceeded 4.9 million m^3 (UNECE/FAO 2013). Structural wood-based composites may represent over 50% of the building materials for residential housing in North America (Moya et al. 2008), with an average-sized single-family home consuming about 1,060 m^2 of OSB (Anonymous 2012).

OSB is composed of approximately 95% wood, 4% resin and 1% wax sizing (Kline 2005). Wood accounts for approximately 68% of the raw material cost of OSB, while resin accounts for 25% and wax for 7% (Spelter et al. 2006). To make OSB, thin, rectangular strands of wood, typically 75 - 150 mm long, 15 - 25 mm wide, and 0.3 - 0.7 mm thick, are blended with thermosetting resin and paraffin wax (Irle and Barbu 2010). The strands are then arranged into a mat with layers of varying grain direction. The layer closest to the face of the mat is generally oriented parallel to its length, while the sub-surface layer (or core) is randomly or cross-oriented. The mat is consolidated in a hot press at platten temperatures of up to 200°C or more (Shmulsky and Jones 2011). A large amount of pressure (4 – 6 MPa) is required to achieve good contact between the strands (Paridah et al. 2006). The high pressure compresses and strains the strands, while the thermosetting resin cures. Hot pressing therefore causes a certain amount of compression strains to set inside the board.

When OSB is exposed to liquid water or high humidity conditions the compressed strands swell and recover some of their original dimensions. This may cause the adhesive bonds to break which leads to further permanent thickness swelling and losses of mechanical strength (Kelly 1977; Hsu and Bender 1988; Wu and Suchsland 1997; Wu and Piao 1999). When in service OSB can be exposed to rain and high levels of relative humidity, especially during the early stages of building construction (Winterowd et al. 2003). The wood strands of OSB are hygroscopic and naturally adsorb and desorb moisture, depending on the relative humidity of their environment. Boards that undergo large fluctuations in moisture content can swell, shrink and buckle. Such boards often need to be replaced or sanded level, before construction can continue (Taylor et al. 2008). Increases in moisture content may also lead to undesirable changes in the appearance of OSB (Biblis 1990) and higher susceptibility to biological attack (Zabel and Morrell 1992).

Moisture ingress into OSB occurs through a series of voids that exist as a result of strands that overlap each other (Suchsland 1962; Maloney 1993; van Houts et al. 2004). These inter-strand voids are relatively large compared to the natural capillary system in wood (Zhang and Smith 2010b). Their presence, on the outer surfaces of the panels, makes it difficult to control the water uptake and dimensional stability of the panels, since they provide an easy passage for moisture ingress (Bolton and Humphrey 1994; van Houts et al. 2006; Zhang and Smith 2010b). The panel edges, for example, have numerous voids (van Houts et al. 2004) that are often coated to prevent excessive edge swelling (Winterowd et al. 2003).

Various different technologies can reduce the thickness swelling of OSB. These include: (1) modification to production processes, such as changes to the board composition and press parameters; (2) chemical treatments of the strands before pressing (pre-treatment); (3) thermal modification of either the strands (pre-treatment) or the consolidated boards (post-treatment); or (4) the application of surface coatings and water repellents (post-treatment). These technologies and their shortcomings will briefly be discussed here.

Increasing the resin content of OSB can improve its dimensional stability, but this increases the cost of the product (Forintek Canada Corp. 1998; Shmulsky and Jones 2011). High performance OSB, with high resin content, is commercially available, but at premium prices. Another method used to improve the dimensional stability of OSB is to spray wax onto the strands before the boards are pressed. The wax acts as a water repellent and reduces thickness swelling when boards in service are exposed to water (Winistorfer et al. 1992). There is, however, an effective limit, of about 2-3%, that can be added to the internal structure of OSB, after which point the water repellency of the board does not significantly increase as wax content increases (Hsu et al. 1990, Winistorfer et al. 1992). Moreover, the mechanical properties of OSB deteriorate as wax content increases above this limit (Lehmann 1978; Winistorfer et al. 1992; Forintek Canada Corp. 1998)

Chemical treatments can be used to reduce the hygroscopicity of the wood strands before the board is pressed, but such treatments are usually expensive and may reduce the mechanical properties of boards. The process of acetylation, for example, is able to bulk the cell wall of wood and limit water adsorption, but this process makes the wood strands less wettable and reduces their bonding ability (Rowell et al. 1987; Papadopoulos and Traboulay 2002; Papadopoulos and Gkaraveli 2003). Another bulking treatment is to impregnate the wood strands with low molecular weight phenol formaldehyde resin before conventional pressing. This treatment is able to improve the dimensional stability of OSB (Paridah et al. 2006; Wan and Kim 2006), but the cost of extra resin and additional blending and drying equipment restricts the technology to speciality products (Haygreen and Gertjejansen 1971).

Thermal modification aims to reduce the hydrophilic nature of OSB. In general, the literature shows that thermal modification of wood strands prior to pressing can reduce the thickness swelling of OSB, but that mechanical properties are often impaired (Goroyias and Hale 2002; Paul et al. 2006; Ohlmeyer 2007; Mendes et al. 2013). Thermal post-treatment of OSB has less severe effects on mechanical properties, but it is also less effective at reducing thickness swelling (Ohlmeyer 2007; Mendes et al. 2013).

Surface coatings and water repellents are by far the most common treatments used to reduce water absorption and improve the dimensional stability of solid wood. Both systems can reduce swelling by preventing water from being absorbed by wood cell walls. Wood coatings retard the ingress of water by creating a low-permeability barrier film at the wood surface (Orman 1955; Huldén and Hansen 1985; Thomas 1991; Derbyshire and Miller 1996; Derbyshire and Robson 1999), but in order for a coating to be effective the coatings must be complete and free of defects (Stamm and Hansen 1935; Stamm and Seborg 1936; Borgin 1965). Any cracks or openings that allow the ingress of moisture will reduce the effectiveness of the system, accelerate its degradation, and result in swelling of the underlying wood. Unfortunately, film-forming coatings are not as effective on OSB as they are on wood. The large voids in the panel surface may remain uncoated and open for water penetration (Feist 1982; Evans and Cullis 2008). The irregular surface of OSB also makes it difficult to achieve a continuous film, unless large quantities of coating material are used (Grossman 1992; Semple et al. 2009). Water repellents, however, can be applied to irregular surfaces, such as those of OSB, and may slow the rate of water ingress by creating a sub-surface moisture-resistant barrier. Wax, for example, can be applied to solid wood to block water pathways and increase the capillary pressure required for spontaneous water absorbtion (Gibson 1965; Borgin and Corbett 1970). In particleboards, wax sizing is able to form an internal water-repellent barrier that reduces the rate of water absorption (Maloney 1993). Semple et al. (2009) showed that certain wax emulsions can be sprayed onto OSB to create a water resistant surface, but their results show that the water-based solutions may also cause pre-swelling of the surface strands. Mantanis and Papadopoulos (2010) dipped OSB samples into a water-repellent solution containing paraffin wax and found that this step could reduce the water absorption and thickness swelling of OSB.

1.2 General hypothesis

Waxes have melting points as low as 40°C and very low viscosities when they are molten. At 10°C above their drop melting point temperature, the viscosities of wax are always lower than 10 Pa·s (Wolfmeier et al. 2000). These properties make it possible to spray wax when it is molten. In fact, up until the late 1990s waxes incorporated into the body of OSB were sprayed directly onto the flakes before pressing, and were not blended with the resin (Shen 1980; Eckert and Edwardson 1998). When molten wax is applied to a hot surface, the wax in contact with the surface will remain liquid until the wax cools below its congealing point temperature.

The surface temperature of freshly pressed OSB can be as high as 250°C, well beyond the congealing point of most waxes (Wolfmeier et al. 2000). Hence, when molten wax is sprayed onto the surface of freshly pressed OSB, it may remain liquid for long enough to flow into the voids between the wood strands, at the surface, where it could act as a water repellent barrier once it solidifies.

Accordingly, I hypothesize that moisture resistance and dimensionally stability of OSB will improve when molten wax is sprayed directly onto its surface, while it is hot. I further hypothesize that low melting point waxes will form more effective water repellent barriers than high melting point waxes, because they will have the ability to flow into inter-strand voids more easily and block moisture ingress into OSB.

1.3 Outline of thesis

Following this introduction, Chapter 2 reviews relevant literature focusing on: (1) the history and current markets for OSB; (2) water absorption and thickness swelling of OSB; (3) the factors that influence the thickness swelling of OSB; (4) treatments that have been used to reduce the thickness swelling of OSB; and (5) wax properties that that are likely to influence their performance as a molten, water-repellent treatment for OSB.

Chapter 3 covers experimental techniques that were used to characterize the properties of 13 different waxes and five custom-made wax blends; focusing on relevant properties identified in the literature review (Chapter 2). Glass slides were coated and OSB surfaces were treated with the waxes. Contact angle measurements were used to examine relationships between the wax properties and the hydrophobicity of wax-coated glass and wax-treated OSB surfaces.

Chapter 4 is a preliminary experimental chapter that compares the ability of seven different waxes to stabilize the dimensions of OSB. Waxes were sprayed onto OSB at a fixed temperature (100°C) and treated samples were immersed in water. Continuous thickness swelling measurements were made over a period of 21 days.

Chapter 5 compares the ability of eleven different waxes and five wax blends to dimensionally stabilize OSB. Untreated commercially available, “moisture resistant” OSB samples, with high resin content, were also included as a benchmark. The waxes that were tested included polar and nonpolar waxes with a wide range of melting point temperatures. Waxes were sprayed at 25°C above their melting point temperatures. Samples were floated face down on water for 72 h and water absorption and thickness swelling measurements were made after 2 h, 24 h, 48 h and 72 h. Samples were then conditioned at 20 ± 1°C and 65 ± 5% relative humidity for a minimum of two weeks before measurements taken again. In combination with the results from Chapter 3 relationships were established between the water repellency of wax-treated OSB surfaces and the water absorption and thickness swelling behaviour of wax-treated OSB samples. Conclusions were drawn on effects of wax polarity and the ability of waxes to restrict the thickness swelling of treated OSB.

Finally, Chapter 6 discusses the results of all three experimental chapters, makes suggestions for further research, and draws overall conclusions.

Chapter 2. Literature review

2.1 History and current markets

2.1.1 A brief history of oriented strandboard

Oriented strandboard (OSB) is technically a type of particleboard that is composed of thin, rectangular strands of wood that are oriented and bonded together with a waterproof adhesive, as mentioned in Chapter 1 (Elmendorf 1965). The literature sometimes refers to OSB as flakeboard, a term which also includes waferboard (Berglund and Rowell 2005). In contrast to OSB, the squarish flakes of waferboard are not usually aligned or oriented in a specific direction. One of the earliest references to a wood composite that resembles OSB is a patent by Watson (1905). He describes a composite board consisting of "thin pieces of wood that are secured together by means of a suitable bonding agent, so that the particles will overlap and interlock." He refers to the use of many different particle shapes and sizes, but does not emphasize how particle geometry and particle orientation can improve board properties. The influence of particle geometry on the mechanical properties of particleboard was described as early as 1954 (Turner 1954), followed by a series of studies on its effects on board properties (Post 1958; Burmabaugh 1960; Jorngensen and Odell 1961; Jorgensen and Murphey 1961; Post 1961; Lehmann 1974). The advantages of particle alignment were also recognized as early as 1952 (Geimer 1976; Snodgrass et al. 1974), but were not capitalized on until practical methods of orienting wood flakes were developed (Vajda 1974; Impellizzeri et al. 1976). Modern OSB, with its slender and oriented strands evolved from waferboard by using these improvements to create a better structural panel.

The commercialization of OSB can be traced back to early work by Armin Elmendorf, who started to develop cement bonded composite boards using oriented strands and shavings in the 1930s (Impellizzeri et al. 1976). He first described OSB in 1949, as a way to use veneer waste (Elmendorf 1950). However, it was not until 1965 that he filed a patent for the product (Elmendorf 1965). Three years later in 1968 Elmendorf and the Potlatch Corporation established the first North American pilot plant to manufacture OSB on a large scale (Snodgrass et al. 1974; Impellizzeri et al. 1976).

Today OSB rivals plywood in the structural panel market (Howard and McKeever 2012). It makes more efficient use of timber resources than plywood and it has better mechanical properties than waferboard, its predecessor. Plywood and OSB have comparable mechanical properties (Cai and Ross 2010), but the manufacturing costs for OSB can be up to 25% lower (Spelter et al. 2006). This is mainly because OSB is able to use lower quality and cheaper logs that are unsuitable for lumber or veneer (Green and Hernandez 1998), and because up to 90% of each log can be used (APA 2009). Plywood, however, is still considered a superior product in terms of dimensional stability, especially thickness swelling (Spelter et al. 2006; Coulson 2012; Mendes et al. 2013).

2.1.2 Current markets

In 2010, OSB production in North America reached 13.5 million m^3 (UNECE/FAO 2012). The U.S. produced about 9.1 million m^3 of this total, which accounted for 60% of its own structural panel market (Howard and McKeever 2012). In the same year European production exceeded 4.8 million m^3 (UNECE/FAO 2012; UNECE/FAO 2013). By 2012, North American production had increased to 15.5 million m^3 (+ 14.6%) and European production had increased to almost 5 million m^3 (+ 2.7%) (UNECE/FAO 2013). The top five producing countries in Europe were Germany, Romania, Czech Republic, Poland and Latvia (UNECE/FAO 2013). Howard and McKeever (2013) estimated that in 2013 the U.S. consumed 8.9 million m^3 on OSB; 26% more than it produced. In Russia, increases in the construction of timber frame buildings have led to an increase in imports of OSB. Russia has just built its first two OSB plants and future demand for OSB may be met in part from domestic production (UNECE/FAO 2013).

Most OSB panels are manufactured to a standard 1220 x 2440 mm size, with thicknesses ranging from 6.3 - 19 mm (Shmulsky and Jones 2011). These panels are mostly used for structural applications such as sheathing for roofs, walls, and subfloors (APA 2009) (Figures 2.1 – 2.1). Other applications include use as insulation panels, I-joist webbing, packaging, and furniture (APA 2009). OSB is also suitable for engineered wood flooring (Barbuta et al. 2012). Together OSB and plywood represent over 50% of the building materials for residential housing in North America (Moya et al. 2008). In 2010, 82% of the OSB consumed in the U.S. was used for structural purposes and this application alone consumed about 9.32 million m^3 of OSB (Howard and McKeever 2012).

OSB panels that are left unprotected against rain and is exposed to high levels of relative humidity absorbs moisture and swells in thickness, particularly at the edges (

Figure **2.3**). Once this occurs panels often need to be sanded, to make them flat, or replaced at extra cost (Winterowd et al. 2003; Taylor and Wang 2007; Shmulsky and Jones 2011).

Figure 2.1. A typical two-story single family home under construction in West Point Grey, Vancouver, Canada. Note the large amount of OSB for wall sheathing

Figure 2.2. A multi-storey building under construction on Marine Drive, North Vancouver, Canada. OSB was used for wall sheathing. The ground floor is typically used for commercial real estate and the upper levels are for medium density residential accommodation

Figure 2.3. A single-family home under construction in West Point Grey, Vancouver, Canada (left). The mud and water in the foreground suggests that the building was exposed to rain water. A close up (right) of OSB wall sheathing that was left unprotected in a rain shower, while the building was under construction

2.2 Water absorption and thickness swelling

2.2.1 Water absorption

OSB is composed of approximately 95% solid wood (Kline 2005). Wood is a hygroscopic material that changes in moisture content depending on the relative humidity of its environment (Skaar 1972). Dry wood adsorbs water when placed in a humid or wet environment, while wood with a high moisture content loses water when placed in a dry environment. The moisture content of OSB increases by absorption and *adsorption* and decreases it by desorption. Absorption is the physical take-up of liquid water (e.g. capillary action), whereas *adsorption* is the attraction of water molecules to hydrogen bonding sites, such as free hydroxyl group in wood cell walls (Orman 1955, Shmulsky and Jones 2011, Stamm 1964). Water in wood fibres may be present inside the cell walls, as bound water, or in the cell cavities, as free water (water vapour) (Tiemann 1906).

Bound water is held within the polymer matrix of wood by hydrogen bonds (Skaar 1972). The polymer matrix of wood consists of three major components: (1) cellulose (40 – 50%); (2) hemicellulose (25 – 35%); and (3) lignin (18 – 35%) (Pettersen 1984). Bound water is primarily bonded to the free hydroxyl groups of hemicellulose (Browning 1963; Burmester 1970; Burmester and Wille 1975; Burmester 1975; Rowell and Banks 1985). Bound water is also bonded to cellulose, but the crystalline structure of the polymer makes its hydroxyl groups less accessible (Stamm 1964). Water adsorption by cellulose thus occurs mostly in its less crystalline, amorphous, regions (Zeronian et al. 1983; Pizzi 1993). Lignin, which is the aromatic structural component of wood, is the least hydrophilic of the three compounds.

Wood only changes in dimensions when bound water is gained or lost (with the exception of collapse of wood cells that can occur above fibre saturation point). The fibres shrink when cell walls lose water and swell when water is gained. The maximum amount of water bound in the cell wall usually ranges from 25 - 30% of the oven dry weight of wood (Skaar 1972). This maximum is known as the fibre saturation point (FSP) (Tiemann 1906). Below FSP, nearly all water is bonded within the cell wall. Above FSP, wood is dimensionally stable, because the addition of free water does not cause fibres to swell. The mechanical strength of wood is also strongly dependent on its moisture content below FSP, and improves significantly as bound water is lost (Tiemann 1906).

Water (liquid and vapour) absorption by OSB is influenced by the structure of the board, particularly the presence of large voids between strands (inter-strand voids) and smaller voids found within strands (intra-strand voids) (Suchsland 1959; Dai et al. 2005). Liquid water is absorbed into these voids by capillary action and then adsorbed into the walls of the wood cells by diffusion. When dry OSB is immersed in water, initial absorption is rapid and occurs primarily through inter-strand voids (Wu and Piao 1999; van Houts et al. 2004; Semple et al. 2009). The amount of water in OSB (or wood) is expressed as a percentage of its oven dry weight (ASTM 2007). OSB undergoes significant changes in both thickness and linear dimensions with an increase in moisture content. According to Wu and Piao (1999) the short-term (24 h) thickness swelling of OSB is directly proportional to the amount of water it absorbs. Thickness swelling can cause substantial losses in panel strength and many other undesirable effects. For example, linear expansion due to water adsorption can create moisture traps and out-of-plane distortion (Coulson 2012).

2.2.2 Thickness swelling

A considerable amount of research has been done in an attempt to understand and reduce the thickness swelling (TS) of OSB. TS can lead to variations in thickness between different boards, as well as variation within boards. Horizontal density differences, across the plane of an individual board, may lead to variable TS (Suchsland 1962), which can be telegraphed through coatings (Williams and Winandy 2008) or resin impregnated overlays (Biblis 1990). TS is pronounced at the panel edges (Carll and Wiedenhoeft 2009) (Figure 2.4.) and several North American companies have developed ways of restricting the edge swelling of OSB exposed to water (Evans et al. 2013). Thickness swelling variations between boards may also lead to out-of-level floors or out-of-plumb walls, which can be time-consuming and expensive to fix (Shmulsky and Jones 2011).

The total thickness swelling (TTS) of OSB is the net result of two components: reversible thickness swelling (RTS) due to natural hygroscopic swelling of wood, and permanent thickness swelling (PTS) due: (1) the release of compressive strains that were imparted to flakes during hot-pressing (Neusser et al. 1965; Halligan 1970; Kelly 1977; Wu and Suchsland 1997); (2) delamination of glue-line between flakes and cracking of wood, both of which create voids within the board (Kelly 1977; Hsu et al. 1988); and (3) the deformation of flakes. PTS is also sometimes referred to as springback.

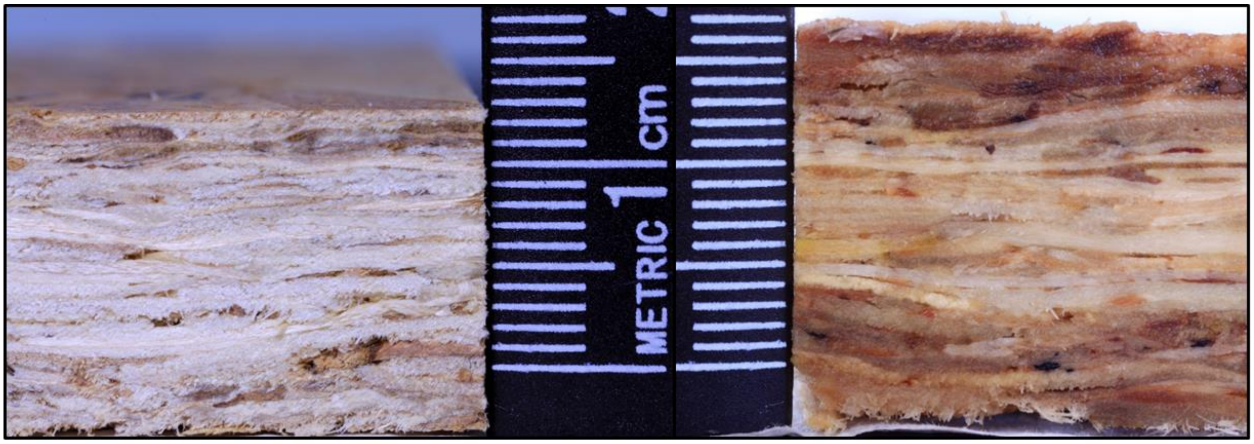


Figure 2.4. Oven dried OSB (left) and the same OSB sample immersed in water for 18 h (right). Note that the panel edge swelled by almost 4 mm (± 20%) after 18 h

The rupture of adhesive bonds when OSB swells, permanently reduces the strength of boards. Hence, mechanical strength properties of OSB are inversely proportional to TS (Suchsland 1973; Suchsland and Xu 1991; Wu and Suchsland 1997; Wu and Piao 1999; Linville and Wolcott 2001). Wu and Piao (1999) reported an average loss of 0.014 MPa internal bond strength for every 1% increase of PTS. Accordingly, if PTS can be reduced then strength losses will be avoided.

PTS can account for 60% to 75% of the TTS of OSB, depending on exposure conditions (Wu and Suchsland 1997; Wu and Piao 1999). The majority of PTS occurs above 80% relative humidity (Gatchell et al. 1966; Wu and Suchsland 1997; Wu and Piao 1999), or above moisture contents of 10% to 15% (Wu and Suchsland 1997; Hartley et al. 2007). PTS has a nonlinear relationship with moisture content: below 5%, barely any PTS occurs, but as moisture content increases above 10% PTS significantly increases (Wu and Suchsland 1997).

It is clear that PTS is associated with strength losses of OSB, as mentioned above. Most PTS occurs rapidly during initial exposure to water and then diminishes over time, until compressive strains are relieved (Post 1961; Johnson 1964; Kelly 1977; Wu and Lee 2002; Moya et al. 2009). It is therefore important to protect OSB building panels during the early stages of construction, when they are vulnerable to rain and high relative humidity. Once construction is complete, panels are not exposed to rain. Furthermore, the relative humidity inside completed buildings is usually lower than that at which significant PTS occurs (Arena et al. 2010; Rudd and Henderson 2007).

2.2.3 Industry standards for measuring thickness swelling

The dimensional stability of structural wood based panels is most often measured in terms of water absorption (WA), thickness swelling (TS), and linear expansion (LE), although other dimensional measurements, such as creep and warp, may also be of interest. According to the standard, ASTM D1037 – 12, WA and TS is measured using a 24 h water submersion test (American Society for Testing and Materials 2012). WA and TS are expressed as a percentage change from values of the sample conditioned at 65 ± 5% relative humidity and 20°C. Linear expansion, on the other hand, is reported as the percentage change in length between 50% and 90% relative humidity, at a constant temperature of 20°C. Although it is not standard practice, longer water submersion tests of 72 h or more are also commonly used by industry.

According to the Voluntary Performance Standard PS 2-04, which most North American OSB manufactures comply to, the average TS of OSB must be limited to 25% (NIST 2004). In Europe, the EN 300 standard limits TS to between 12% and 25%, depending on board type and end-use (EN 2006).

2.3 Factors that affect thickness swelling

The material processing variables that affect the TS of OSB have been well established and include: wood species, strand geometry, board density, resin content, blending efficiency, hydrophobic additives, and pressing conditions (Halligan 1970; Kelly 1977; Maloney 1993). The following three factors will be discussed here in more detail: (1) raw materials; (2) board density; and (3) board porosity.

2.3.1 Raw materials

2.3.1.1 Wood species

The dimensional stability of OSB can be altered by changing the species or mix of species used to make the boards. Species related variables that influence the dimensional stability of OSB include wood density, acidity, and extractives content (Maloney 1993). Of these factors wood density has the largest effect (Halligan 1970; Maloney 1993). Low density wood is usually used to make OSB, because the strands can be pressed together more easily during manufacture, thus ensuring better inter-strand bonding (Maloney 1993). Such compression of strands, however, comes at a price, because compressive strains that are set in the wood strands when they are pressed and bonded together can increase the permanent thickness swelling that occurs when OSB is subsequently exposed to moisture.

The most common hardwood species used to manufacture OSB is trembling aspen (*Populus tremuloides* Michx.) (Wang and Winistorfer 2000; Cai 2012). In fact, the first waferboards produced in Canada consisted of 95% trembling aspen and 5% black poplar (*Populus balsamifera* L.) (Shen 1980). The most common softwood species used to manufacture OSB in North America are southern yellow pine species, such as longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata* Mill.), loblolly pine (*Pinus taeda* L.), and slash pine (*Pinus elliottii* Engelm.) (Wang and Winistorfer 2000). In Europe, Scots pine (*Pinus sylvestris* L.) is used as raw material for OSB, while in Southern Hemisphere countries, such as Brazil, Chile, South Africa and Australia, there is potential for the use of eucalyptus species (*Eucalyptus* spp.) as raw material (Iwakiri et al. 2004). Grant (1995) provided a comprehensive literature review on the effects of alternate wood species on OSB properties. Many studies have also investigated the potential of bamboo as raw material for OSB and have found that the dimensional stabilities of the bamboo boards are sufficient to pass the standards for wood-based OSB (Lee et al. 1996; Sumardi et al. 2006; Malanit et al. 2011).

2.3.1.2 Strand geometry and orientation

It is well known that strand geometry affects the dimensional stability of OSB (Mottet 1967; Turner 1954). Both Halligan (1970) and Kelly (1977) wrote comprehensive reviews of the effects of flake geometry on the TS of flakeboards and other particleboards. They noted that the thickness stability of flakeboard increases as strand thickness decreases and strand length increases. More recently, Brochmann et al. (2004) examined the effect of flake thickness on the TS of OSB. They found that the TS of OSB after 24 h immersion in water was significantly lower for boards that had thin strands at the face of the board and thicker strands in the core. The reduced thickness swelling of boards with thinner strands occurs as a result of reduced densification during pressing (Brochmann et al. 2004). Dai (2004) also reported that TS of OSB decreases as flake width increases and strand thickness decreases. Zhang et al. (1998) showed that high performance OSB composites can be manufactured by using very thin strands for the face layer. Avramidis and Smith (1989) examined the effects of face-to-core ratios on TS of OSB, and did not observe any significant differences for boards made with different layer ratios. Geimer et al. (1975) made flakeboard with different combinations of core material (19 mm pulp chips cut to 0.5 mm with a ring flaker) and face material (50 x 12.7 x 0.5 mm^3 with a disk flaker). They observed that 3-layer flakeboard swells less than boards manufactured from only core strands.

As mentioned in Chapter 1, flake alignment can influence the dimensional stability of flakeboard and OSB. These effects, however, primarily influence linear expansion and flake alignment has little effect on the TS of flakeboard composites (Geimer 1982; Sekino and Suzuki 1984; Shupe et al. 2001).

2.3.1.3 Resin content

The most common resins used to bond OSB are: (1) phenol formaldehyde (PF), (2) methylene diphenyl diisocyanate (pMDI); and (3) urea formaldehyde (UF) resins (Gomez-Bueso and Haupt 2010; Kloeser et al. 2007). These resins are added as a liquid or a powder to the wood flakes before they are pressed together (Gomez-Bueso and Haupt 2010 Ellis 1993; Forintek Canada Corp. 1998; Chapman 2006). Resin type has a significant influence on the TS of OSB (Gillespie 1984; Brochmann et al 2004). Using isocyanate resins instead of phenolic resins, for example, can reduce TS of OSB (Taylor et al. 2008). The use of iscocyanate resins, however, is often restricted due to their higher cost compared to PF or UF resins (Forintek Canada Corp. 1998; Chapman 2006). Increasing the resin content of OSB can also improve the dimensional stability of boards (Linville and Wolcott 2001), but there is an optimal level, after which additional resin no longer reduces TS (Kelly 1977). The optimal resin content for OSB has been reported to be between 6 – 12 %, depending on resin type (Kelly 1977; Generalla et al. 1989; Biblis 1990;). Other factors that affect the optimal resin content include resin distribution (Ellis 1993) and the extent to which the resin fully cures (Halligan 1970; Brochmann et al. 2004). Since adhesives can represent between 15 - 20% of the production costs of OSB, resin content is usually kept to a minimum (Forintek Canada Corp. 1998), with average resin contents being in the range of 2 – 4% of dry board weight (Forintek Canada Corp. 1998; Kline 2005). Premium-grade OSB panels containing up to 10% isocyanate resin are used commercially for I-beams webs, flooring panels, and other applications that require enhanced dimensional stability (Forintek Canada Corp. 1998, Spelter et al. 2006).

In a report by Taylor and Wang (2007), which was later published in a peer-reviewed journal (Taylor et al. 2008), the properties of high performance "moisture resistant" OSB panels were measured. Although the report did not provide information on the resin content of the boards, it did imply that the different manufacturers used high loadings of pMDI resins. The TS of some "moisture resistant" panels after 24 h of immersion in water, was reported to be approximately 70% less than regular OSB. After 72 h the TS of the same boards was approximately 50% less than regular OSB.

2.3.1.4 Wax sizing

About 0.5 – 1.5% paraffin wax is added to OSB to improve its short-term water repellency (Kline 2005; Maloney 1993). The rate of WA and TS of OSB is slowed by the addition of wax sizing (O'Halloran 1989; Roffael and May 1983), but the extent of TS at high humidity conditions is not reduced according to Hsu et al. (1990). Before OSB is pressed, paraffin wax is added to its strands as a molten slack wax or as a water-based wax emulsion (Eckert and Edwardson 1998). Some studies have suggested that emulsion wax is more effective at reducing the rate of WA and TS than neat, molten wax, as a result of differences in wax distribution (Hsu et al. 1990; Eckert and Edwardson 1998). The rate of WA and TS of OSB decreases as its wax content increases (Winistorfer et al. 1996; Winistorfer et al. 1992; Zhang et al. 2007), however, there is a limit to the amount of wax sizing that can be added, after which point additional increases have little effect on thickness stability (Hsu et al. 1990; Maloney 1993). Maloney (1993) provides excellent theory on how wax sizing reduces the rate of WA and TS of particleboards. According to Hsu et al. (1990) the swelling of waferboards manufactured without wax sizing was unacceptable. The literature often emphasizes that wax sizing does not prevent water vapour absorption (Heebink 1967; Maloney 1993). Neimsuwan et al. (2008), however, reported that wax sizing does reduce the rate of water vapour absorption of individual strands, but that this effect is likely to be small in relation to WA by the entire board.

2.3.2 Board density

According to Maloney (1993) the ingress of free water into particleboard is inversely related to board density, is because boards with higher densities are usually less porous; with less space for the ingress of free water via capillaries between the particles. Thickness swelling of OSB and flakeboard increases as board density increases (Linville and Wolcott 2001; Rice and Carey 1978). Linville and Wolcott (2001) reported that the relationship is proportional for OSB, while Rice and Carey (1978) reported a similar but not proportional relationship for flakeboard.

Differential swelling between the high density face and lower density core layers of OSB is well documented (Suchsland 1962). It has been shown that TS increases as density increases and that the rate of TS is highest in the surface layers (Winistorfer and Xu 1996; Wang and Winistorfer 2003; Gu et al. 2005; Tackie et al. 2008). Thus, efforts to improve the dimensional stability of OSB often focus on stabilizing surface layers.

2.3.3 Porosity

Water absorption into OSB is influenced by the permeability, and thus the porosity of the boards (Zhang and Smith 2010a). OSB is highly porous, mainly because of the presence of large inter-strand voids, as mentioned above (Suchsland 1959, Dai et al. 2005). Furuno et al. (1983) described three types of inter-strand voids in flakeboard and named them: Type-I, Type-II and Type-III voids (Figure 2.5). Type-I voids occur between two flakes as a result of their delamination; Type-II occur between the tips of two flakes which are not in contact, but are held in place by two other flakes; and Type-III voids are formed at the tip of a single flake that is squeezed between two other flakes.

Type I **Type II** **Type III**

Figure 2.5. Three types of inter-strand voids in flakeboard, as classified by Furuno et al. (1983)

Dai et al. (2005), who also classified inter-strand voids in OSB, referred to Type-II voids as non-contact voids and Type-III as partially filled edge voids. Perhaps more descriptively, Zhang et al. (2010a) referred to Type-II voids as rectangular voids and Type-III as triangular voids.

The size and shape of inter-strand voids are affected by board density and strand geometry (Dai et al. 2005; Li et al. 2008; Li et al. 2009; Li et al. 2010; Standfest et al. 2009), as well as strand orientation (Lenth and Kamke 1996; Standfest et al. 2009; van Houts et al. 2003). Void sizes decrease when board density increases or when strand thickness decreases. According to van Houts et al. (2003), as well as Lenth and Kamke (1996), boards that are made with long strands that are oriented in a specific direction, produce voids that are also long and thin. As strand length decreases or when orientation is randomized, the voids become shorter and more spherical in shape. According to Li et al. (2009) voids reach a maximum size when strand length is around 110 mm and decrease as the strands become longer or shorter. The average void diameter in OSB normally varies between 100 µm and 300 µm (Li et al. 2009; Li et al. 2010), however, larger voids of 1.5 mm or more in diameter are not uncommon (Standfest et al. 2009).

In terms of volume; voids represent one of the three main components of OSB (Dai et al. 2005). Wu et al. (2006) used X-ray tomography to characterize the void structure of OSB. For a threshold level of 100, they reported that boards with a density of 650 kg / m^3 contained about 4% void space, while boards with a density of 750 kg / m^3 contained about 2% void space. The voids were not distributed evenly throughout the boards. Core layers contained up to 8% void space, while surface layers contained about 1% void space. Standfest et al. (2009), who also used X-ray technology to examine void volumes, reported that voids in surface layers are on average smaller than those in the core. Wu et al. (2006) noted that the ratio of void volume to total board volume increases substantially when higher threshold levels are used during image analysis. Void analysis by X-ray tomography techniques may therefore be biased.

Shaler (Shaler 1986; Shaler and Blankenhorn 1990) used mercury porosimetery to measure the total void volume for flakeboard made of either aspen or maple (*Acer* spp). He developed equations that can be used to determine the inter-strand void volume, based on board density. According to his equations, aspen flakeboard, with a density of 700 kg/m^3, contains of approximately 7.3% inter-strand voids.

Although these descriptions of voids in OSB are helpful, they do little to describe how inter-strand voids are connected and how they affect liquid water flow. In fact, there is very little literature available on this subject. Bolton and Humphrey (1994) argued that the moisture flow paths in flakeboard are heterogeneous, consisting of different types of pores geometries in series. According to them, inter-strand voids may or may not be “connected via low, long and wide slit pores between the flat faces of the flakes.” Their hypothesis is supported by two observational studies that used nuclear magnetic resonance (NMR) imaging to examine the flow of water into OSB (van Houts et al. 2004, van Houts et al. 2006). These studies observed that once inside the board, water consistently traveled in thin corridors, along the length and width of the panel. Another interesting observation was that, in some cases, water penetrated the surface and the edge of OSB at a similar rate (van Houts et al. 2004). This observation was surprising, since the edges of OSB are considered to offer easier access for water ingress than the surface of the board. Indeed, as mentioned before, the edges of OSB boards are usually coated with edge seals to slow WA. Lastly, van Houts et al. (2006) also reported that large strands on the surface of OSB were able to inhibit water ingress into the interior of the board, by blocking access to sub-surface inter-strand voids (van Houts et al. 2006).

2.4 Treatments that reduce thickness swelling

As mentioned above, OSB undergoes reversible thickness swelling (RTS) when moisture is absorbed by wood strands, while permanent thickness swelling (PTS) occurs when compressive stresses are relieved and adhesive bonds fail. Most technologies to control the TS of OSB focus on limiting the amount of moisture that the wood elements absorb, although there are some, such as steam injection pressing, that try to reduce internal strains.

According to Rowell and Banks (1985) there are three types of treatments that can improve the dimensional stability of solid wood: (1) water repellent treatments (Type-I); (2) dimensional stabilization treatments (Type-II); and (3) treatments that are both water repellent and dimension-stabilizing (Type-III). Water repellent treatments, such as film-forming surface coatings or penetrating wax solutions, retard the rate of water absorption, but not the extent of swelling. Dimensional stabilizing treatments do not change the rate of water absorption, but decrease the extent of swelling. According to Hill (2007), the properties of solid wood can be modified through thermal, chemical, and biological processes, or by impregnating wood with polymers. These methods of modification can be used to improve the dimensional stability of solid wood. Three such treatments include: (1) the reduction of hygroscopicity (e.g. thermal modification); (2) bulking treatments (e.g. acetylation and polymer impregnation); and (3) chemical cross-linking (e.g. formaldehyde reaction) (Rowell and Banks 1985).

Many of the same treatments that improve the dimensional stability of solid wood can also be used to improve the dimensional stability of OSB. Technologies available to reduce the TS of OSB can be divided into three main groups: (1) pre-treatment of strands; (2) post-treatment of consolidated boards; and (3) production processes (Del Menezzi and Tomaselli 2006; Mantanis and Papadopoulos 2010). Pre- and post-treatment include thermal and chemical modification, similar to the dimensional stabilizing techniques for solid wood, while "production processes" may include changes in resin content, wax sizing, particle geometry, or steam injection pressing. The following dimensional stabilizing and water repellent treatments for OSB will be discussed here: (1) thermal modification; (2) chemical modification; (3) film-forming surface coatings; and (4) penetrating water repellent treatments.

2.4.1 Thermal modification

When wood is subjected to temperatures over 100°C for extended periods it becomes more dimensionally stable due to thermal degradation of its three major chemical constituents (cellulose, hemicellulose, and lignin) (Beall and Eickner 1970; Esteves and Pereira 2008). As mentioned before, most bound water in wood is bonded to the hydroxyl groups of hemicellulose. Hemicellulose is the least thermally stable of wood's major components and decomposes at temperatures ranging from 130°C to 200°C (Runkel and Wilke 1951; Kudo and Yoshida 1957). Cellulose starts to degrade at temperatures above 200°C (Fengel and Wegener 1989). Lignin is the most stable and the least hydrophilic of the three components. Significant thermal degradation of lignin is reported to begin around 280°C (Kudo and Yoshida 1957; Paul et al. 2006); although some degradation is also reported at temperatures below 200°C (Esteves and Pereira 2008; Fengel and Wegener 1989).

The capacity of the cell wall to hold water decreases markedly as the hydroxyl groups on hemicelluloses are degraded. At the same time the proportion of crystalline cellulose in wood increases when it is exposed to high temperatures (Bhuiyan et al. 2001; Pétrissans et al. 2003;

Wikberg and Maunu 2004; Bhuiyan and Hirai 2005; Boonstra and Tjeerdsma 2006). Thus heat treatment makes wood less hygroscopic. Further reasons for the loss of hygroscopicity during thermal degradation can be attributed to increased cross-linking of lignin and the formation of water insoluble chemicals, such as furfural and acetic acid (Rowell and Youngs 1981; Tjeerdsma et al. 1998; Esteves and Pereira 2008).

The use of thermal modification techniques to improve the dimensional stability of OSB and related products, such as flakeboard, has received considerable attention. Most work aims at removing or degrading the hemicellulose component of the wood, while keeping cellulose and the lignin matrix intact. Theoretically this approach will maintain the structural integrity of the wood elements, while making them less hygroscopic. In general, the literature shows that thermal treatments can reduce the TS of OSB, but at the same time mechanical properties, such as internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE), are often significantly compromised (Mendes et al. 2013; Ohlmeyer 2007).

Peleaz-Samaniego et al. (2013) divided thermal treatments of wood composites into two groups: (1) dry processes, such as torrefaction, which occurs in an environment with limited moisture; and (2) moist or wet processes, such as hot water extraction or steam treatment. The authors emphasized that the classification is unofficial and should only be used for discussion purposes. The same classification will be used here to discuss first pre- and then post-treatments that reduce the TS of OSB using thermal modification.

Thermally pre-treating OSB strands in a dry environment (i.e. torrefaction) decreases the wettablilty of wood strands, which reduces their bonding ability (Suchsland and Xu 1991; Šernek et al. 2004). The IB strength of OSB made with thermally modified strands is, therefore, lower than boards made with untreated strands (Goroyias and Hale 2002; Paul et al. 2006; Ohlmeyer 2007; Mendes et al. 2013). Furthermore, the MOR and MOE of such thermally pre-treated boards is also reduced, because exposure to high temperature in a dry environment embrittles wood strands (Goroyias and Hale 2002; Paul et al. 2006; Ohlmeyer 2007; Mendes et al. 2013).

Thermal pre-treating of OSB strands in wet environments includes processes such as hot water extraction of hemicellulose or pre-steaming of wood strands. Hsu et al. (1988) pre-treated wood flakes (*Populus* ssp.) with saturated steam and founds that the TS of flakeboards made with these flakes decreased as steam pre-treatment time increased. A short treatment time (3 min) did not markedly affect the mechanical properties of the boards, but MOR and IR reduced as treatment time increased. A treatment time of 4.5 min reduced MOR by about 10% and IB strength by about 17%. The authors suggested that partial hydrolysis of hemicellulose reduced the development of stresses during hot pressing. Recently, there has been greater focus on hot water extraction of hemicellulose, since the additional advantage of this technology is that the sugar by-products may be used to produce biofuels (Sattler et al. 2008). Paredes et al. (2008) reported that OSB panels made with hemicellulose-extracted red maple (*Acer rubrum* L.) strands absorbed more water than untreated boards, while TS was only slightly reduced. The authors attributed this surprising finding to increased cell porosity and lower initial equilibrium moisture content (EMC) of hot water extracted strands. Conversely, Hosseinaei et al. (2011a) reported a substantial reduction in WA for OSB made with hemicellulose-extracted southern yellow pine (*Pinus* spp.) strands. These boards were less susceptible to TS than untreated boards and maintained most of their mechanical properties when exposed to water. An increase in bending properties was attributed to the increased cellulose crystallinity of treated wood flakes, while lower IB strength was attributed to a number of factors, including poor adhesion due to low wettability. These findings were later confirmed by Paredes et al. (2010), who also examined the properties OSB made with hemicellulose-extracted pine strands.

Unlike thermal pre-treatments, post-treatments do not improve TS simply by removing or degrading hemicellulose. Instead, it has been suggested that one of the main effects of thermal post treatment is the relaxation of internal strains which normally lead to permanent TS (Suchsland and Enlow 1968; Del Menezzi et al. 2009). Thermal post-treatment in a dry environment is usually done by keeping the boards in a hot press, under low, contact pressure, for short periods of time; or by hot stacking the boards at high temperatures (> 150°C) for extended periods of time. The literature shows that thermal post-treatments can significantly decrease the TS of OSB (Del Menezzi and Tomaselli 2006); however, there are conflicting reports about how the treatments alter mechanical properties. Some results show that mechanical properties, particularly IB strength and MOR, are significantly reduced (Ohlmeyer 2007; Del Menezzi et al. 2009), while others have found that they are unaffected or slightly improved (Hsu 1987, Hsu et al. 1989, Okino et al. 2007, Mendes et al. 2013). According to Ohlmeyer (2007), the mechanical properties of OSB bonded with pMDI resins are less affected by thermal treatments than other types of resin.

Fewer studies have investigated the effects that thermal post-treatment in wet environments have on the properties of OSB. Most of the research in this field has focused on steam injection, during hot pressing (Geimer and Kwon 1999), rather than post-production treatment. Heebink and Hefty (1969) demonstrated that a steam post-treatment quickly releases the internal strains in flakeboard, by allowing the board to swell without restriction. Unrestrained boards decreased in density and mechanical strength upon steam post-treatment. Boards that were restrained during treatment were less dimensionally stable than unrestrained boards, but had better initial strength properties. A patent by Go et al. (2000) describes how steam post-treatment, under vacuum, can significantly reduce the TS of OSB. Steam post-treatment, however, does not seem to be commercially viable, due to the need for additional steaming equipment and the extra sanding that is required to achieve a uniform final thickness after steaming (Hujanen 1973; Kelly 1977). Furthermore, steam post-treatment is also known to degrade the adhesive bonds of UF bonded OSB (Kelly 1977).

Of all the thermal treatments, hot water extraction and dry contact pressing appear to be the ones that are most suited to industrial applications. Hot water extraction, however, is very sensitive to variation in wood stock, temperature, and treatment time. Dry contact pressing offers only limited reductions in TS and the additional treatment time can significantly increase production costs.

2.4.2 Chemical treatments

The two most promising chemical treatments for reducing the TS of OSB include acetylating and pre-treating wood strands with low molecular weight PF resin. Lehmann (1964) evaluated various methods to improve the dimensional stability of particleboard, including the following chemical treatments: (1) impregnating particles with PF resin; (2) adding polyethylene glycol; (3) and cross-linking with formaldehyde vapour. None of these treatments produced boards that were significantly more stable than untreated boards. Other studies, however, have found that impregnating wood particles with low molecular weight PF resin, prior to spraying the particles with conventional adhesive, significantly improves the dimensional stability of particleboards. Early work on PF impregnation of flakeboard particles includes studies by Talbott (1959), Maxwell et al. (1959), and Brown et al. (1966). Low molecular weight PF resin is able to bulk the capillary system inside wood flakes, without chemical bonding, thus restricting moisture ingress (Rowell and Banks 1985). Haygreen and Gertjejansen (1971) found that impregnation of wood flakes with 5 – 10% low molecular weight PF resin significantly reduced the TS of flakeboards. Increased resin content improved the strength properties of flakeboard, regardless of whether flakes were impregnated or sprayed with resin before hot pressing. These results are supported by other studies (Hujanen 1973; Kajita and Imamura 1991). More recently it was reported that impregnating wood strands with as little as 1 - 2% low molecular weight PF resin, in addition to 4 - 5% conventional adhesive, significantly reduced the TS of OSB (Paridah et al. 2006; Wan and Kim 2006). PF impregnation can, therefore, be commercially used to dimensionally stabilize OSB, however, the additional resin blending and drying equipment restricts the technology to speciality products (Haygreen and Gertjejansen 1971).

Another chemical treatment that is able to significantly reduce the TS of OSB is acetylation. Acetylation substitutes hydroxyl groups in wood with less hygroscopic acetyl groups, thus bulking the wood and leaving it in a swollen state. OSB produced with acetylated strands, therefore, absorbs much less water and boards undergo significantly less TS (Papadopoulos and Traboulay 2002). One drawback of acetylation is that water soluble PF and UF resins are less able to bond the acetylated strands together (Papadopoulos and Traboulay 2002; Papadopoulos and Gkaraveli 2003). The acetylated strands are more hydrophobic and water soluble resins are unable to effectively penetrate them (Rowell et al. 1987). Furthermore, the low moisture content of acetylated strands during hot pressing makes them less compressible and thus increased pressures are required for good adhesion (Youngquist et al. 1986). For these reasons, OSB panels produced with acetylated strands and water-soluble resins have poor mechanical properties. Papadopoulos and Traboulay (2002) reported that, depending on the percentage weight gain during acetylation, the IB strength of PF bonded OSB made from acetylated strands was 17.5 - 30 % less than boards made from unmodified strands. Others reported similar reductions in mechanical properties for acetylated and PF bonded flakeboard and particleboard (Rowell et al. 1987; Youngquist et al. 1986). Alternative resins, such as a pMDI (Vick et al. 1991; Youngquist and Rowell 1990) or methylmelamines (Wagner et al. 2007) can be used to bond acetylated flakes without significant losses in strength properties, but these adhesives are usually more expensive than PF resin. Other drawbacks to the use acetylation for the production of dimensionally stable OSB include: (1) the need for large amounts of chemicals; (2) the long reaction times required to acetylate wood particles (Rowell et al. 1986); and (3) the unpleasant vinegar-like smell of acetylated wood (Wagner et al. 2007). Rowell et al. (1986) described a “simplified” acetylation procedure for flakeboard production, which required a reaction time of 3 h to achieve 15% weight gain.

An interesting study by Baştürk (2007) showed that the short-term WA and TS of OSB can be reduced by pre-treating wood strands with chitosan. Chitosan is a modified carbohydrate polymer derived from chitin, the main component of many natural materials, such as insect exoskeletons, crustacean shells and fungal cell walls. According Baştürk water-soluble chitosan acetate is converted back to chitin during hot pressing and acts as a water-repellent film around OSB strands.

2.4.3 Film-forming surface coatings

Little research has been done on the use of film-forming surface coatings to reduce the WA and TS of OSB. He et al. (2000) coated the surfaces or edges of OSB samples using five different types of paint. Such coatings significantly reduced the WA and TS of OSB immersed in water for 24 h. Evans and Cullis (2008) examined the dimensional stability of OSB samples that were coated with UV-cured finishes. They noted that UV radiation is unable to cure coatings that penetrate below the surface of OSB and also that the surface topography of OSB makes it a less than ideal material when using roller coater. Garay et al. (2009) coated OSB samples with either paint or a non-film forming coating called Lasur, and measured the dimensional stability of the samples when they were exposed to 95% relative humidity and a temperature of 40°C for 800 h. They reported that both treatments significantly reduced thickness swelling, but that the penetrating stain, Lasur, was the most effective treatment for the samples that were exposed to high humidity conditions for longer than 200 h. According to Grossman (1992), very thick surface coatings are needed to totally prevent moisture from being absorbed by OSB. He describes acrylic elastomeric coatings that are capable of producing very thick and highly elastic protective films, which can be used to make OSB suitable for exterior applications. He goes further to describe the specific building techniques required to make such a coating system work in practice.

A number of studies have evaluated the long term performance of coatings applied to OSB (Hann et al. 1962; Feist 1982; Grozdits and Bibal 1983; Williams and Winandy 2008). Feist (1982) coated waferboard surfaces with various film-forming finishes and exposed them to natural weathering for 21 – 43 months. He observed that fungal growth occurred in many of the samples and suggested that coatings with defects allowed moisture to penetrate the waferboards, but that the coatings then prevented the moisture from escaping. Williams and Winandy (2008) painted OSB with one or two coats of latex paint and mounted the samples vertically on an outdoor fence. After three years of natural weathering the one-coat system failed, with delamination of surface flakes, while the two-coat system clearly showed the contours of the flakes beneath the paint. They reported that latex paint was only effective at reducing TS when two coats were applied and when the sample edges were sealed with a commercial OSB edge seal. No short-term water soak tests were conducted.

Biblis (1990) examined the physical and mechanical properties of OSB overlaid with resin impregnated paper. He found that when water was sprayed onto the surface, the flakes underneath the overlay would swell up and telegraph through the overlay. According to Biblis applying coats of paints or primers underneath the overlay did not prevent the telegraphing effect of the swollen flakes. A patent by Hetzler and Martin (1983) describes the addition of a porous paper layer onto the surface of waferboard, which might provide limited water resistance.

2.4.4 Penetrating water-repellent treatments

Wax is possibly the most common water repellent used to increase the water resistance of wood products, such as millwork (Feist and Mrax 1978, Williams 2000), decking, and wood based composites (Maloney 1993). When paraffin wax is applied to solid wood, it is normally blended with resin, solvent and fungicides (Feist and Mraz 1978; Banks and Voulgaridis 1980). Solvents allow wax to penetrate the capillary system of wood and block voids, thus forming an internal water-repellent barrier (Borgin 1965). Very little literature is available on the subject of penetrating water repellents for OSB. Two relevant studies and one patent will be discussed here.

Borgin and Corbertt (1970) used various waxes as water repellents for radiata pine wood (*Pinus radiata* D.Don). The water repellents consisted of 2.5%, 10%, 25% or 50% of wax in mineral turpentine. The waxes in their study included paraffin waxes, petroleum jelly, beeswax, and carnauba wax. They found that all waxes were effective at preventing water uptake by and swelling of solid wood, but the best performing waxes were paraffin waxes. They also showed that beeswax's ability to prevent swelling improved over time and that it was consistently better at dimensionally stabilizing wood than carnauba wax and petroleum jelly. They concluded that paraffin waxes could perform even better if they contained hydrophilic groups that would increase their affinity to wood.

A patent by Racota (2007) describes a latex-free wax emulsion that can be sprayed onto the surface of OSB before or after hot pressing. The process she developed is claimed to make the panel more water resistant. The patent, however, does not provide any details on the physical properties of panels sprayed with the emulsion, nor does it mention the use of neat molten wax.

Semple et al. (2009) sprayed water-based wax emulsions and linseed oil-wax solutions onto the surface of hot (120°C) OSB samples. The waxes in their study included soy wax, beeswax, carnauba wax, and paraffin wax. The solid wax spread rates for the water-based emulsions and oil-wax solutions were approximately 9 g / m^2 and 87 g / m^2, respectively. Some of the water-based emulsions were able to reduce the short-term TS of OSB, but many of them caused pre-swelling of the surface strands, which increased the rate of WA and TS. Based on the linear relationship they found for WA and TS, they concluded that the water-based wax emulsions did not significantly reduce water ingress into the intra-strand voids of OSB. Linseed oil and wax solutions were more effective at reducing the short term WA and TS of OSB than water-based emulsions, however, oil-based solutions also failed to block surface voids. The authors mentioned that the best results were obtained when linseed oil dried to form a uniform and continuous film over the surface voids of OSB. Linseed oil solutions that contained beeswax rarely performed better than those containing paraffin or soy wax, and almost never performed better than those containing carnauba wax.

The findings by Semple et al. (2009) indicate that spraying wax onto the surface of OSB may be an effective and reliable method of improving the water repellency of OSB; if wax is able to penetrate the OSB and block inter-strand voids. Spraying neat, molten wax onto the surface of hot OSB will not cause pre-wetting of the surface strands. Such a treatment might be able to form an effective internal water-repellent barrier, without the need for a defect-free surface coating.

2.5 Waxes and their properties

Waxes are notoriously difficult to define. A definition by the German Association for Fat Science (Deutsche Gesellschaft für Fettwissenschaft) include the following criteria: (1) drop melting point temperatures above 40°C; (2) melt viscosities below 10 Pa·s when molten; (3) at 20°C they must be kneadable or hard to brittle, coarse to finely crystalline, transparent to opaque, but not glassy, or highly viscous or liquid (Wolfmeier et al. 2000).

The properties of wax can be engineered according to the needs of an application. According to Neimsuwan et al. (2008) the water repellency of OSB is closely related to wax properties such as chemical composition, melting point, viscosity, and oil content. The following paragraphs will discuss the origin of wax and the following three properties: (1) its chemical composition; (2) water repellency; and (3) melting point temperature.

2.5.1 Origin

Wax can be sourced directly from nature or it can be synthesized from coal, oil, or gas. “Natural waxes are formed through biochemical processes and are products of plant and animal metabolism” (Wolfmeier et al. 2000). Natural wax can be subdivided into three main groups, namely: (1) animal waxes; (2) vegetable waxes; and (3) mineral waxes. Mineral waxes, which include paraffin waxes, such as lignite (montan) and peat waxes, are sometimes referred to as fossil waxes, because they were formed through biological processes during earlier geological periods (Wolfmeier et al. 2000). Synthetic waxes, on the other hand, are manufactured by bonding hydrocarbons to form *n*-alkane and alkene bonded polymer chains. There are two main types of synthetic wax, namely: (1) Fischer-Tropsch waxes; and (2) polyolefin waxes.

2.5.2 Chemical composition

The chemical structure of any wax is dominated by hydrocarbon chains. These chains are also why wax is strongly hydrophobic (Adam 1963; Wolfmeier et al. 2000). The carbon chains can be straight or branched, and their length can range from several thousand carbon atoms to as few as 16 (Wolfmeier et al. 2000). The chemical composition of different waxes can vary considerably, as functional groups, such as aromatic, carboxyl, ester, and amide groups, are often bonded to their carbon chains. Beeswax and carnauba wax, for example, consist mostly of complex esters, as well as fatty acids and fatty alcohols (Kolattukudy et al. 1976; Greener-Donhowe and Fennema 1993). Paraffin wax and microcrystalline waxes, on the other hand, consist entirely of saturated hydrocarbons (Bennett 1963; Hilditch 1965; Greener-Donhowe and

Fennema 1993). Paraffin wax consists primarily of straight chains, while microcrystalline wax contains straight, branched or cyclic components (Hsu and Bender 1988). All waxes are, therefore, blends of various hydrocarbon chains that are either straight or branched, and may or may not contain aromatic and polar components. Waxes can also contain additional compounds. Beeswax, for example, may contain propolis, a resin that is produced by bees (*Apis* spp.) to protect and seal the honeycomb (Budija et al. 2008).

Wax properties depend on the length of the carbon chains and the degree of branching, as well as the presence of functional groups. For example, wax emulsions that consist of long chain n-alkanes are more effective at reducing WA and TS of medium density fibreboard (MDF) and particleboard than those consisting of short chain n-alkanes (Roffael and May 1983; Schriever and Roffael 1984; Hague 1995; Roffael et al. 2005). Hsu and Bender (1988) used contact angle measurements to show that the water repellency of paraffin wax and microcrystalline wax generally increases as the length of the carbon chains increased, while water repellency decreased as the degree of branching increased. The carbon number distribution of the wax and the ratio of straight versus branched carbon chains can be determined by gas chromatography or mass spectrometry (Levy et al. 1961). Another technique used to characterize the chemical structure of wax is infra-red (IR) spectroscopy. IR spectroscopy can be used to identify the functional groups and the bond types that are present, while the degree of branching can be inferred (Coates 2000).

2.5.3 Water repellency

The following paragraphs review: (1) the principles of water repellency; (2) the water-repellency of wood and thermally modified wood; (3) the water repellency of pure wax; and (4) the water repellency of wax-treated wood.

When a liquid droplet is placed on a solid surface, there are adhesive forces between the liquid and the solid, as well as cohesive forces within the liquid (Young 1805). At the edge of the droplet, where the liquid and solid interfaces simultaneously meet the surrounding air, the contact angle (θ) can be measured (Figure 2.6). The angle (θ), which is conventionally measured within the liquid, can be used to assess the wettability of the solid surface according to Young's equation (Young 1805):

$$\gamma_S = \gamma_{SL} + \gamma_L \cos\theta \qquad \textbf{(Equation 2.1)}$$

where:
γ_S = surface energy of solid
γ_{SL} = surface energy of solid/liquid interface
γ_L = surface tension of liquid
θ = contact angle (that liquid makes with solid)

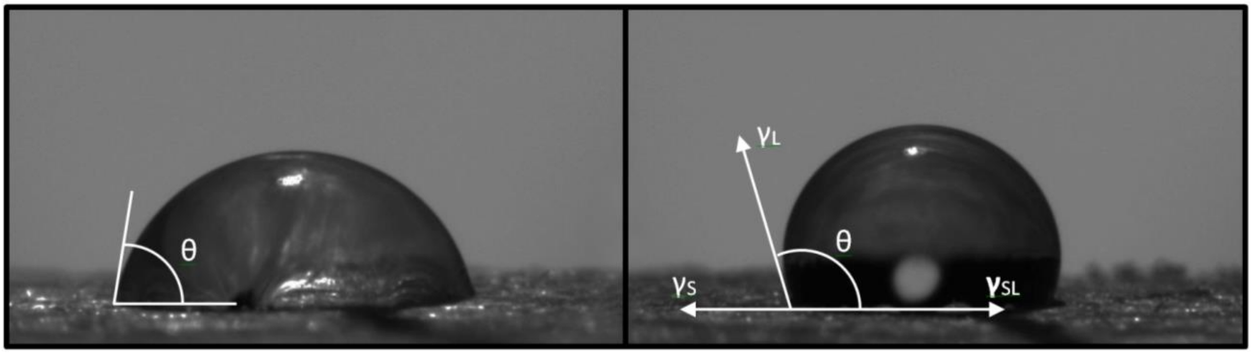


Figure 2.6. Initial contact angle of a 5µL water droplet on a hydrophilic surface (left) and a hydrophobic surface (right). A solid is considered to be hydrophobic when θ > 90°

If the cohesive force within the liquid is larger than the adhesive force between the liquid and the solid, the droplet will bead on the solid surface, and the contact angle will be between 0 and 180 degrees. On the other hand, if the adhesive force is larger than the cohesive force, the droplet will spread over the surface and the contact angle will be zero (Adam 1963).

A common method used to determine the water repellency of materials, including porous materials, such as wood and OSB, is to determine whether the initial contact angle of a water droplet placed on the surface of the material is larger or smaller than 90° (Borgin 1965). If the angle is smaller than 90°, spontaneous capillary action will occur, and the water droplet will quickly be absorbed into the porous medium (Borgin 1965; Richardson 1993; Rowell and Banks 1985). The material is then defined as hydrophilic. Conversely, if the initial contact angle is larger than 90°, the material is hydrophobic, and the water droplet is absorbed into the material at a much slower rate. In this case, most of the water droplet may even be lost due to evaporation, rather than absorption. Thus, a second measure, commonly used to evaluate the water repellency of wood, is to examine the rate of change of contact angle over time (Rak 1975).

The longer it takes for the contact angle of a water droplet to reduce to less than 90°, the more hydrophobic the wood surface is. Water droplets sitting on strongly hydrophobic surfaces tend to have contact angles that remain above 90° until the droplet almost completely evaporates. Semple et al. (2009) sprayed heated OSB surfaces with water-based wax emulsions and linseed oil-wax solutions. They found reported that initial contact angles of water droplets on wax-treated OSB surfaces were similar to those on untreated OSB surfaces, but that the droplets remained on wax-treated surfaces for much longer. It also should be noted that the surface roughness of the solid can have a significant effect on contact angle (Wenzel 1949). The leaves of the lotus plant (*Nelumbo nucifera,* Adams), for example, are extremely hydrophobic as a result of the leaf's rough surface texture, in addition to the presence of wax (Barthlott and Neinhuis 1997).

The contact angles of water droplets on wood surfaces can vary considerably, although they are almost exclusively below 90°. In a study by de Meijer et al. (2000), the static contact angles of water droplets on various wood species were measured along the grain. They measured contact angles on unmodified wood surfaces to be between 54° and 78°. These results agree with those of others who measured static contact angles of water droplets on the surfaces of wood samples cut from various wood species (Gindl et al. 2001; Mantanis and Young 1997; Mohammed-Ziegler et al. 2004). Interestingly, de Meijer et al. (2000) measured contact angles on thermally treated wood to be as low as 61°. Gérardin et al. (2007) reported advancing wood-water contact angles on heat-treated European beech (*Fagus sylvatica* L.) to be 69.4°, and those on heat treated Scots pine to be to be 81.3°; while Pétrissans et al. (2003) reported advancing contact angles of 42.2° on heat treated European beech and 88.9° on Scots pine. Contrary to these findings, Hakkou et al. (2005) reported the contact angles on heat treated European beech to be much higher, with values close to or equal to 90°. Nonetheless, all of these studies observed that the contact angles of water droplets were higher on heat treated surfaces than on unmodified wood surfaces. Hosseinaei et al. (2011b) also found that hot water extraction of wood resulted in larger wood-water contact angles.

As mentioned above, wood can also be made hydrophobic by using water repellents (Borgin and Corbett 1970; Voulgaridis and Banks 1983). Initial contact angles for water droplets on pure paraffin wax surfaces typically range from 105° to 114° (Adam 1963). Meiron et al. (2004) measured the advancing contact angle of water droplets on a smooth beeswax surface to be 111°. Bartell et al. (1936) found the contact angles of water droplets on carnauba wax to be 107°. Holloway (1969) reported the contact angles of water droplets on leaf waxes (i.e. vegetable waxes) to be between 94° and 109°.

Holloway (1969) also reported that waxes with polar functional groups, such as esters and ketones, are less hydrophobic than waxes without these groups. He concluded that the orientation of functional groups affects the hydrophobic properties of wax. Adam and Jessop (1925), for example, reported the contact angles of water droplets on stearic acid to be anywhere between 50° and 105°, depending on the orientation of the polar groups. The literature suggests that waxes with polar functional groups tend to be more effective at increasing the water repellency of wood than waxes without these groups (Adam 1963; Borgin 1965; Rowell and Banks 1985). Polar groups increase the attraction of wax to the wood, while methyl groups and other saturated hydrocarbons repel water. A common method to determine the polarity of wax is to measure the number of carboxylic acids. This is done by measuring the amount of potassium hydroxide necessary to neutralize a sample of known weight (ASTM 2010).

2.5.4 Melting point temperature

The melting point or congealing point of a material is the temperature at which the material changes between liquid and solid phase and is usually reported as a single temperature. For waxes, however, there is no distinct temperature at which it changes between solid and liquid phases; instead wax changes phase over a range of temperatures (Bennett 1963). Greener-Donhowe and Fennema (1993) presented melting curves that accurately plot the melting (or congealing) temperatures for beeswax, microcrystalline wax, and carnauba wax. Most waxes melt at temperatures somewhere between 40°C and 100°C, although some remain solid at temperatures above this range. The melting point temperature of wax increases as the length of the carbon chain and the number of polar functional groups increase, and it decreases as the degree of branching of the wax increases (Wolfmeier et al. 2000). A wax with a high melting point, therefore, generally, has a larger molecular mass and possesses stronger intermolecular forces, than a wax with a low melting point.

Voulgaridis (1986) suggested that stronger intermolecular bonding forces within wax may increase the water resistance of wax-treated wood. He treated Scots pine and European beech samples with solvent-based resin/wax solutions and immersed the samples in water at different temperatures (20°C, 40°C, 60°C, and 80°C). The different water repellent solutions contained paraffin waxes (including microcrystalline wax) with different melting point temperatures (56°C, 85°C, and 115°C). Voulgaridis (1986) found that at low water temperatures (20°C), water-repellent solutions that contained wax with low melting point temperatures performed better than those containing higher melting point waxes, while at higher water temperatures, he found the opposite. At water temperatures of 40°C, 60°C, and 80°C, water repellent solutions that contained the highest melting point wax (115°C) performed the best. These results suggest that wood treated with high melting point waxes might be more effective than those treated with low melting point waxes, because they are better able to resist the effects of warm water.

Eckert and Edwardson (1998) used six different slack waxes, with a wide range of melting point temperatures, to test the effects of melting point temperature on the water repellent properties of OSB. They blended between 0.6 - 1.2% of neat wax with wood strands before boards were pressed, but found no clear relationship between the melting point temperatures of the waxes and WA of test samples after 24 h of immersion in water.

Hsu and Bender (1988) used differential scanning calorimetry and contact angle measurements to examine the effect of melting point temperatures on the water repellency of paraffin wax and microcrystalline wax, but they did not find a relationship between the two properties.

2.6 Summary

Oriented strandboard is a relatively inexpensive building material that is extensively used for residential and commercial construction (Spelter et al. 2006). One shortcoming that limits the use of OSB is the excessive thickness swelling (TS) that occurs when it is exposed to moisture (Spelter et al. 2006, Coulson 2012, Mendes et al. 2013). The porous structure of OSB allows water (liquid and vapour) to easily penetrate it (Suchsland 1959, Dai et al. 2005). According to the literature, initial water absorption by OSB is fairly rapid and occurs primarily through the void network between overlapping strands (Wu and Piao 1999, van Houts et al. 2004, Semple et al. 2009).

TS of OSB often causes problems during building construction, when the panels are unprotected and exposed to rain (Winterowd et al. 2003). Uneven surfaces, created by differential swelling, often need to be sanded level before construction can continue (Shmulsky and Jones 2011). In some cases the affected boards may even need to be replaced (Taylor et al. 2008). TS may also cause boards to lose mechanical strength (Wu and Piao 1999). The standard method to test the TS of OSB is to immerse samples in water for 24 h and to measure their thickness increase, relative to their original dimensions. The most widely used industry standard requires the TS of OSB to be less than 25% after 24 h of immersion in water (NIST 2004).

There are many technologies available that can reduce the rate or extent of OSB thickness swelling; few of these, however, are used in practice. Those that are used are limited to speciality products that are sold at premium prices. For example, high performance OSB products, which are bonded with large amounts of superior, but expensive isocyanate-based resins, are commercially available (Forintek Canada Corp. 1998). Such premium-grade OSB products, however, can cost up to three times more than regular OSB (Evans, P.D., personal communication, March 5, 2014). Film-forming surface coatings, such as paint, can be used as a post-treatment to improve the thickness stability of OSB, but they are ineffective, unless thick coatings are applied (Grossman 1992). Post-treating OSB with water repellents, particularly wax, may be more effective than film-forming surface coatings at improving the thickness stability of OSB. Waxes are effective water repellents for solid wood (Gibson 1965, Borgin and Corbett 1970, Feist and Mraz 1978), but almost no research has investigated their use as a post-treatment for OSB; except for the work of Semple et al. (2009) and Mantanis and Papadopoulos (2010). Waxes are already blended with OSB strands before pressing to make the panels more water resistant (Maloney 1993). These waxes are able to increase the capillary pressure required for spontaneous water absorption by OSB (Gibson 1965; Borgin and Corbett 1970). There is, however, a limit to the amount of wax that can be blended with the strands before pressing, after which point additional increases in wax content have little effect on thickness stability (Hsu et al. 1990, Winistorfer et al. 1992).

This thesis explores whether it is possible to increase the water repellency and improve the dimensional stability of OSB by spraying molten wax onto the surface of hot OSB. Waxes have melting point temperatures as low as 40°C and they have very low viscosities when they are liquids (Wolfmeier et al. 2000). It is, therefore, possible to spray molten wax onto the surface of OSB as a post-treatment. When OSB exits the hot press its surface temperature may be as high as 250°C. If molten wax is sprayed onto such hot OSB surfaces it may be able to flow into and block the inter-strand voids of OSB, before solidifying to form a water repellent barrier. I hypothesize that such wax-treatments may reduce the rate of water absorption and thickness swelling of OSB, as hypothesized in Chapter 1.

Chapter 3. Wax properties that affect the water repellency of wax-treated OSB

3.1 Introduction

The aim of this chapter is to characterize the waxes that I sprayed onto OSB surfaces in Chapters 4 and 5. Some of the properties that are likely to affect the performance of wax as a molten water-repellent treatment for OSB were identified and discussed in the previous chapter. The properties that are measured in this chapter are: (1) chemical composition; (2) water repellency; (3) melting point temperature; and (4) viscosity.

Thirteen waxes were sourced based on their expected melting point temperatures and chemical composition. Three wax blends, each consisting of equal proportions of two waxes with notably different properties, were prepared to determine the combined effect of their properties on the water repellency of wax-treated OSB. Two more wax blends were prepared by mixing one part ethylene maleic anhydride (EMA) with three parts wax. This was done to created wax blends with expected melting point temperatures and polarity of the wax blends (Grauman 2013). All wax blends were prepared by melting the individual waxes or additives together.

The water repellency of pure wax surfaces and molten wax-treated OSB surfaces were determined by measuring the contact angles that water droplets made on treated surfaces. Two response variables were measured: (1) initial contact angle; and (2) the time it took for water droplets to spread and form a contact angles of less than 90° (abbrev. as t<90°). Regression analysis was used to examine the relationship between the water repellency of pure wax and molten wax-treated OSB surfaces. I hypothesize that there will be a positive correlation between the variables measured on each of the two surface types. Because surface roughness affects apparent contact angle (Wenzel 1949), a profilometer was used to measure the roughness of the pure wax surfaces. The roughness data was statistically analysed and the results were used to help explain the contact angles of water droplets on pure wax surfaces.

There are also factors that may affect the contact angles that form on wax-treated OSB surfaces. The wood strands in OSB, for example, are thermally modified and partially coated with resin and wax when the board is manufactured. Unsal et al. (2010) measured contact angles on thermally post-treated OSB panels and reported the initial contact angle to be as large as 100°, while contact angles on untreated OSB were approximately 75°. Semple et al. (2009) reported the initial contact angles of water droplets on untreated OSB surfaces to be 108°. They also reported that water droplets placed on untreated OSB surfaces remained there for a shorter time than when placed on OSB surfaces sprayed with water-based wax emulsions or linseed oil-wax solutions. Thus, I hypothesize that the initial contact angles of water droplets placed on molten wax-treated OSB surfaces will be higher than those on untreated OSB surfaces, and that the $t<90°$ times on wax-treated surfaces will be longer than those on untreated surfaces.

Lastly, based on suggestion that waxes with polar functional groups are better water repellents for solid wood (Borgin 1970), I examine the relationship between the acid number of wax, a proxy measure for polarity, and the contact angles that water droplets make on wax-treated OSB surfaces.

3.2 Materials and methods

3.2.1 Waxes

The thirteen individual waxes and the five wax blends are listed in Table 3.1. Animal waxes included beeswax and lanolin, while vegetable waxes included carnauba wax, soy wax, and stearic acid (sourced from palm wax). Mineral waxes included microcrystalline wax, Vaseline, Merkur 300, Tekniwax 600, and a paraffin wax commercially called “synthetic beeswax”. Synthetic beeswax is used as a cheap alternative to beeswax when making candles. The original patent for Vaseline states that it is: “the residuum of petroleum that is left after the greater part of petroleum has been distilled off” (Chesebrough 1872). Merkur 300, which was donated by Sasol Wax (South Africa), is also a petroleum jelly, similar to Vaseline. Original, unscented Vaseline was sourced from a local pharmacy in Vancouver, Canada. The raw, unfiltered lanolin was donated by Cape Mohair and Wool (South Africa), while carnauba wax (grade T1), filtered beeswax, stearic acid, synthetic beeswax, and microcrystalline wax were purchased from Wicks and Wax, in Burnaby, Canada. Soy wax was purchased from Maiwa Supply, on Granville Island in Vancouver, Canada. Synthetic waxes included three Fischer-Tropsch waxes that were donated by Sasol Wax (South Africa) (Figure 3.1). Sasol Wax also donated Tekniwax 600.

The wax blends that were custom-made for the study were melted together at a 1:1 or a 3:1 weight ratio (Table 3.1). Proportional amounts of each wax were weighed and the solids were placed together in a single glass beaker. The glass beaker was then placed in an oven, set at approximately 10°C above the melting point temperature of the wax with the highest melting point. Once the wax in the glass beaker was liquid, the blend was stirred together using a glass rod. The required amount of wax for each experimental replication, of each experiment, was independently blended, shortly beforehand, using new parent stock. Therefore, only small quantities of the wax blends, typically between 15 to 50 g, were freshly prepared whenever needed. Two of the blends that were prepared contained ethylene maleic anhydride (EMA). These blends were included because of their expected high melting point temperatures and polarity.

Table 3.1. The 13 waxes and five wax blends used to treat OSB

Wax	**Origin**
Beeswax	Animal
Lanolin	Animal
Soy wax	Vegetable
Stearic acid	Vegetable
Carnauba wax	Vegetable
Sasolwax C	Fischer-Tropsch
Tekniwax 801	Fischer-Tropsch
Tekniwax 600	Petroleum
Sasolwax M3M	Fischer-Tropsch
Merkur 300	Petroleum jelly
Vaseline	Petroleum jelly
Microcrystalline wax	Petroleum
Synthetic Beeswax	Petroleum
Beeswax + Sasolwax C (1:1)	Blend
Beeswax + Vaseline (1:1)	Blend
Beeswax + Synthetic Beeswax (1:1)	Blend
Beeswax+ Ethylene Maleic Anhydride (3:1)	Blend
Sasolwax M3M + Ethylene Maleic Anhydride (3:1)	Blend

Figure 3.1. Fischer-Tropsch and paraffin waxes as they were received from Sasol Wax, South Africa

3.2.2 Contact angle measurements

3.2.2.1 Experimental design

The sessile drop method was used to measure the contact angle of water droplets on two types of surfaces: (1) wax-coated glass slides; and (2) wax-treated OSB surfaces. Wax-coated glass slides are sometimes referred to as "pure wax surfaces" in the text below. A randomized block design was used to examine the effect of the different waxes on the contact angles that water droplets made on each of the two surface types (pure wax or OSB). Measurements on wax slides were replicated eleven times and measurements on OSB were replicated six times. OSB panels were donated by Tolko Industries, Canada (more information on the OSB panels can be found in Section 4.2.3). An independent OSB panel was used for each experimental replication (block), and panels were sampled from Tolko's production line at different times to account for random variation in board properties caused by variation in raw materials and the manufacturing process. A 5 µL droplet of distilled water was placed onto the surface in question (pure wax or OSB) and images of the droplets were recorded over time. Water droplet volume had a standard deviation of 0.3 µL. Contact angles were calculated using software programed with a Young-Laplace algorithm (CAM 200 software, KSV Instruments, 2007. CAM 200, 3rd edition, Espoo, Finland). Analysis of variance, for a randomized block design, was used to determine how the wax-treated surfaces differed with regard to: (1) initial contact angle; and (2) the time it took water droplets to spread and form contact angles less than 90°. The statistical program Genstat 12.1 (VSN International 2009) was used to analyze data with a 95% confidence interval ($\alpha = 0.05$) and to check the assumptions of ANOVA (i.e. independent observations, normality, and equal variance). Results are presented in graphs and error bars on each graph (± standard error of difference, $p < 0.05$) can be used to estimate whether differences between individual means are statistically significant.

3.2.2.2 Sample preparation

A table saw (Altendorf F45 ELMO) was used to cut a square piece of OSB (150 x 150 x 18 mm^3) from a random location on an independent OSB panel. A band saw (Ryobi BS 902) was then used to divide the square into 20 strips (75 x 15 x 18 mm^3); so that the surface strands of each strip were oriented perpendicular to its length. A wax treatment was randomly assigned to 18 of the strips and one strip was left untreated. The remaining (20th) strip was discarded. The 19 selected samples were then oven dried at 100 ± 2°C for 24 h, and once dried they were placed in a vacuum oven at 90 ± 1°C.

OSB samples, including untreated control samples, were then individually placed in a second oven (170°C), between two heated metal plates (1kg each), for 10 min. This was done to mimic the temperatures reached when OSB is pressed and to ensure that the surface was hot enough to prevent molten wax, which was subsequently applied, from solidifying too quickly on the surface of the sample. Approximately 20 g of each wax type was placed in a 125 mL glass beaker and heated to 100 ± 2°C. A disposable pipette was used to apply a 1 µL drop of molten wax close to the center of each sample. Voids on the surface of the sample were avoided when placing the wax droplet on the OSB and care was taken to ensure the wood grain of the treated area ran perpendicular to the length of the OSB strip. The molten droplet was left to absorb into the OSB surface for ten seconds, before the remaining wax, on top of the surface, was wiped off using a clean cotton cloth. This was done to prevent the excess wax forming a thick coating over the wood surface. The treated OSB samples were conditioned at 20 ± 1 °C and 65 ± 5% relative humidity for a minimum of five days before contact angle measurements were made.

Similarly, wax-coated glass slides were also prepared for each wax type. Approximately 20 g of each wax was individually placed in a 125 mL glass beaker, which was then placed in an oven (100 ± 2°C) until the wax was molten. Individual glass slide were vertically dipped into the molten wax for 1 min, before being removed and horizontally placed on a flat surface; where the wax was left to solidify. Coated slides were placed in a desiccator for a minimum of 1 hour before contact angle measurements were taken. Care was taken to keep the prepared samples free of any surface contamination, which could have affected contact angle measurements.

3.2.2.3 Contact angle measurements

The sessile drop method was used to measure contact angles. All measurements were made in a climate controlled room (20 ± 1 °C and 65 ± 5% r.h.), using a goniometer (KSV CAM 101). The goniometer consisted of a digital camera, a height-adjustable stage, and a syringe filled with distilled water (Figure 3.2). The digital camera was connected to a personal computer, so that its image could be viewed on-screen, in real time. The height-adjustable stage was positioned directly in front of the camera, and the syringe was fixed in a vertical position above the stage. Samples (pure wax or OSB) were placed on the stage and it was adjusted so the surface of interest appeared on the lower portion of the computer screen. OSB surfaces were positioned so that the wood's grain directly below the syringe ran parallel to the image plane, i.e. perpendicular to the location of the camera. This was done to record how water droplets spread along the grain. A 5 µL drop of distilled water was placed on the positioned surface and images were recorded every 1 s for 480 frames and every 15 s for 360 frames thereafter. The left and right contact angle of each image was calculated using software programed with a Young-Laplace algorithm (CAM 200 software, KSV Instruments, 2007. CAM 200, 3rd edition, Espoo, Finland). From each measurement, the initial contact angle (Ci) and the time it took for the contact angle to spread and form an angle of less than 90 degrees (t<90°) was recorded.

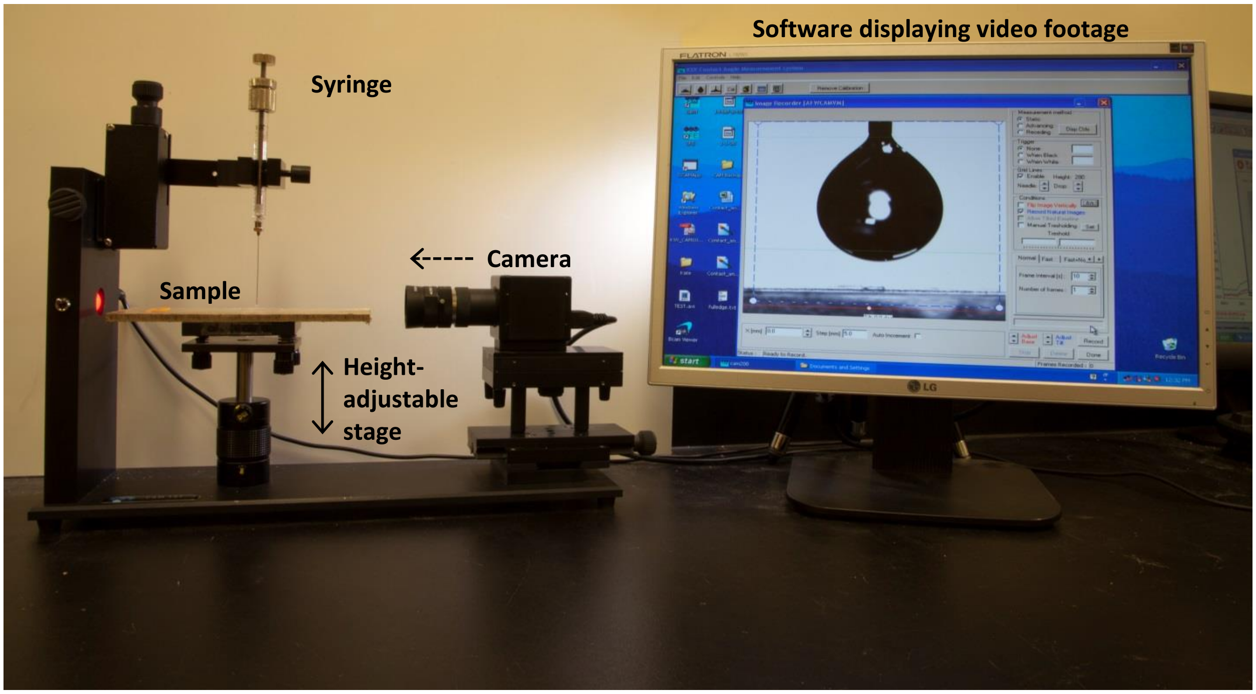


Figure 3.2. Goniometer equipped with a camera and syringe (left) and CAM 200 software (right), which was able to calculate the geometry of water droplets using a Young-Laplace algorithm

3.2.3 Surface confocal profilometry

3.2.3.1 Surface roughness measurements on pure wax surfaces

A white-light non-contact confocal profilometer (Altisurf 500 ®, ALTIMET, France) was used to measure the roughness of wax-coated glass slides (Figure 3.3). Wax-coated glass slides were prepared as described above (Section 3.2.2.2). A randomized block design, with a single factor (wax type) was used to determine whether the surface roughness of wax-coated glass slides differed. The experiment was replicated three times and new samples were prepared for each replication (block). Statistical analysis was performed using Genstat 12.1 (VSN International 2009) (α = 0.05), as described above (Section 3.2.2.1).

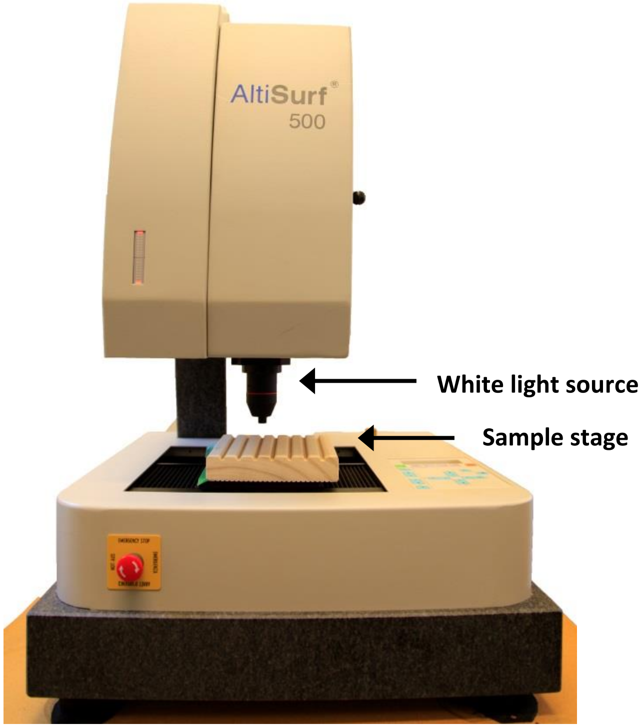


Figure 3.3. The white-light non-contact confocal profilometer (Altisurf 500 ®, ALTIMET, France) used to scan the surface profiles of pure wax surfaces

The profilometer was used to scan a 10 x 10 mm^2 area on each sample surface. The gauge resolution was set at 0.333 nm (Head No.3) and the sampling rate was 30 Hz. Profiles were scanned from west to east with an x-axis spacing of 8.5 µm and y-axis spacing of 1111 µm. Ten profiles, each consisting of 1179 measured points, were scanned per specimen. Measurement speed was 250 µm / s and each scan took 8 min 4 s.

The image analysis software package, AltiMap Premium (Version 6.2.6142), was used to analyse the profiles and extract the roughness data for each scanned sample. First, the ten profiles were uploaded into the program and any non-measured points were filled using data from neighbouring points. The average surface roughness (R_a) of each profile was then calculated, using a 0.8 mm roughness cutoff (λ_c). The R_a value of a profile is the arithmetic mean deviation of its peaks and valleys from its center line (Ashori et al. 2008). The R_a values of the ten profiles were averaged to estimate the mean roughness of the entire 10 x 10 mm^2 area.

3.2.3.2 Profilometry image rendering

Topographical images of five of the different types of wax-coated glass slides were rendered by combining high resolution profile scans for each surface. The following five pure wax surfaces were scanned: (1) stearic acid; (2) carnauba wax; (3) microcrystalline wax; (4) Vaseline; and (5) Merkur 300. The methods used were similar to those described Section 3.2.3.1, however, the profiles were scanned at much higher resolutions. The sampling rate was set at 30 Hz and the gauge resolution was set at either 3.333 nm (Head No.2) or 0.333 nm (Head No.3). Scan areas were either 10 x 10 mm^2, or 5 x 5 mm^2, or 1 x 1 mm^2. The areas were scanned from west to east, with an x-axis spacing of 3.5 µm and y-axis spacing varying between 3.5 µm and 4.5 µm. The measurement speed was 100 µm / s. The image analysis software, AltiMap Premium (Version 6.2.6142), was used to render the images. Each individual profile was levelled by subtracting the points from a 3rd degree least squared polynomial. A thresholding function was then used to reduce the heights of peaks and the depths of valleys that fell outside the 99.5th percentile. Rendered images are presented in Section 3.3.2.2.

3.2.4 Scanning electron microscopy

Five OSB surfaces, each coated with a different wax type, were examined using scanning electron microscopy (SEM). The waxes were: (1) beeswax; (2) carnauba wax; (3) Merkur 300;

(4) Tekniwax 600; and (5) Vaseline. A table saw (Altendorf F45 ELMO) was used to cut a square piece of OSB (150 x 150 x 18 mm^3) from a random location on an independent OSB panel (more information on the OSB panel can be found in Section 4.2.3). A small resaw was then used to isolate 5 mm of the face layer by splitting each block across its horizontal plane. The isolated surface layer, therefore, measured 150 x 150 x 5 mm^3 after resawing. A bandsaw (Ryobi BS 902) was then used to cut five small equilateral triangles, with side lengths of 10 mm, from areas on the face layer that were free of voids. The side lengths of the triangular samples were then reduced to approximately 5 mm by holding the samples between thumb and forefinger and sanding the sides down with 220 grit abrasive paper. The triangular shaped samples were then placed in an oven at 100 ± 2°C for a minimum of 1 h. Approximately 20 g of each of the five waxes mentioned above were individually placed in separate 125 mL glass beakers. The five beakers were then placed in an oven (100 ± 2°C) until the waxes were molten. Each of the five small triangular OSB samples was picked up using clean tweezers and was dipped into one of the molten waxes for three seconds. The hot, wax-coated samples were then placed in a Petri dish and left in a vacuum desiccator for 1 h at 22°C, before being attached to a 12 mm diameter aluminum SEM stub using epoxy resin as an adhesive. All samples were mounted on the same stub, hence the need for samples to be triangular. A digital photograph of the mounted samples was taken and individual samples were labelled on the picture for future identification (Figure 3.4). A sputter coater (Nanotech SEMPrep II) was used to coat the samples with an 8 nm layer of gold, before they were examined using a field emission scanning electron microscope (Hitachi S-4700, FESEM), with an accelerating voltage of 5 kV. Secondary electron images of the wax coated OSB surfaces were obtained and saved as TIFF files.

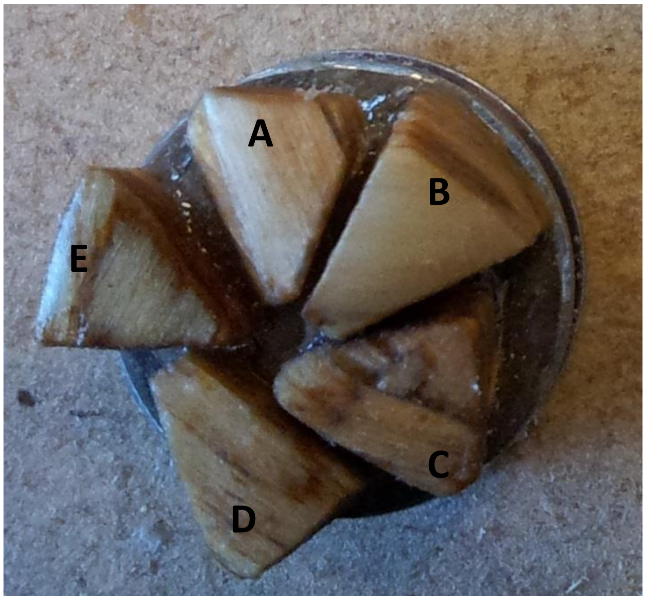


Figure 3.4. The 12 mm diameter SEM stub with the five wax-treated OSB samples that were examined using scanning electron microscopy: (A) beeswax; (B) carnuaba wax; (C) Merkur 300; (D) Tekniwax 600; (E) Vaseline

3.2.5 Melting point temperatures

Melting point temperatures of waxes were characterized by measuring their congealing points (ASTM D938 – 12) and their drop melting points (ASTM D127 – 08)). Together these two measurements provide an estimate of the melting point range of each wax.

3.2.5.1 Congealing point: ASTM D938 – 12

A drill press was used to drill a 5 mm hole through the length of a small cone-shaped cork stopper. A thermometer was pushed through the hole, so that the bulb of the thermometer extended 20 mm from the narrow side of the cork. Approximately 50 g of wax was placed in a 125 mL glass beaker. The glass beaker, containing the wax, and an empty Erlenmeyer flask (125 mL) were both heated to 100 ± 2°C. Once the wax was molten, the beaker was removed from the oven and the bulb of the thermometer was dipped into the wax. The thermometer was used to gently stir the wax until the thermometer reading stabilized. The thermometer was then quickly removed from the beaker and turned horizontally, so that a liquid wax droplet remained attached to its end. The thermometer was continuously rolled between thumb and forefinger to ensure that the droplet remained hanging on the end of the bulb. While doing this, the hot Erlenmeyer flask was removed from the oven and the thermometer bulb was secured inside the flask by fitting the cork stopper. The hot Erlenmeyer flask slowed the rate of cooling of the molten wax droplet. The entire assembly was slowly rotated about its horizontal axis until the hanging wax droplet congealed enough to rotate up with the bulb. The temperature at which this occurred was recorded as the congealing point temperature of the wax in question. The procedure was repeated three times for each wax and the average (mean) temperature is reported (Table 3.3).

3.2.5.2 Drop melting point: ASTM D127 – 08.

Two small cone-shaped cork stoppers were collected. A number of small grooves (3 mm deep) were then cut along the sides of both corks using a hand saw. A drill press was then used to drill a 5 mm diameter hole through the length of each cork. A thermometer was pushed through each hole, so that the bulb of the thermometers extended 100 mm from the narrow side of the corks. Both thermometers were then placed in a refrigerator and chilled to approximately 4°C.

Approximately 50 g of wax was placed in a 125 mL flask and heated to 100 ± 2°C. One of the chilled thermometers was removed from the refrigerator. Its tip was wiped clean of any moisture and it was very briefly dipped into the molten wax. The thermometer bulb, with its wax-covered tip, was then immersed in water (16 ± 2°C) for a minimum of 5 min. This procedure was repeated for the second thermometer. Each thermometer was then fitted to an empty test tube (25 mm in diameter and 150 mm long). A 1500 mL flask was filled with water and placed on a heating plate. The two test tubes were vertically suspended in the water bath so that the water level was just below their rims. The hot plate was switched onto “medium heat” (approximately 160°C) and the water was heated. The two temperatures, when the wax at the tip of each of the two thermometers melted and dropped off, were recorded. The drop melting point of the wax is reported as the average of these two temperature measurements.

3.2.6 *Viscosity*

The apparent viscosity of each wax was measured using the standard test method, ASTM D2669 – 06, however, the amount of wax used for each measurement was reduced from 800 g to 200 g, because insufficient amounts of each wax were available to use the standard test amount. Approximately 200 mL of molten wax was poured into a 250 mL glass beaker (Griffin standard form). The glass beaker was placed on a hot plate and a thermometer was suspended, with its bulb immersed just below the surface of the molten wax. A Brookfield synchro-electric viscometer (model LVT, 60 rpm, No. 2 spindle) was positioned above the glass beaker, so that its spindle was immersed up until the indicated immersion mark. The wax was heated to ~60°C above its melting point and then slowly cooled. The dynamic viscosity of the wax was measured at 100°C, as well as at temperatures 25°C, 15°C, and 5°C above the melting point of the wax. Measurements were repeated three times and the average for each wax is reported in Table 3.4.

3.2.7 *Acid number titration*

The empirical acid number was calculated according to the standard test procedure ASTM D1386-10. A 0.1 N solution of ethanolic potassium hydroxide was made by slowly dissolving 6.6 g of potassium hydroxide (KOH) (Sigma-Aldrich, ACS reagent, ≥85%, pellets) in 5.6 g of distilled water and then diluting the solution to 1000 mL with ethanol (reagent grade, anhydrous, denatured, Sigma-Aldrich). The ethanolic potassium hydroxide solution was then standardized with a 0.1 N solution of hydrochloric acid (HCl) (hydrochloric acid concentrate, standard solution, Sigma-Aldrich). As an indicator, 1 g of phenolphthalein was dissolved in 100 mL of ethanol. Between 1 - 2 g of the wax in question was weighed and placed in a 250 mL glass beaker. The beaker was placed on a warm hot plate and 40 mL of xylene (reagent grade, Sigma-Aldrich) was added to dissolve the wax. Five drops of phenolphthalein was added to the xylene solution. The solution was then titrated with ethanolic potassium hydroxide until it turned pink for at least 10 s. The volume of ethanolic potassium hydroxide necessary to neutralize the solution was used to calculate the acid number. The acid number represents "the number of milligrams of potassium hydroxide necessary to neutralize 1 g of the sample” (ASTM 2010).

The following equation was used to calculate the acid number:

$$Acid\ number = (A - B)(0.1N)(56.1) \div C \quad \textbf{(Equation 3.1)}$$

Where:
A = millilitres of alkali solution required for titration of the sample
B = millilitres of alkali solution required for titration of a blank sample
N = normality of the alkali solution
C = grams of sample used

3.2.8 Fourier transform infrared (FTIR) spectroscopy

Wax slides were prepared by individually placing 10 g of each wax in 125 mL glass beakers, heating the waxes in an oven (100 ± 2°C), and then vertically dipping a glass slide into each wax. The coated slides were placed on a horizontal surface to allow the waxes to cool and solidify to form an even surface. The slides were then placed in a desiccator for a minimum of 1 h, before infra-red spectra were obtained using an FTIR spectrometer (Perkin Elmer Spectrum One, Waltham, MA, USA) equipped with a single bounce attenuated total reflectance accessory (PikeMiracle, PIKE Technologies, WI, USA). Before each measurement a background spectrum was obtained. Each infra-red spectrum consisted of 24 scans taken over a range from 4,000 – 700 cm^{-1} at a resolution of 4 cm^{-1}. The recorded FTIR spectra can be found in Appendix 1.

3.2.9 Statistical methods

Regression analysis was used to examine the relationships between selected wax properties and the water repellency of wax-treated OSB. The statistical program, “R Studio”, was used to analyze the data with a 95% confidence interval ($\alpha = 0.05$) and to check the assumptions of ANOVA (RStudio2014). Results for the regression analysis are reported in Section 3.3.7 -3.3.8.

3.3 Results

3.3.1 Contact angles

Analysis of variance revealed significant ($p < 0.05$) differences between the initial contact angles of water droplets on different types of wax-coated glass slides ($p < 0.001$), as well as on different types of wax-treated OSB surfaces ($p = 0.01$) (Table 3.2). Furthermore, there were also significant differences ($p < 0.001$) in the time it took for water droplets to form contact angles of less than 90°, on both wax-coated glass slides and wax-treated OSB surfaces. The analyses of variance and relevant data is appended to this thesis (Appendix 1).

Table 3.2. Summary of the ANOVA for the initial contact angles of 5 µL water droplets and the time it took droplets to form contact angles of less than 90° (t<90°) on wax-coated slides and wax-treated OSB surfaces (averaged across all wax types)

	p -value	
Surface type	**Initial contact angle (°)**	**t<90° (min)**
Wax-coated glass slides	< 0.001	< 0.001
Wax-treated OSB surface	0.01	< 0.001

3.3.1.1 Glass slides coated with different wax types

Water droplets that were placed on glass slides coated with stearic acid formed initial contact angles of 128°, significantly larger than those of droplets on any of the other wax types (Figure 3.5). Slides coated with a blend of Sasolwax M3M and ethylene maleic anhydride had the second largest initial contact angles, measuring 109.7°, significantly larger than most other wax types; except for slides coated with the six wax types that have clear data points in Figure 3.5. The smallest contact angle formed on slides coated with lanolin (100.6°), however, there were no significant ($p > 0.05$) differences in the contact angles of water droplets on lanolin coated slides and slides coated with: (1) carnauba wax (100.8°); (2) Sasolwax C (101.6°); (3) synthetic beeswax (103.6°); or (4) Vaseline (102.1°).

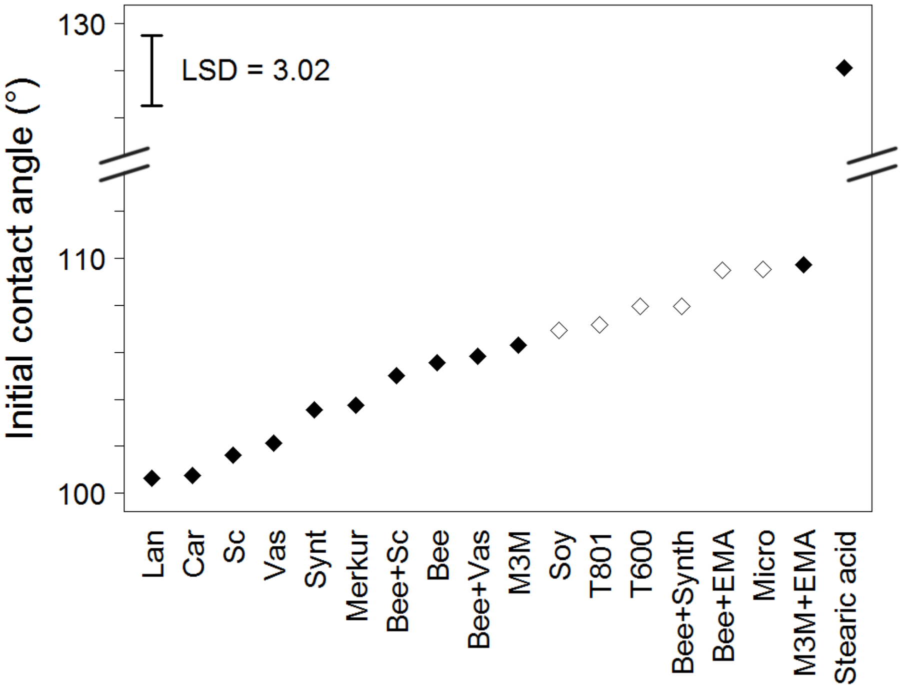


Figure 3.5. Initial contact angle of 5µL water droplets placed on glass slides coated with different wax types (n = 11). Note the large mean initial contact angle of water droplets on stearic acid. Differences larger than the least significant difference (LSD = 3.02°) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for a blend for Sasolwax M3M and ethylene maleic anhydride (M3M+EMA). Refer to Appendix 1 for precise numerical values

The t<90° on microcrystalline wax surfaces was 42.7 min, significantly longer than those on any of the other wax coated slides (Figure 3.6). The 2nd longest t<90° was for glass slides coated with Tekniwax 600 (37.3 min) and the 3rd longest time was for slides coated with stearic acid (31.8 min). The t<90° times for these three waxes were significantly ($p < 0.05$) different from each other, as well as those of all other wax types. The 4th longest t<90° was for slides coated with Tekniwax 801 (22 min), however, there was no significant ($p < 0.05$) difference in this time and the t<90° times of the four wax-coated slides that have clear data points in Figure 3.6. The t<90° on lanolin coated slides was 21.6 seconds, smaller than those of any of the other wax-coated slides, but not significantly different from those of slides coated with Merkur 300 (1.35 min) or Sasolwax C (2.3 min).

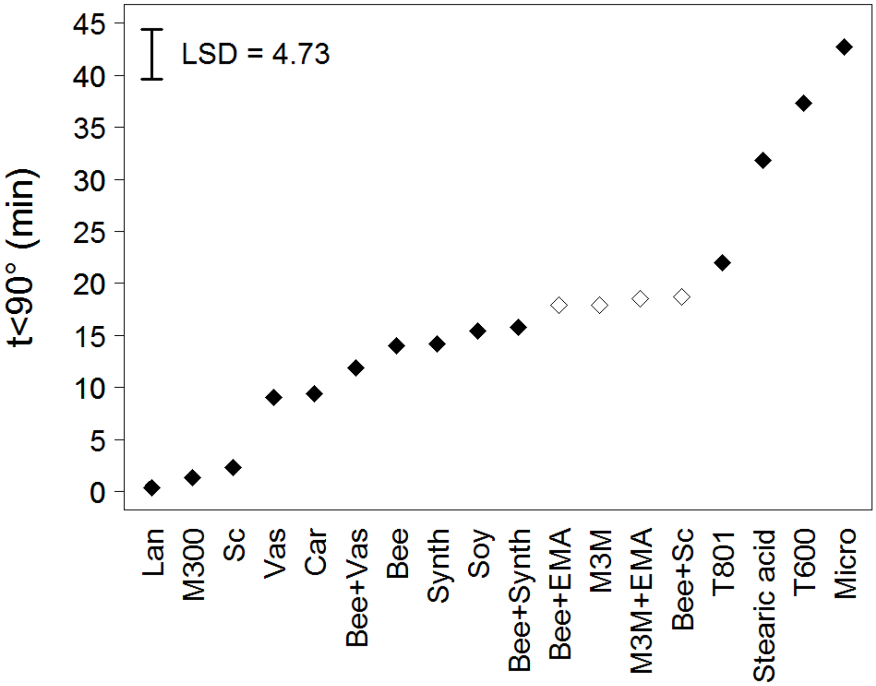


Figure 3.6. The time it took for 5µL water droplets to form contact angles of less than 90° on glass slides coated with different wax types (n = 11). Differences larger than the least significant difference (LSD = 4.73 min) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for Tekniwax 801 (T801). Refer to Appendix 1 for precise numerical values

3.3.1.2 OSB samples treated with different wax types

On untreated OSB surfaces, water droplets formed an initial contact angle (118.6°) significantly larger ($p < 0.001$) than on OSB surfaces treated with soy wax (105°) (Figure 3.7). OSB surfaces treated with soy wax had the smallest initial contact angles, significantly smaller than those of most of the other wax types, but not significantly smaller than those of surfaces treated with: (1) carnauba wax (114.3°); (2) lanolin (113.6°); (3) microcrystalline (114.2°); or (4) synthetic beeswax (113.7°). The largest initial contact angles were formed on surfaces treated with Merkur 300 (124.8°), however, there were no significant ($p > 0.05$) differences between these contact angles and those formed on untreated OSB surfaces, nor were there any differences between them and those formed on OSB surfaces treated with any of the eleven wax-treated surfaces that have clear data points in Figure 3.7.

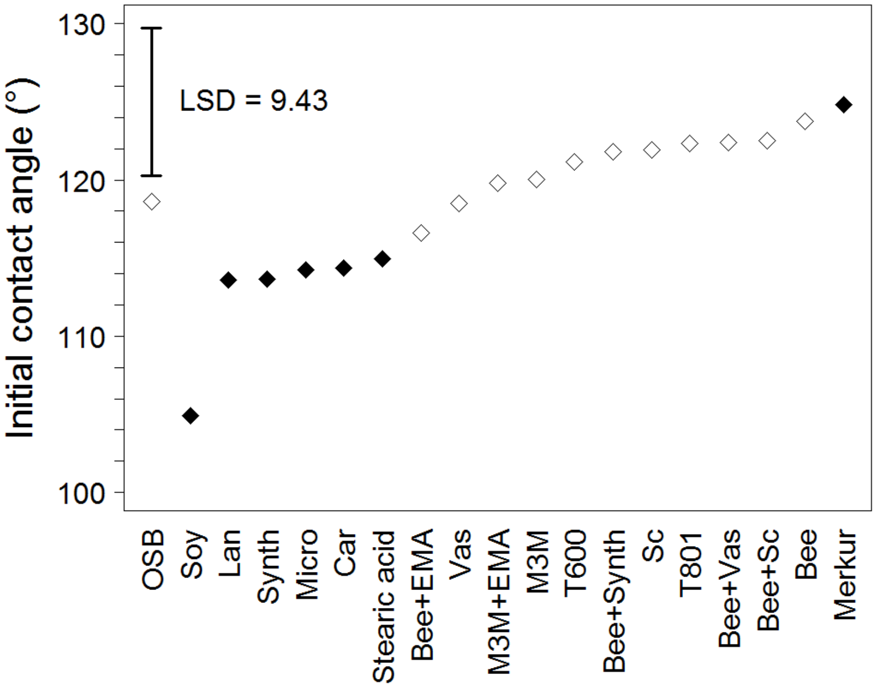


Figure 3.7. Initial contact angle of 5µL water droplets placed on OSB surfaces treated with different wax types (n = 6). Differences larger than the least significant difference (LSD = 9.4°) are statistically significant at a 5% level. Clear data points are not significantly ($p > 0.05$) different to the data point for Merkur 300. Refer to Appendix 1 for precise numerical values

The average t<90° time for water droplets that were placed on untreated OSB surfaces was 8.3 min (Figure 3.8). There were no significant differences between this t<90° time and those of droplets on surfaces treated with any of the following five wax types: (1) lanolin (0.49 min); (2) Sasolwax C (5.3 min); (3) soy wax (13.1 min); (4) Tekniwax 801 (14.8 min); or (5) Vaseline (14.9 min). The shortest t<90° time was for water droplets placed on OSB surfaces treated with lanolin, however, there were no significant ($p > 0.05$) differences between these times and those of droplets placed on either untreated OSB surfaces or surfaces treated with Sasolwax C. The longest t<90° time was for droplets placed on surfaces treated with a blend of beeswax and Sasolwax C (31.5 min), however, there were no significant differences between the t<90° times of these droplets and those of droplets placed on surfaces treated with any of the nine wax types that have clear data points in Figure 3.8.

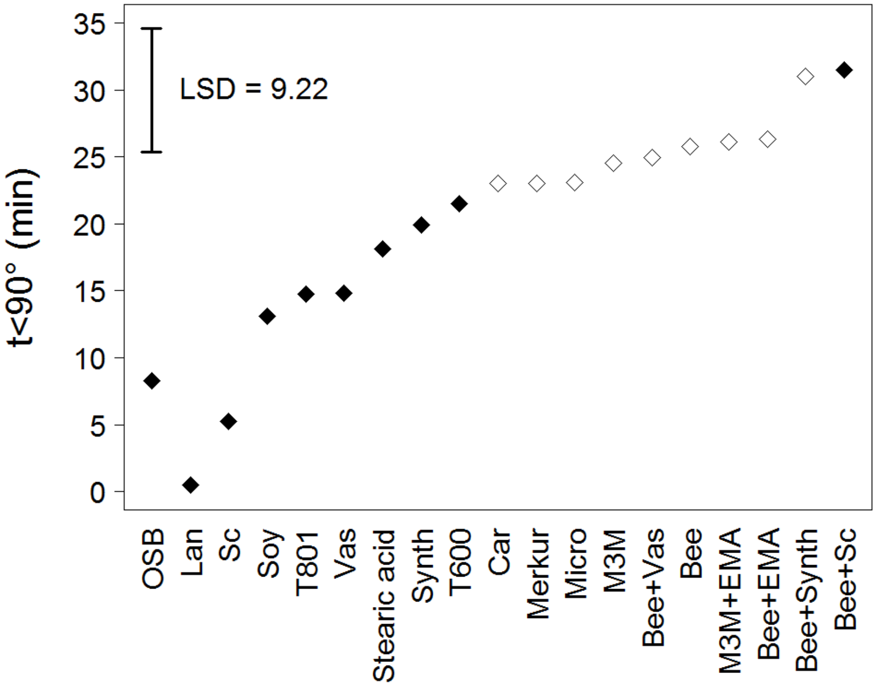


Figure 3.8. The time it took for 5µL water droplets to form contact angles of less than 90° on OSB surfaces treated with different wax types (n = 6). Differences larger than the least significant difference (LSD = 9.22 min) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for a blend of beeswax and Sasolwax C (Bee+Sc). Refer to Appendix 1 for precise numerical values

3.3.2 Surface confocal profilometry

3.3.2.1 Surface roughness measurements of wax-coated glass slides

The average surface roughness (R_a) of glass slides coated with stearic acid was 64.8 µm, higher than those of any of the other wax-coated slides (Figure 3.9). Tekniwax 600 coated slides had the 2nd roughest surface (18.2 µm), followed by Sasolwax C (14.2 µm). These three waxes had surfaces roughness values that were significantly ($p < 0.05$) different from each other as well as from those of surfaces created by the other waxes. The 4th roughest surfaces were those of glass slides coated with a blend of beeswax and Sasolwax C (7.7 µm). These surfaces , however, were not significantly ($p > 0.05$) rougher than those of wax slides coated with any of the following five wax types: (1) soy wax (6.8 µm); (2) Sasolwax M3M (6 µm); (3) beeswax (5.8 µm); (4) Vaseline (5.8 µm); and (5) a blend of beeswax and ethylene maleic anhydride (5.2 µm). The smoothest surfaces were those of glass slides coated with lanolin (1.6 µm). The surface roughness of lanolin coated surfaces, however, was not significantly ($p > 0.05$) different than those of the five waxes that have clear data points in Figure 3.9.

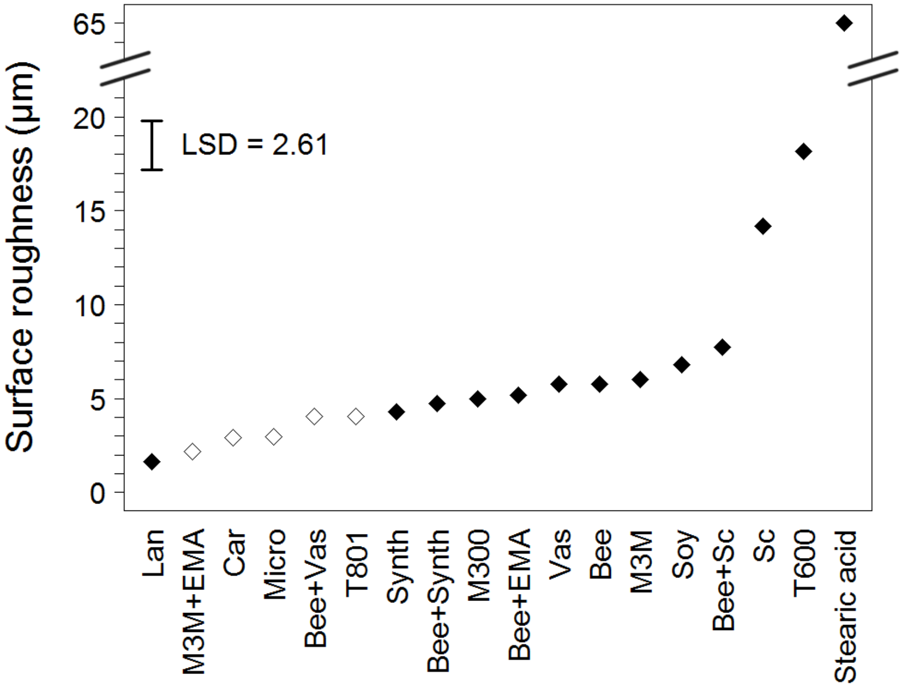


Figure 3.9. Average surface roughness (R_a) of glass slides coated with different wax types (n = 3). Differences larger than the least significant difference (LSD = 2.61 µm) are statistically significant at a 5% level. Clear data points are not significantly different to the data point for lanolin (Lan). Refer to Appendix 1 for precise numerical values

3.3.2.2 Profilometry images

Topographical images of five of different types of wax-coated glass slides are shown in Figures 3.10 to 3.13. Notice that the z-axis scale for Figure 3.10 is reported in millimetres while those in the other figures are reported in micrometers. Stearic acid crystals were large enough to be visible to the naked eye. The height differences between the top and bottom of the stearic acid crystals were so large that the valley regions fell beyond the 3 mm focal plane of the profilometer (Figure 3.10).

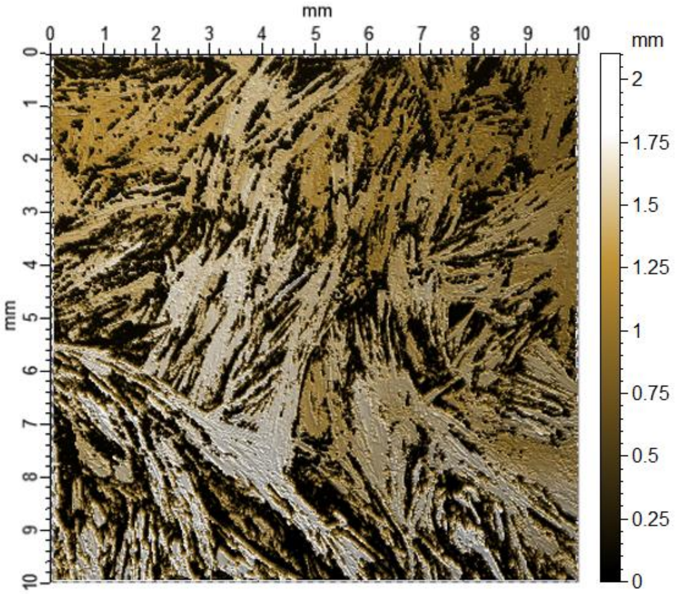


Figure 3.10. Profilometry image of the surface of a glass slide coated with stearic acid. The 10 x 10 mm^2 image consists of 1177 profile scans, scanned with x-axis spacing of 8.5 µm and y-axis spacing of 8.5 µm. The gauge resolution for the z-axis was 0.333 nm (Head No.3). The white and brown areas represent large wax crystals, while the black areas represent unmeasured points that were beyond the 3 mm focal plane of the profilometer head

The surfaces of glass slides coated with carnauba wax (Figure 3.11) and Vaseline (Figure 3.13) appeared to be relatively smooth, while the surfaces of the slides coated with microcrystalline wax (Figure 3.12) had microscopic peaks (colored white) and valleys (colored black).

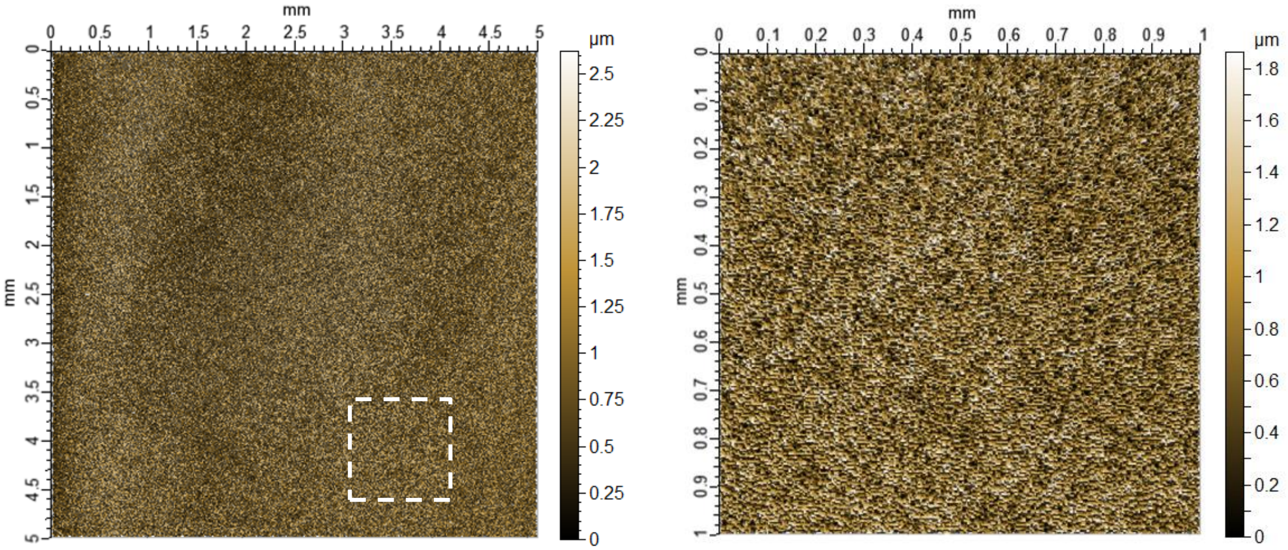


Figure 3.11. Profilometry images of the surface of a glass slide coated with carnauba wax. The original 5 x 5 mm^2 image (left) consists of 1251 profile scans with x-axis spacing of 3.5 µm and y-axis spacing of 4 µm. The area within the dashed white square on the original image is magnified on the right. The gauge resolution for the z-axis was 3.333 nm (Head No.2)

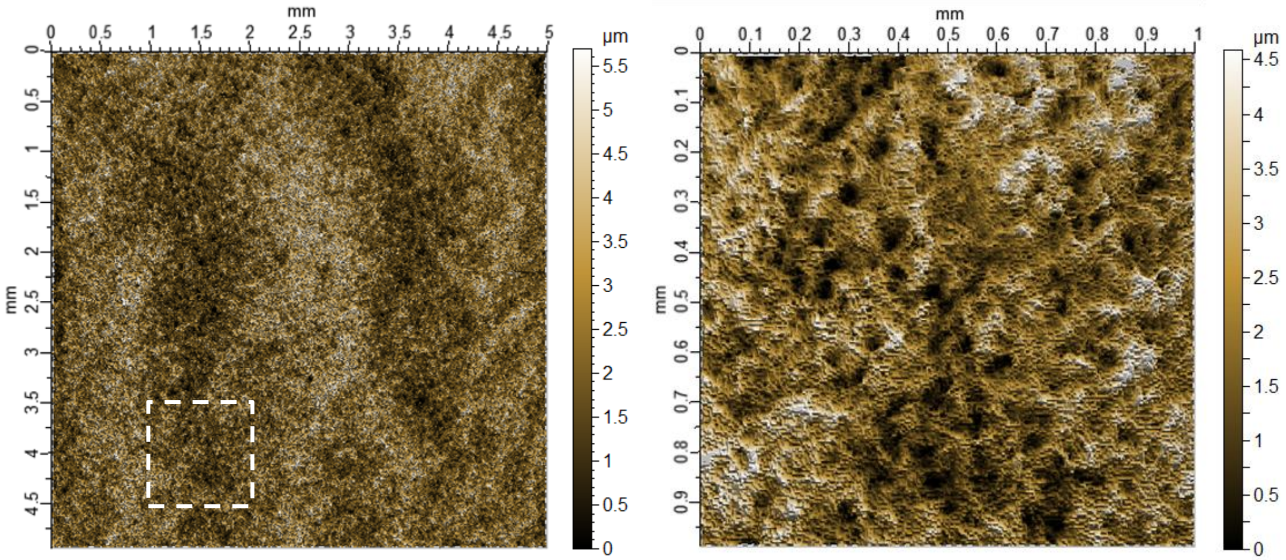


Figure 3.12. Profilometry images of the surface of a glass slide coated with microcrystalline wax. The original 5 x 5 mm^2 image (left) consists of 1112 profile scans, scanned with x-axis spacing of 3.5 µm and y-axis spacing of 4.5 µm. The gauge resolution for the z-axis was 3.333 nm (Head No.2). The magnified image of the area within the dashed white square (right) shows that the surface of microcrystalline wax formed microscopic peaks (white) and valleys (black), similar to those found on the super-hydrophobic surfaces of the leaves of some plant species (Barthlott and Neinhuis 1997)

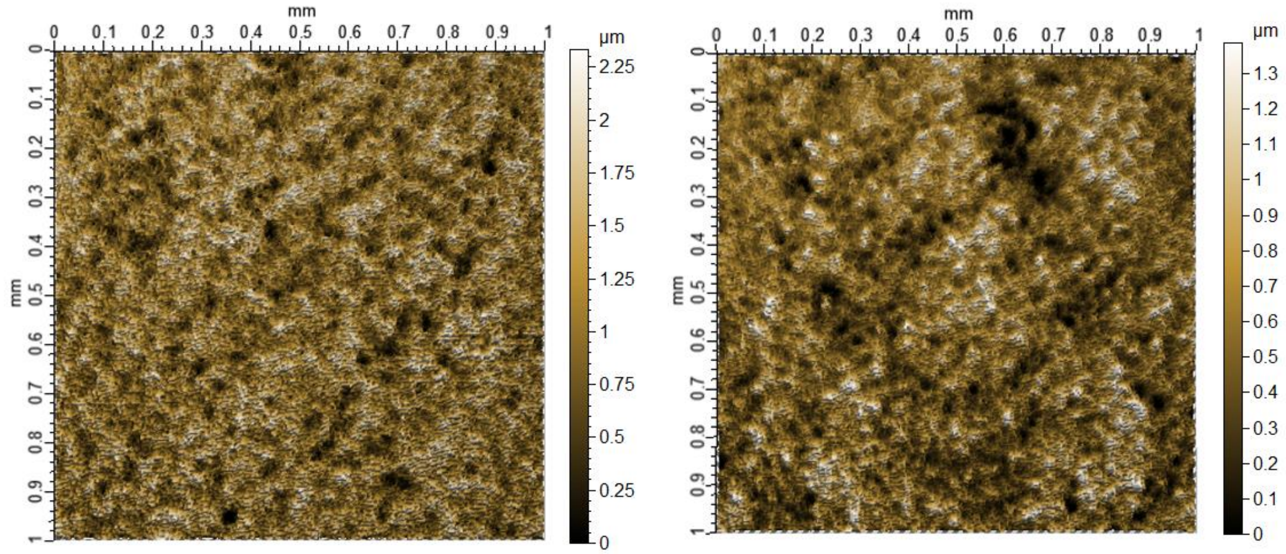


Figure 3.13. Profilometry images of the surface of a glass slide coated with two different petroleum jellies, Vaseline (left) and Merkur 300 (right). The 1 x 1 mm^2 images consists of 287 profile scans, scanned with x-axis spacing of 3.5 µm and y-axis spacing of 3.5 µm. The gauge resolution for the z-axis was 3.333 nm (Head No.2)

3.3.3 Scanning electron microscopy

SEM photomicrographs of (1) beeswax; (2) carnauba wax; (3) Merkur 300; (4) Tekniwax 600; and (5) Vaseline on OSB are shown in Figures 3.14 – 3.18. The surfaces of all wax-treated samples were totally covered (coated) with wax and there were considerable differences in the morphology of the surfaces. OSB surfaces coated with beeswax had tiny holes present on the surface (Figure 3.14). Whether these holes were merely superficial, or whether they penetrated the OSB surface, was not clear. OSB surfaces coated with carnauba wax were smooth, but large cracks were present (Figure 3.15). Merkur 300 tended to agglomerate on certain areas on OSB surfaces and its surface morphology was not as smooth as those of beeswax and carnauba wax (Figure 3.16). OSB coated with Tekniwax 600 had small crater-like formations on the surface (Figure 3.17). Vaseline coated OSB surfaces were very smooth and the morphology suggests that a certain amount of Vaseline was absorbed into the hot OSB surface (Figure 3.18).

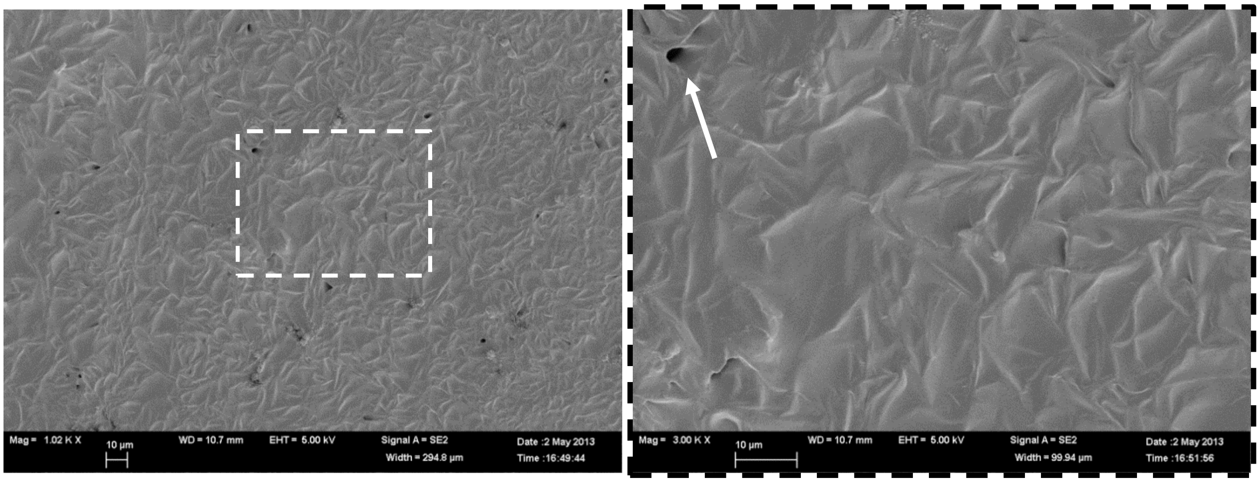


Figure 3.14. SEM photomicrographs of an OSB surface coated with beeswax. The lower magnification image (left) shows that wax covered the OSB surface, but that tiny holes were present in the coating. The image on the right showes the area within the dashed white rectangle at a higher magnification

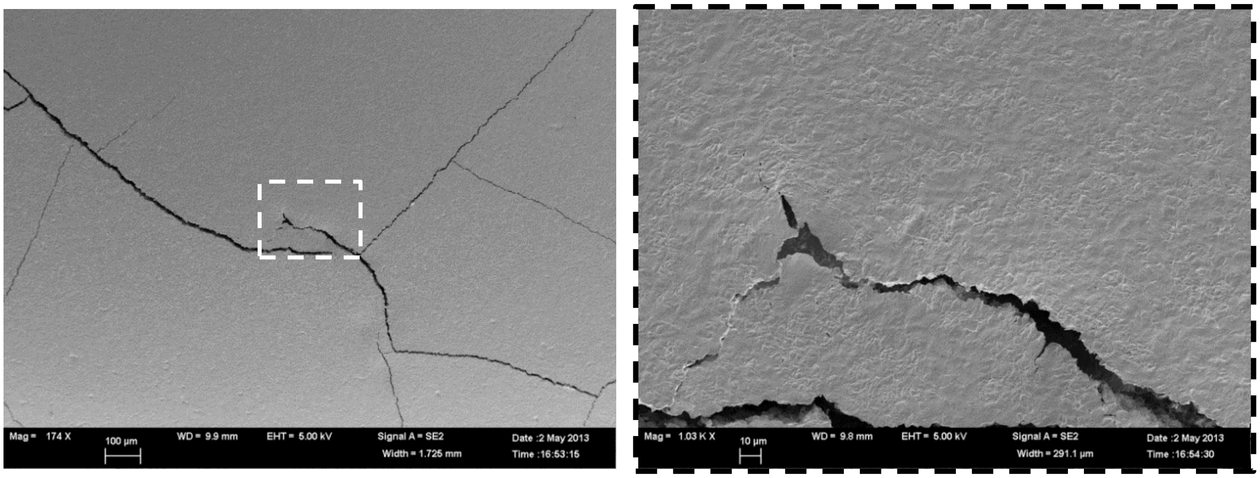


Figure 3.15. SEM photomicrographs of an OSB surface coated with carnauba wax. The lower magnification image (left) shows that the wax totally covered the OSB surface and formed a smooth coating with large and small micro cracks at the surface. The image on the right shows the area within the dashed white rectangle at a higher magnification

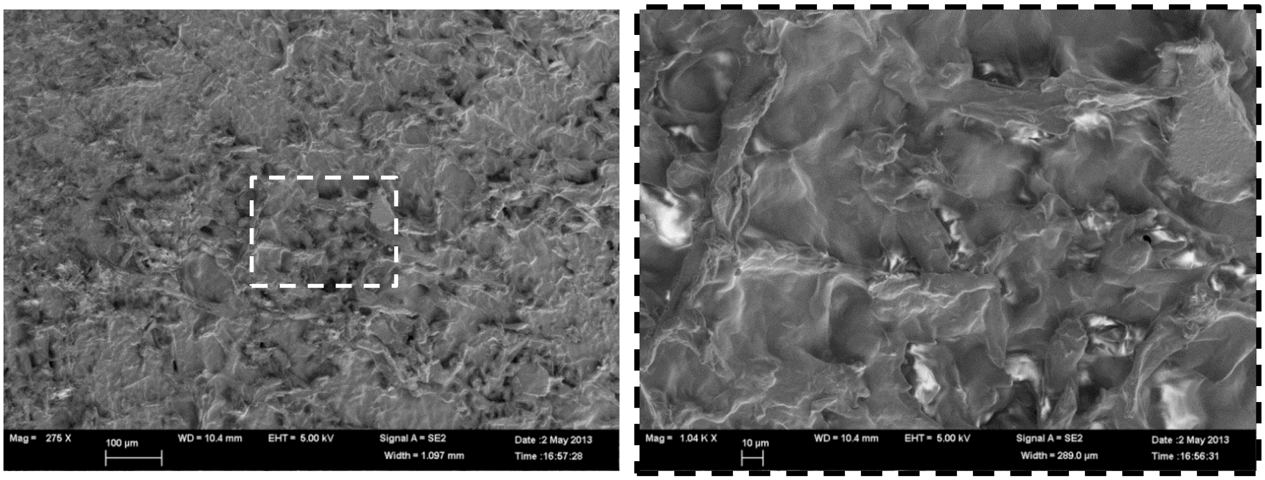


Figure 3.16. SEM photomicrographs of an OSB surface coated with a Fisher-Tropsch wax (Merkur 300). The lower magnification image (left) shows that the surface of Merkur 300 is not as smooth as those of beeswax or carnauba wax. The image on the right shows the area within the dashed white rectangle at a higher magnification. Merkur 300 tended to agglomorate around certain areas

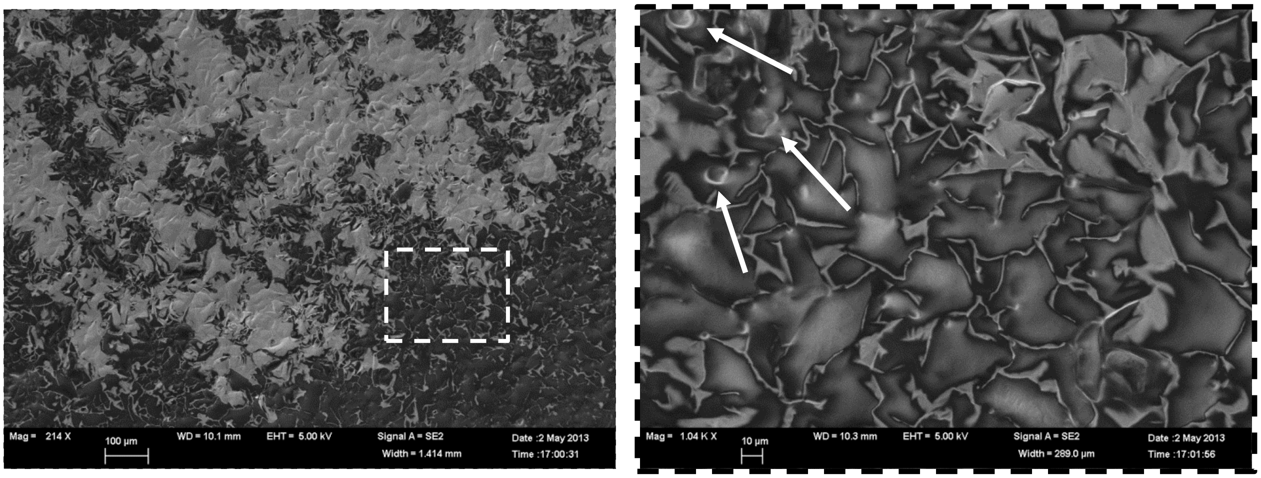


Figure 3.17. SEM photomicrographs of an OSB surface coated with a paraffin wax (Tekniwax 600). The lower magnification image (left) shows that the surface of Tekniwax 600 appeared to be relatively rough. The image on the right shows the area within the dashed white rectangle at a higher magnification. Crater-like formations were visible on the surface

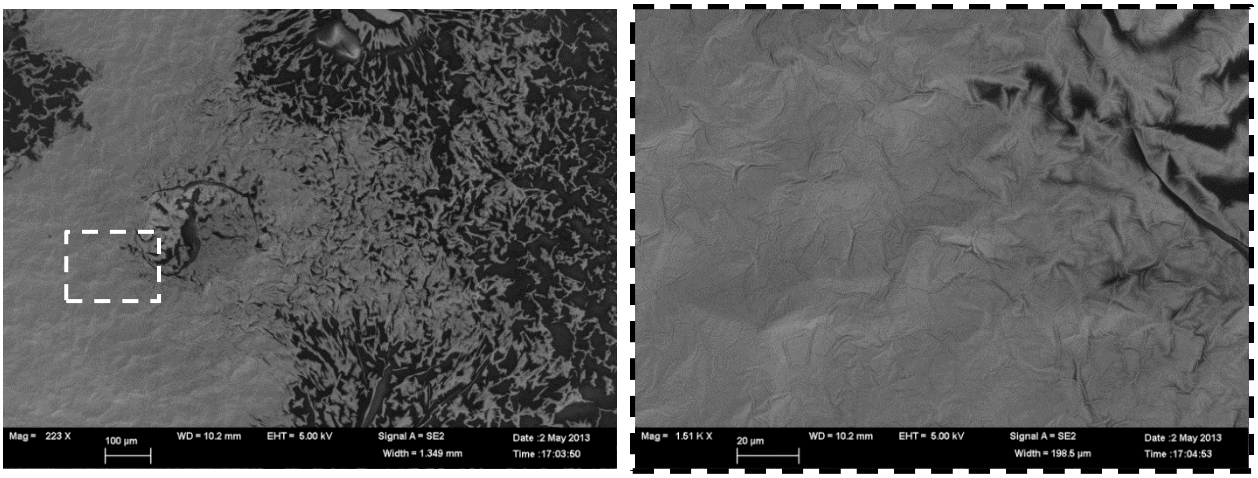


Figure 3.18. SEM photomicrographs of an OSB surface coated with a Vaseline. The lower magnification image (left) suggests that some Vaseline was absorbed into the hot OSB surface. The image on the right shows the area within the dashed white rectangle at a higher magnification. The surface topography of an area coated with Vaseline was very smooth

3.3.4 Melting point temperature

The drop melting and congealing point temperatures of the 18 different waxes are reported in Table 3.3. The congealing point temperatures were on average 2.6°C lower than the drop melting point temperatures. Together these two temperatures can be used to estimate the melting point temperature range of a wax.

The highest two drop melting point temperatures (87°C and 85°C) were recorded for wax blends that contained ethylene maleic anhydride. Carnauba wax had the 3rd highest drop melting point temperature (81°C). Both microcrystalline wax (73°C) and synthetic beeswax (77°C) also had relatively high drop melting point temperatures. Sasolwax M3M (63°C) had the highest drop melting point temperature of all the Fischer-Tropsch waxes, while Sasolwax C (31°C) had the lowest drop melting point temperature of this group of synthetic waxes.

Table 3.3. Melting point temperatures of different waxes measured according to ASTM D938-12 and ASTM D127 08

Wax	Origin	ASTM D938-12: Congealing point (°C)	ASTM D127 08: Drop melting point (°C)
Sasolwax C	Fischer-Tropsch	29	31
Lanolin	Animal	35	-
Tekniwax 801	Fischer-Tropsch	42	44
Soy wax	Vegetable	51	54
Merkur 300	Petroleum Jelly	54	55
Vaseline	Petroleum Jelly	53	59
Beeswax + Sasolwax C (1:1)	Blend	54	59
Beeswax + Vaseline (1:1)	Blend	58	62
Tekniwax 600	Petroleum	62	63
Stearic acid	Vegetable	61	63
Beeswax	Animal	64	65
Sasolwax M3M	Fischer-Tropsch	63	68
Beeswax + Synthetic beeswax (1:1)	Blend	69	73
Microcrystalline wax	Petroleum	72	73
Synthetic beeswax	Petroleum	75	77
Carnauba wax	Vegetable	81	81
Sasolwax M3M + EMA* (3:1)	Blend	-	85
Beeswax + EMA* (3:1)	Blend	-	87

*EMA = Ethylene maleic anhydride

3.3.5 Viscosity

The apparent viscosities of the 18 waxes are reported in Table 3.4. The wax with the highest viscosity at 25°C above its melting point was raw, unfiltered lanolin. This was much higher than those of any of the other waxes, and was most likely affected by the presence of wool fibres in the lanolin. The blend of beeswax and ethylene maleic anhydride also had a viscosity that was noticeably higher than those of most of the other waxes. The viscosity of microcrystalline wax increased dramatically as it approached its congealing point. The three waxes that consistently had the lowest viscosities were Sasolwax C, Merkur 300, and Tekniwax 801.

Table 3.4. Apparent viscosity of different waxes according to ASTM D2669-06

	Viscosity (mPa·s)			
	100°C	**MP[†]+5°C**	**MP+15°C**	**MP+25°C**
Sasolwax C	4.4	6.9	6.3	5.3
Merkur 300	4.8	9.4	6.8	6.0
Tekniwax 801	5.5	11	8.8	7.5
Stearic acid	6.6	10.5	8.3	7.7
Sasolwax M3M	6.6	9.6	8.4	8.1
Beeswax + Sasolwax C (1:1)	7.5	12.8	10.3	10.2
Beeswax + Vaseline (1:1)	9.2	15.8	13.3	11.4
Vaseline	9.4	15.8	12.0	9.5
Tekniwax 600	10.3	18.3	15.0	12.8
Synthetic Beeswax	11.2	15.6	13.1	8.4
Soy wax	12.1	25.0	19.6	15.8
Beeswax	13.1	20.4	17.5	14.5
Beeswax + Synthetic Beeswax (1:1)	16.4	20.7	17.6	16.2
Microcrystalline wax	17.0	139.3	19.6	17.5
Carnauba wax	24.8	50.8	26.9	22.2
Lanolin	28.5	400	295	134.1
Sasolwax M3M + EMA* (3:1)	36.5	46.0	36.5	29.5
Beeswax + EMA* (3:1)	68.8	83.9	63.5	51.3

[†] MP = Wax melting point temperature (°C)

*EMA = Ethylene maleic anhydride

3.3.6 Acid number titration

The empirical acid numbers of the 18 different waxes are reported in Table 3.5. Stearic acid had the highest acid number (215.3 mg KOH / g), followed by soy wax (31.5 mg KOH / g). Beeswax had an acid number of 18.5 mg KOH / g and pure ethylene maleic anhydride had an acid number of 34.4 mg KOH / g. A blend of three parts beeswax and one part ethylene maleic anhydride had an acid number of 22.4 mg KOH / g, while a 3:1 blend of Sasolwax M3M and ethylene maleic anhydride had an acid number of 8.6 mg KOH / g. Since Fischer-Tropsch and mineral waxes all had acid numbers of zero, blends that contained any of these waxes and an equal amount of beeswax, had acid numbers of 9.2 mg KOH / g.

Table 3.5. Empirical acid number of waxes according to ASTM D1386-10

Wax	Origin	Acid value (mg KOH / g)
Stearic acid	Vegetable	215.3
Soy wax	Vegetable	31.5
Beeswax + EMA* (3:1)	Blend	22.4
Beeswax	Animal	18.5
Beeswax + Sasolwax C (1:1)	Blend	9.2
Beeswax + Vaseline (1:1)	Blend	9.2
Beeswax + Synthetic Beeswax (1:1)	Blend	9.2
Sasolwax M3M + EMA* (3:1)	Blend	8.6
Carnauba wax	Vegetable	6.8
Lanolin	Animal	5
Sasolwax C	Fischer-Tropsch	0
Tekniwax 801	Fischer-Tropsch	0
Tekniwax 600	Petroleum	0
Sasolwax M3M	Fischer-Tropsch	0
Merkur 300	Petroleum jelly	0
Vaseline	Petroleum jelly	0
Microcrystalline wax	Petroleum	0
Synthetic Beeswax	Petroleum	0

*EMA = Ethylene maleic anhydride

3.3.7 Relationships between contact angles on pure wax and on wax-treated OSB surfaces

As mentioned above, the water droplets placed on glass slides coated with stearic acid had the highest initial contact angles, but this may have been due to the rough surfaces that stearic acid formed upon crystallisation (Figures 3.9 – 3.10). Unlike the other waxes, stearic acid formed large crystals that could be seen with the naked eye, as mentioned above. These large crystals caused surfaces coated with stearic acid to be much rougher than those of the other wax types. For this reason, and the pronounced effect of surface roughness on contact angles (Wenzel 1949), stearic acid samples were excluded from analysis of the effects of wax type on the contact angles of water droplets on pure wax surfaces.

There was no correlation between the initial contact angles of water droplets on pure wax surfaces and those on wax-treated OSB surfaces. However, the initial contact angles of water droplets on pure wax surfaces were positively correlated with the t<90° times of water droplets on both pure wax surfaces ($p < 0.001$) and wax-treated OSB surfaces ($p = 0.02$) (Figures 3.19 – 3.20). There was no statistically significant ($p > 0.05$) relationship between the initial contact angles of water droplets on wax-treated OSB surfaces and the t<90° times on either of the two surface types.

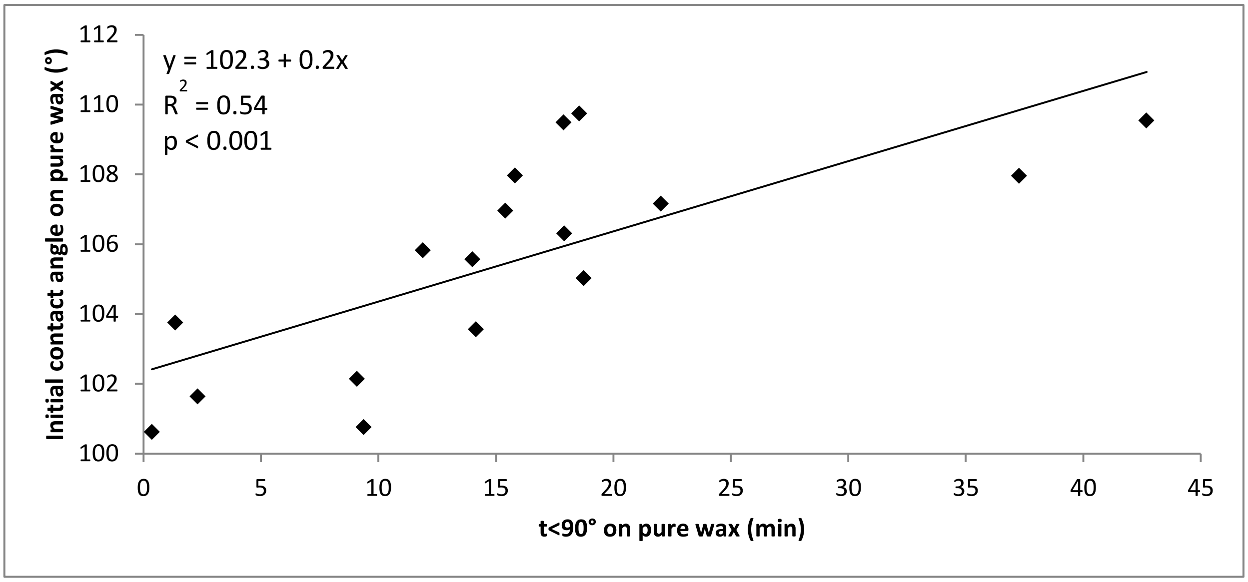


Figure 3.19. Relationship between (1) the initial contact angle of 5μL water droplets placed on glass slides coated with different wax types and (2) the time it took those droplets to spread and form contact angles of less than 90° on a pure wax surface (α = 0.05)

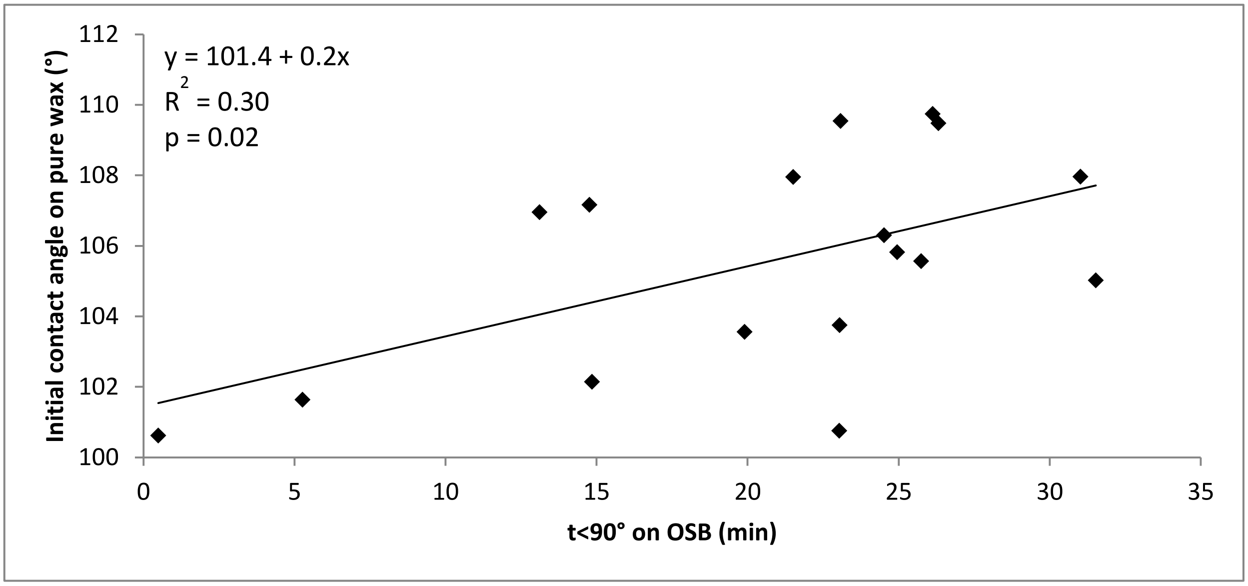


Figure 3.20. Relationship between (1) the initial contact angle of 5µL water droplets placed on glass slides coated with different wax types and (2) the time it took water droplets placed on wax-treated OSB surfaces to spread and form contact angles of less than 90° (α = 0.05)

3.3.8 Relationships between contact angles and melting point temperatures

There was a weak positive correlation ($p = 0.04$; $R^2 = 0.25$) between the initial contact angles of water droplets placed on pure wax surfaces and the melting point temperatures of the different wax types (Figure 3.21).

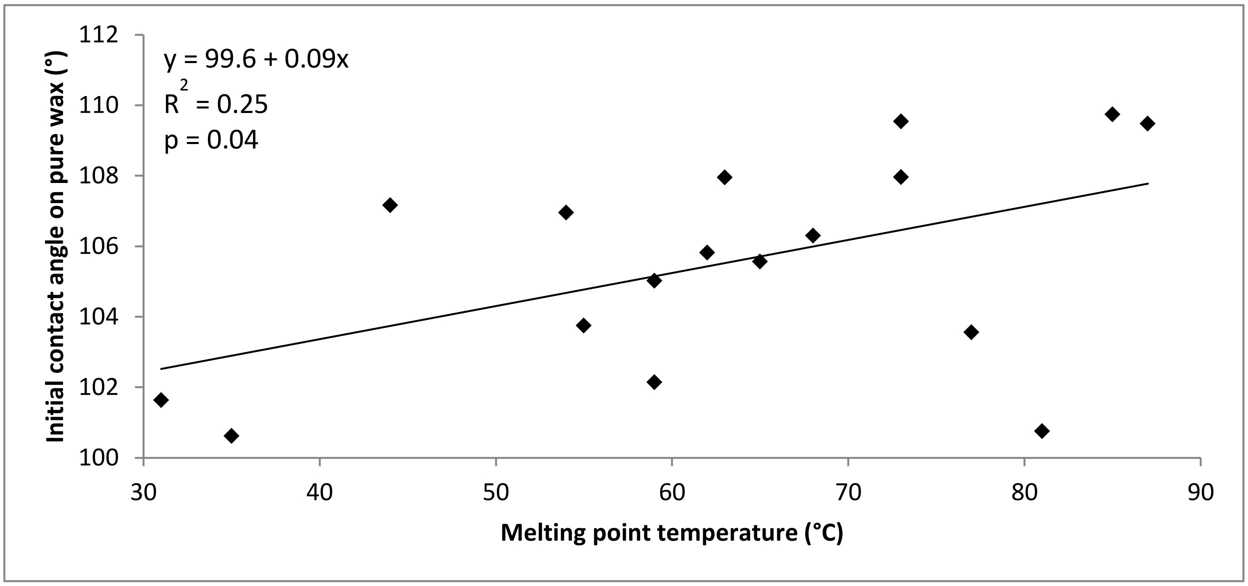


Figure 3.21. Relationship between (1) the melting point temperatures of the different wax types and (2) the initial contact angles of 5μL water droplets placed on pure wax surfaces (α = 0.05)

Furthermore, the melting point temperatures of the different waxes had a moderate positive correlation ($p < 0.001$; $R^2 = 0.57$) with the t<90° times of water droplets on wax-treated OSB surfaces (Figure 3.22). There was, however, no relationship between melting point temperatures and the initial contact angles formed on wax-treated OSB surfaces, or between the melting point temperatures and the t<90° times of water droplets on pure wax surfaces.

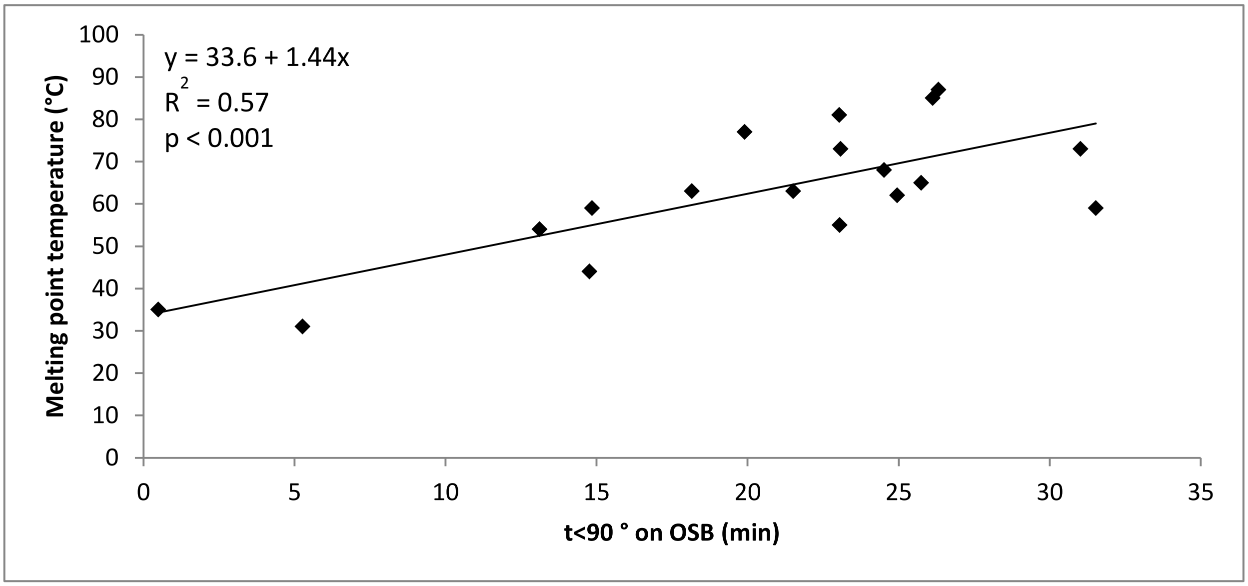


Figure 3.22. Relationship between (1) the melting point temperatures of the different wax types and (2) the times it took 5µL water droplets to spread and form contact angles of less than 90° on OSB surfaces treated with different wax types (α = 0.05)

3.4 Discussion

In the introduction to this chapter I hypothesized that the initial contact angles of water droplets placed on molten wax-treated OSB surfaces would be higher than those on untreated OSB surfaces, and that the t<90° times on wax-treated surfaces would be longer than those on untreated surfaces. I was also interested in examining the relationship between the acid number (polarity) of wax and the contact angles that water droplets form on wax-treated OSB surfaces. In the following paragraphs I discuss: (1) the extent to which my results support or refute the aforementioned hypothesis; and (2) the relationship between the wax polarity and water-repellency of wax-treated surfaces.

The initial contact angles of water droplets on wax-treated OSB surfaces were not significantly different from those on untreated surfaces. This suggests that wax treatment did not affect the water repellency of OSB, however, the t<90° times on most wax-treated OSB surfaces were much longer than those of untreated OSB surfaces. The initial contact angles of water droplets on pure wax surfaces were all greater than 100°, indicating that all the waxes were hydrophobic as expected. The t<90° times on wax-treated OSB surfaces are likely to have been affected by penetration of the waxes into wood strands. This supposition is supported by the observation that there was no relationship between t<90° times on pure wax surfaces and t<90° times on wax-treated OSB surfaces. This suggests that most, but not all, waxes penetrated the OSB surfaces and did not form coatings. Wax-treated OSB surfaces with no coatings probably retained their surface morphology, which could have affected the initial contact angle measurements.

There were no clear relationships between the polarity of the waxes and the contact angles on either pure wax surfaces or wax-treated OSB surfaces. Adam and Jessop (1925) suggested that when molten wax with polar functional groups solidifies, the polar functional groups orient themselves in layers between the aliphatic chains, thus leaving the terminal methyl groups exposed at the surface. Such orientation would result in similar contact angles for polar and nonpolar waxes. My findings accord with this suggestion.

There was a positive correlation between the melting point temperatures of the waxes and the t<90° times on wax-treated OSB surfaces. This observation suggests that there were underlying interactions between the OSB surfaces and the wax; interactions which are related to the melting point temperatures. According to Wolfmeier et al. (2000) the melting point temperature of wax increases as the length of the carbon chain and the number of polar functional groups increases, and it decreases as the degree of branching increases. Furthermore, it has been observed that wax emulsions which consist of long chain n-alkanes, are more effective at reducing WA and TS of MDF and particleboard than those made with short chain n-alkanes (Roffael and May 1983; Schriever and Roffael 1984; Hague 1995; Roffael et al. 2005). Hsu et al. (1988) also suggested that a high number of branched carbon chains could reduce the water repellency of paraffin wax. My findings also suggest that the chemical structure of waxes (possibly the length and degree of branching of the carbon chains) may have affected the water repellency of wax-treated OSB. Alternatively, the physical properties of the wax and whether it formed a coating on OSB may also be affected by its melting point temperature.

The average initial contact angles of water droplets on untreated OSB surfaces were higher than anticipated. Based on previous findings I expected the initial contact angle on untreated OSB to be between 75° (Unsal et al. 2010) and 108° (Semple et al. 2009), but instead the average initial contact angle of water droplets on untreated OSB was 118.62°. There are a number of factors that could account for this discrepancy between my results and those of previous studies: (1) thermal modification of OSB surfaces during sample preparation; (2) presence of resin and wax sizing on strands at the surface of the OSB samples; (3) presence of silicone release agent from press platens; and (4) the rough surface of untreated OSB. My results suggest that the initial contact angle of water droplets on the surface of untreated OSB may not be a good indicator of the moisture resistance of OSB. Instead, it appears that $t_{<90°}$ times might be better at predicting the WA and TS of OSB panels.

Most of the initial contact angles on pure wax surfaces were within the expected ranges of 94° to 109° for vegetable waxes (Holloway 1969), and 105° to 114° for paraffin waxes (Adam 1963). Meiron et al. (2004) reported a slightly larger contact angle for beeswax, but this was expected since they measured the advancing contact angle, which is always larger than the static contact angle which I measured (Adam 1963). Similarly, Bartell et al. (1936) measured a slightly larger contact angle for carnauba wax. The initial contact angles of water droplets on stearic acid (128°) were markedly larger than those reported in the literature. Adam and Jessop (1925) reported the contact angles of water droplets on stearic acid to be anywhere between 50° and 105°, depending on the orientation of its polar groups. This discrepancy can be explained by the rough surface that molten stearic acid formed when it solidified on the glass slides. The surfaces that Adam and Jessop measured were presumably smooth, since they were cut from a solid lump (Adam and Jessop 1925).

The melting point temperatures of waxes from animals (beeswax and lanolin) and plants (carnauba wax and soy wax) agreed well with those found in the literature (Wolfmeier et al. 2000). Similarly, the melting point temperatures measured for the Fischer-Tropsch and paraffin waxes provided by Sasolwax (South Africa) matched those reported in the material safety data sheets (MSDS) that accompanied them. The melting point temperatures of microcrystalline wax and synthetic beeswax were similar to those of other paraffin waxes (Wolfmeier et al. 2000). The melting point temperature of Vaseline was not verified. The melting point temperatures of wax blends could be verified using a simple calculation based on the proportions of blended waxes and the melting point temperatures of the individual waxes (Bennett 1963). Thus, by combining ethylene maleic anhydride with beeswax or Sasolwax M3M, wax blends with higher melting point temperatures were created. According to the definition of wax proposed by the German Association for Fat Science, waxes must have melting points above 40°C (Wolfmeier et al. 2000). Based on this definition two of the waxes in this thesis cannot technically be defined as waxes. Nevertheless, for convenience, they will still be referred to as waxes in the rest of this text. Sasolwax C had a melting point of 29°C and lanolin had a melting point of 35°C. The viscosities of all the waxes were within the expected range, as defined by the German Association for Fat Science (Wolfmeier et al. 2000). The acid value numbers also agree with values reported in the literature (Wolfmeier et al. 2000). By combining ethylene maleic anhydride with beeswax or Sasolwax M3M, wax blends with increased polarity were produced.

The SEM photomicrographs of beeswax and carnauba wax on OSB resembled those published by Greener-Donhowe and Fennema (1993). The authors prepared very thin films using the same type of waxes and examined the microstructure of the prepared surfaces. They reported that tiny pores were visible in the surface of the wax. It is possible that these small pores may develop into larger cracks when thicker wax films solidify; such as the films prepared in this study. For carnauba wax, such cracks can be explained by its large density increase upon crystallisation, while its smooth surface can be explained by its fine crystalline structure. Conversely, beeswax formed coatings which did not develop visible fractures, possibly because the wax is softer and more flexible than carnauba wax. Greener-Donhowe and Fennema (1993) did not observe any defects on the surface of thin beeswax films either. According to Tulloch (1970) the flexibility of beeswax results from the presence of a small amount of unsaturated hydrocarbons in the wax. No literature that contained SEM photomicrographs of the surfaces Vaseline or Fischer-Tropsch waxes could be found.

Water droplets placed on pure microcrystalline wax surfaces took a long time (42.7 min) to form contact angles smaller than 90°. Water droplets placed on these surfaces flattened slightly as water evaporated over time, however, before the contact angle became smaller than 90°, the droplets suddenly contracted and beaded up again, increasing the contact angle. Droplets placed on other wax types behaved in a similar "slip-and-stick" manner, but their contact angles decreased well below 90° before the droplets contracted and beaded up again. The high resolution profilometry image of the surface of a glass slide coated with microcrystalline wax showed that this wax solidified to form microscopic peaks and valleys, similar to the strongly hydrophobic surfaces found on some plant leaves (Barthlott and Neinhuis 1997). Despite this observation, the average surface roughness (R_a) of pure microcrystalline wax surfaces appeared to be similar to those of many of the other wax types. R_a is the arithmetic mean deviation of a surface profile's peaks and valleys from its center line. Thus, the microscopic peaks and valleys on microcrystalline wax may not have been accounted for by the R_a value that was measured.

One unexpected finding was that water droplets placed on glass slides coated with Merkur 300 spread faster than those of water droplets on most of the other wax types. However, once these droplets spread out they remained on the surface for much longer than those on any of the other wax-coated surfaces. It is possible that Merkur 300 may have contained an oil that created a film over the water droplet, thus preventing water from evaporating. Further research is necessary to fully test this hypothesis.

3.5 Conclusion

I conclude that contact angles on pure wax surfaces are not good indicators of the water repellency of wax-treated OSB surfaces, since most molten waxes tended to penetrate OSB when applied to the surface of OSB. The contact angle measurements of the waxes tested in this chapter were not useful as a measure of the effect that polarity had on the water repellency of wax-treated OSB. The most reliable indicator of the water repellency of wax-treated OSB surfaces is the t<90° times of water droplets on wax-treated OSB surfaces.

The water repellency of wax-treated OSB increases as wax melting point temperature increases. This suggests that waxes with higher melting point temperatures might be able to form more effective water-repellent barriers than waxes with low melting point temperature, when they are sprayed onto the surface of hot OSB.   On the other hand lower melting point waxes may be able to penetrate OSB to a greater extent than higher melting point waxes and form a more effective water repellent barrier. I examine the effect of wax melting point temperature on the effectiveness of molten-wax treatment for OSB in the next chapter.

Chapter 4. Effects of wax treatments on thickness swelling

4.1 Introduction

It is well known that the effectiveness of water repellents applied to solid wood decrease over time when treated samples are immersed in water or exposed to weather (Adam 1963; Borgin 1965 ; Miniutti et al. 1961; Verrall 1971; Voulgaridis and Banks 1979). The effectiveness of such water repellents can be improved by increasing the penetration of the water repellent into wood (Borgin 1965). Water repellents, such as wax, can be displaced by water, since waxes are only weakly bonded to wood cell walls (Rowell and Banks 1985). Borgin (1965) called such displacement of wax in water-repellent treated wood "preferential wetting". Preferential wetting can be slowed by limiting the penetration of water into areas where the water repellent is deposited. Thus, a wax that is able to penetrate deeper into OSB may be less susceptible to preferential wetting than one that does not penetrate OSB to the same extent. Hence, deeper penetration of wax into OSB may create a more effective water-repellent barrier than wax that does not penetrate as deeply.

When molten wax is sprayed onto the surface of OSB, its melting point and rheology is likely to affect its ability to penetrate into the surface (Hsu et al. 1988). Waxes have low viscosities at temperatures above their congealing points, and when they are in this state, they have less resistance to flow. Dullien et al. (1989) showed how capillary forces caused molten paraffin wax to rise upwards through a pack of small glass beads. Numerous other studies, especially in the fields of petroleum geology and soil sciences, have also investigated the flow of oils and liquid hydrocarbons through porous media (Debye and Cleland 1959; Morrow 1970; Liu et al. 2011). The volumetric flow of fluids through porous media can be estimated using Darcy's law which states that volumetric flow is inversely proportional to the viscosity of the fluid (Equation 4.2).

Darcy's law

$$\boldsymbol{Q} = (\frac{\boldsymbol{kA}}{\mu})(\frac{\boldsymbol{\Delta P}}{\boldsymbol{L}}) \quad \textbf{(Equation 4.1})$$

Where:
$Q = volumetric\ flow\ rate$
$k = permeability\ of\ OSB$
$A = cross\ sectional\ area\ perpandicular\ to\ liquid\ flow$
$\mu = viscosity\ of\ the\ fluid$
$\Delta P = pressure\ gradient$
$L = sample\ length$

Accordingly, Scheikl and Dunky (1998) noted that the penetration of liquids into wood surfaces is retarded by increasing the viscosity of the liquids. When molten wax is sprayed onto the surface of hot OSB the wax directly in contact with the board will remain molten and at a relatively low viscosity until the temperature of the board cools below the congealing point of the wax. As wax congeals and solidifies its viscosity will increase and its ability to penetrate porous substrates will decrease accordingly (and eventually stop). Grigsby and Thumm (2012a) characterized the distribution and mobility of wax on wood fibres during the manufacture of medium density fibreboard and found that the mobility of waxes were greatest during hot pressing, when they were molten. Hsu and Bender (1988) suggested that a liquid wax with a high viscosity would be less able to spread over and wet wood fibres. According to Bennett (1963) the penetration of wax into paper may be increased by: (1) increasing wax temperature; (2) lowering wax viscosity; or (3) adding solvents or oils. Conversely, Bennet (1963) explained that wax penetration into paper can be minimized by: (1) reducing wax temperature; (2) increasing wax viscosity; (3) applying wax to a surface with a low temperature; and (4) increasing the melting point of the wax. If molten wax is sprayed onto hot OSB, with all other factors remaining the same, waxes with low melting points will remain liquid, and at lower viscosities, for longer than waxes with high melting points. Based on Darcy's law (Equation 4.1.), this may enable more wax to flow and penetrate deeper into the board, thus blocking a larger number of inter-strand voids and creating a more effective water-repellent barrier. If this is correct waxes with low melting points may be more effective water-repellent treatments for

OSB than waxes with high melting points. In Chapter 3, however, I showed that higher melting point waxes were more effective at restricting the spread of water on wax-treated OSB. Based on these arguments, I hypothesize that the melting point temperatures of waxes will affect their ability to restrict the moisture uptake and TS of OSB. This chapter seeks to determine the relationship between wax melting point and the effectiveness of molten wax treatments applied to OSB.

4.2 Materials and methods

4.2.1 Experimental design

A randomized block design was used to determine the effect of a single fixed factor (wax type) on TS and rate of TS of OSB. Waxes that covered a wide spectrum of melting points were chosen. A wax treatment was considered effective if the wax was able to penetrate OSB without forming a visible coating on top of the sample and if the treated OSB samples swelled less, or at a slower rate, than untreated controls. The swelling of untreated OSB samples (control) and samples treated with seven different waxes were examined. The experiment was replicated seven times, using panels supplied by Tolko Industries, Canada. A single panel was used for each experimental replication (block) and panels were sampled from the production line at different times to account for random variations in board properties caused by variation in raw materials and the manufacturing process. The total sample population of the experiment was 56 samples (8 treatments x 7 panels).

Eight samples, measuring 120 x 100 mm^2, were cut from each panel, and a wax type was randomly assigned to each of the seven samples. The samples were treated accordingly, and one sample was left untreated as a control. All samples were immersed in water, at 20 ± 2°C, for 21 days and TS measurements were recorded every 1 min, using linear variable displacement transducers.

Analysis of variance, for a randomized block design, was used to examine the effect of wax type on the following response variables: (1) total thickness swelling after 21 days; (2) rate of TS expressed as the time it took samples to reach 25% and 50% of their total thickness swell (25% TTS and 50% TTS); and (3) amount of TS after 2 h, 24 h, 72 h, 240 h, and 480 h. The hierarchical design of the experiment accounted for random variation between panels, as well as the fixed effects of wax type. The amount of wax applied to each sample was included as a covariant in the statistical analysis to account for variation in response variables due to differences in the amount of wax sprayed onto samples. The statistical program Genstat 12.1 (VSN International 2009) was used to analyze the data with a 95% confidence interval ($\alpha = 0.05$) and to check the assumptions of ANOVA, as described in Chapter 3. A sub-routine (convsstrt), within Genstat, was used to compare the performance of all the wax types, as well as individual wax types, to that of the untreated control. Results are presented in graphs and error bars on each graph (± standard error of difference, $p < 0.05$) can be used to estimate whether differences between individual means are statistically significant.

4.2.2 Waxes

Seven waxes were chosen based their melting point temperatures, as mentioned in the introduction (Table 4.1). The congealing point of each wax was determined according to ASTM D938-12 and the drop melting point temperature was determined according to ASTM D127-08. Dynamic viscosities, at temperatures between 95°C and congealing point, were measured using a stress-controlled rheometer (Anton Paar MCR 501).

Table 4.1. The origin, melting point tempeatures, and viscosities of seven waxes

Wax	**Origin**	**Melting point (°C)**		**Viscosity (mPa·s) at**	
		Congealing point	**Drop point**	**95°C**	**Congealing point + 10°C**
Sasolwax C	Fischer-Tropsch	29	31	2.20	4.34
Lanolin	Animal	35	-	34.5	223
Vaseline	Petroleum Jelly	53	59	6.14	7.98
Tekniwax 600	Petroleum	62	63	7.05	9.59
Sasolwax M3M	Fischer-Tropsch	63	68	5.11	6.17
Beeswax	Animal	64	65	11.2	15.6
Carnauba wax	Vegetable	81	81	24.9	25.7

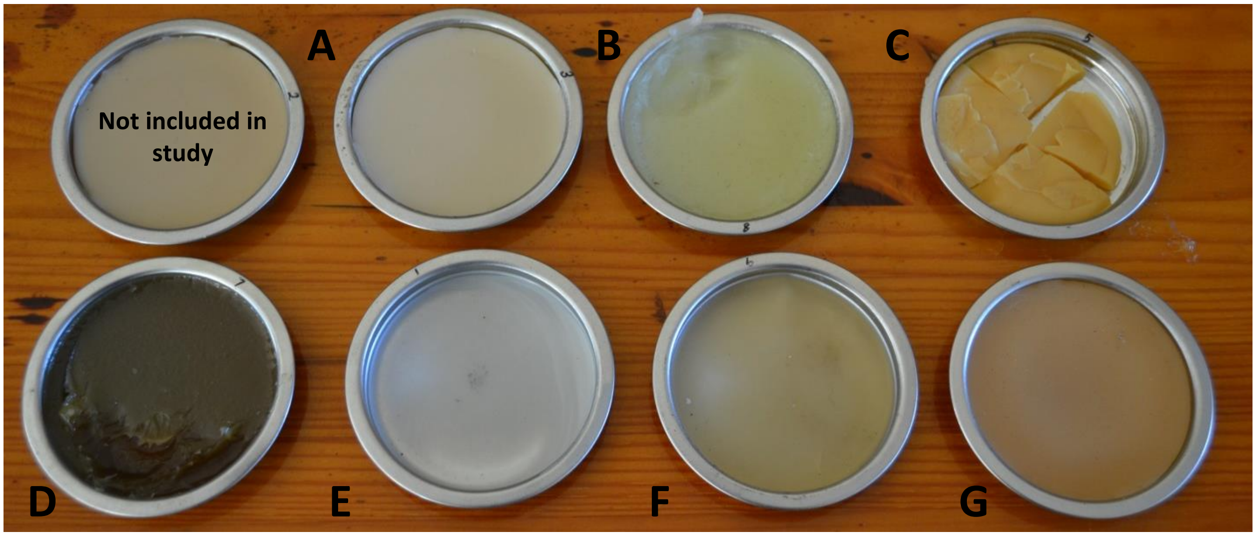


Figure 4.1. The seven waxes used in this chapter (and one wax that was not included) after dynamic viscosities were measured using a stress-controlled rheometer (Anton Paar MCR 501). (A) Sasolwax M3M; (B) Vaseline; (C) carnauba wax; (D) lanolin; (E) Sasolwax C; (F) Tekniwax 600; (G) beeswax

4.2.3 Oriented strandboard

Seven independent OSB panels, measuring 2440 x 1220 x 18 mm, were supplied by Tolko Industries, Canada. The panels consisted of 95% aspen wood, 4% resin and 1% emulsified wax; by weight (Blau, K., personal communication, February 4, 2013). The core to surface ratio of the panels was 1:1, with 4% liquid phenol formaldehyde used in the surface and 4% pMDI adhesive used in the core. The emulsified wax (Cascowax EW-58S) was manufactured by Hexion Specialty Chemicals, Springfield, OR. The panels were pressed at approximately 200°C and had a moisture content of 1 - 2% when leaving the press. Panels were sampled from the production line at different times to account for random variation in board properties caused by variation in raw materials and the manufacturing process.

4.2.4 Sample preparation

Samples for each experimental replication (block) were cut from a single OSB panel. A table saw (Altendorf F45 ELMO) was used to trim off 200 mm from one end of each board. Two more strips, 1220 x 120 mm^2, were then sawn from each freshly cut side. A cross-cut saw (Omga T55-300) was used to trim off 50 mm from the ends of each strip and the remaining lengths were cross-cut into 100 mm wide samples. Eight samples, 120 x 100 mm^2, were chosen at random and a wax treatment (wax type or control) was randomly assigned to each of them.

The samples were labeled on their top surface using a permanent marker and their edges were sealed using a two-part epoxy resin (G-2, System Three). The lower surface of each sample was coated with a layer of spar varnish (Cabot Spar Varnish #8042 Satin). Before the spar varnish and the epoxy resin cured, aluminium foil was tightly wrapped around each sample, so that only the top surface of the sample was uncovered (Figure 4.2). The wrapped samples were left to cure overnight and the excess foil was neatly trimmed off using a utility knife. Sealed samples were oven dried at 105 ± 1°C for a minimum of 24 h, weighed and placed in a vacuum oven at 90 ± 1°C.

Samples were then individually placed in a second oven (170°C), between two heated metal plates (1 kg each), for 10 min. This was done to mimic the temperatures reached when OSB is pressed, and to ensure that the surface was hot enough to prevent molten wax, which was subsequently sprayed onto the samples, from solidifying too quickly upon contact with the surface of the board.

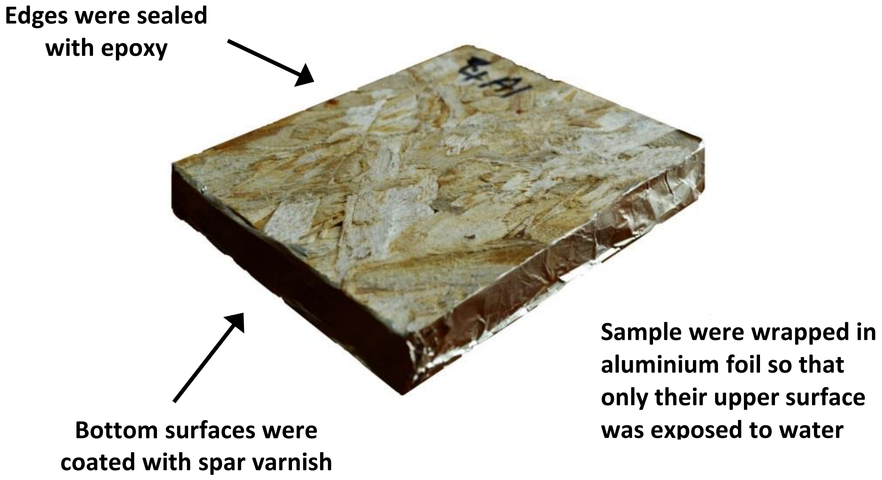


Figure 4.2. An OSB sample prior to application of molten wax

4.2.5 Wax application

Wax was sprayed onto the exposed upper surface of each sample using a pneumatic hot wax spray gun (Champ 10s, Glue Machinery Corporation) (Figure 4.3.). The gun consisted of a temperature controlled heating chamber that was set at 100°C. The air pressure inside the chamber was set at 300 kPa and the air pressure at the nozzle tip was set at 200 kPa. The spray nozzle had a single orifice (0.6 mm), which was opened and closed pneumatically with a ball and spring mechanism (Figure 4.4). When the gun was activated, the pressure from inside the chamber forced the ball to compress the spring. This allowed molten wax from inside the chamber to flow around the ball and out of the orifice. Behind the nozzle a second pneumatic line helped atomize the molten wax that escaped. When pressure was released the spring pushed the ball back and closed the nozzle, preventing liquid wax form dripping out. Videos of the application process can be found on the appended CD.

Figure 4.3. The Champ 10s pneumatic spray gun used to spray molten wax onto the OSB samples. Solid wax is inserted into the temperature controlled heating chamber at the back of the spray gun (left). The contol panel (right) is used to set the pressure inside the heating chamber and spray pressure at the nozzle tip

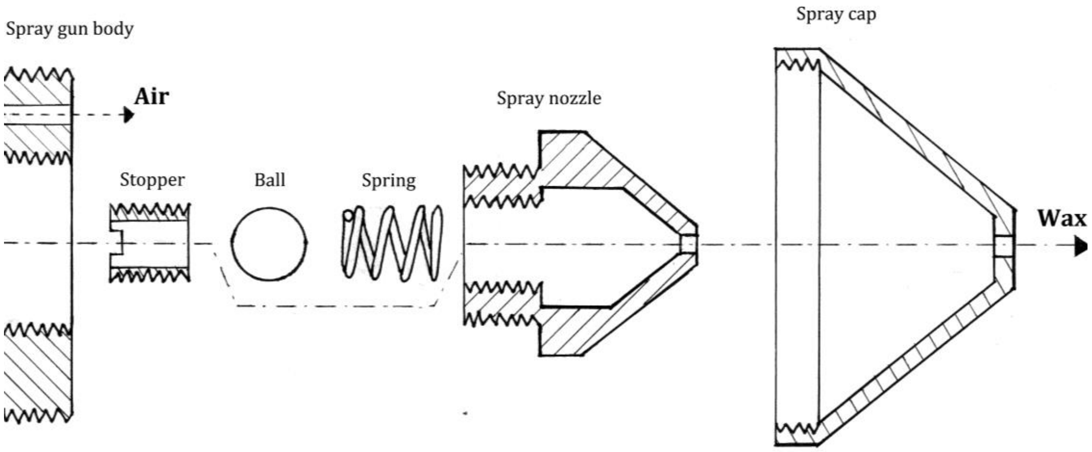


Figure 4.4. A schematic drawing of the Champ 10s spray gun's nozzle assembly. The spring, the ball and the stopper is housed inside the spray nozzle. The ball and spring is held in place by the stopper, which is screwed into the back of the nozzle. The spray nozzle, with the three parts inside it, is screwed onto the head of the spray gun body. The spray cap is also screwed onto the spray gun body, and it covers the spray-nozzle assembly. Molten wax is forced out of the spray gun when the chamber pressure is high enough to force the ball to compress the spring. A second pneumatic line, at the top of the spray gun body, helps to atomize the molten wax that escapes

Samples were treated with 200 g / m^2 of wax (approximately 2% based on oven dry board weight). There was variation in the amount of wax applied to individual samples, as mentioned above (Table 4.2). Application rates had a standard deviation of 62 g / m^2. This variation was accounted for in the analysis of data by including the weight of wax applied to each sample as a covariant. After application of waxes all treated samples and untreated controls were placed in a conditioning room at 20 ± 1 °C and 65 ± 5% relative humidity for a minimum of one week.

Table 4.2. Amounts of wax applied to individual samples

Replication	Wax applied (g/m^2)						
	Beeswax	Carnauba	Lanolin	Sasolwax M3M	Sasolwax C	Tekniwax 600	Vaseline
1	260.0	323.3	299.2	277.5	275.0	251.7	270.0
2	318.3	302.5	279.2	244.2	279.2	230.0	265.8
3	139.2	241.7	186.7	140.8	169.2	211.7	179.2
4	215.8	240.0	197.5	225.0	219.2	205.0	206.7
5	230.8	168.3	144.2	225.8	108.3	145.0	126.7
6	121.7	172.5	135.0	132.5	125.8	112.5	130.8
7	159.2	136.7	162.5	130.0	166.7	113.3	170.8
Mean	206.4	226.4	200.6	196.5	191.9	181.3	192.9
σ	70.7	70.6	64.6	60.7	68.0	57.0	58.3

4.2.6 Thickness swelling measurement

The TS of all samples in a single experimental replication (block) were made simultaneously, using a swellometer (Oh et al. 2000, Evans and Cullis 2008). OSB samples were mounted horizontally in a metal frame, at the bottom of a stainless steel tank (70 x 40 x 15 cm). Each sample was gently held down by a thin metal bar that ran across its treated surface. Compressed springs, above the bars, supplied a small amount of downward force, which kept the buoyant OSB samples stationary when immersed in water, without restricting TS (Figure 4.5, left).

Directly above each sample, midway along one edge, and 25 mm in from the edge a dedicated linear variable differential transducer (LVDT) measured TS (Figure 4.5, right). Once each LVDT was zeroed onto the surface of the OSB samples any further changes in thickness were picked up by the LVDT converted into proportional electrical signals, which were interpreted by a computer and recorded in millimetres. Each transducer was lowered onto an OSB sample and secured as soon as its foot pad made contact with the sample. The transducers were then zeroed and the tank was filled with approximately 25 litres of tap water. Samples were immersed in water at 20 ± 2°C for a total of 21 days and thickness measurements were recorded every 1 min.

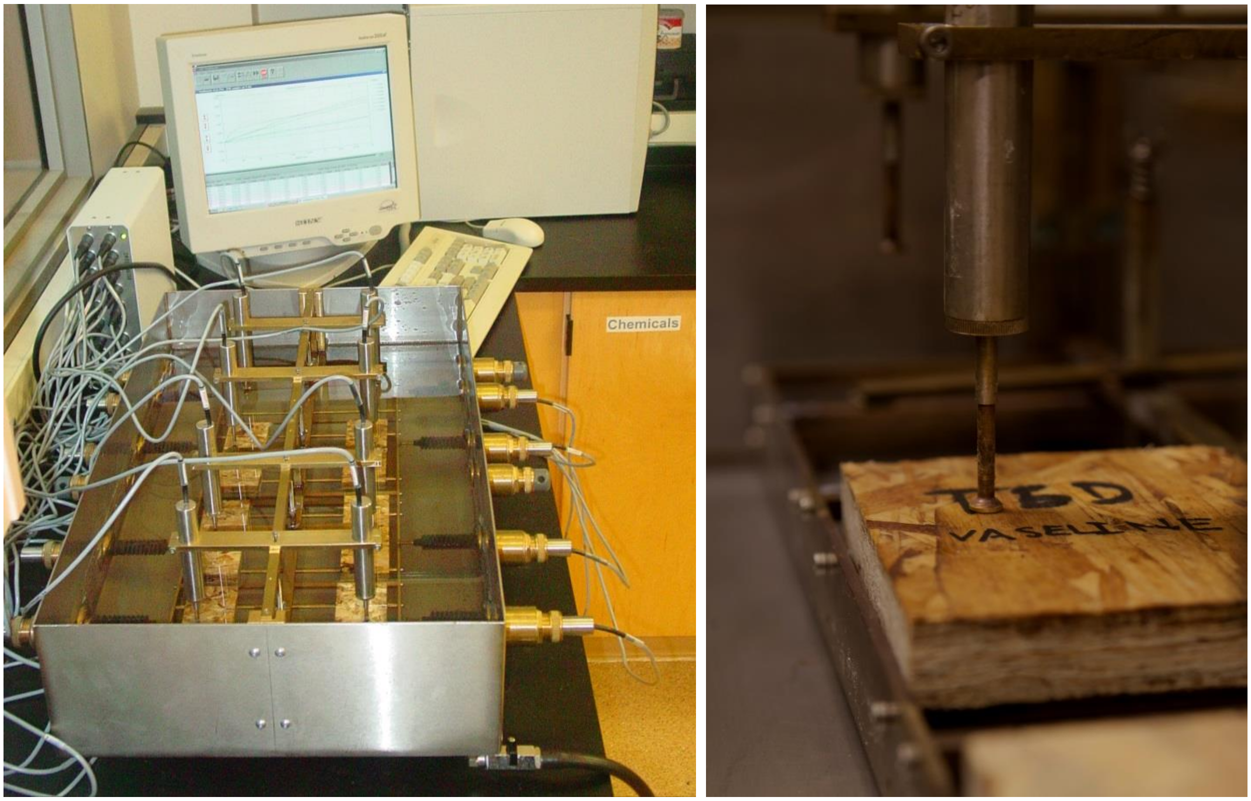


Figure 4.5. Eight OSB samples mounted in the swellometer tank and immersed in water (left). Each sample had one linear variable differential transducer (LVDT) mounted above it, which measured thickness swelling over time. A close up (right) of a LVDT with its footpad zeroed onto the surface of an OSB sample treated with molten Vaseline

4.3 Results

The overall effect of wax treatments on the TS of OSB is summarized in Table 4.3. Wax-treatments did not have a significant effect on the TTS (total thickness swelling) of samples 21 days of immersion in water. Wax treatment, however, had a significant effect on the rate and extent of TS that occurred over periods of ten days or less. Wax-treated samples swelled less and at a slower rate than untreated samples during the first ten days immersion in water.

Table 4.3. The effect of wax treatments on the thickness swelling of OSB samples immersed in water (α = 0.05)

	Total thickness swelling (mm) *	**Rate of thickness swelling (h) †**		**Thickness swelling (mm)**				
		25% of TTS	50% of TTS	2 h	24 h	72 h	240 h	480 h
Untreated samples (n=7)	2.74	44	103.1	0.06	0.41	1.04	2.29	2.706
Wax-treated samples (n=49)	2.65	93.5	181.7	0.01	0.22	0.65	1.76	2.572
p-value	0.59	0.01	0.002	< 0.001	0.003	< 0.001	0.02	0.52
LSD‡	0.34	35.77	47.51	0.02	0.13	0.22	0.42	0.42

* Total thickness swelling after 21 days of immersion in water

† Rate of thickness swelling as time to reach 25% or 50% of total thickness swelling

‡ Least significant difference (α = 0.05)

Table 4.4 summarises the effect that each wax had on the TS of OSB samples. The rate of TS was significantly different for samples treated with different waxes. There were significant differences in the swelling of untreated samples and samples treated with wax after 24 h ($p = 0.04$), 72 h ($p < 0.001$), and 240 h ($p = 0.01$) of immersion in water, but there were no significant differences in the swelling of untreated and different types of wax-treated samples after 2 h or 480 h ($p > 0.05$). There were also significant ($p = 0.003$) differences in the TTS of samples treated with different waxes. The best performing wax treatment was beeswax, which consistently was the most effective wax at reducing the rate of swelling of samples.

Table 4.4. The effect of wax on the thickness swelling of OSB samples immersed in water (α = 0.05)

	Total thickness swelling (mm) *	Rate of thickness swelling (h) [†]		Thickness swelling (mm)				
		25% of TTS	50% of TTS	2 h	24 h	72 h	240 h	480 h
Untreated	2.74	44.0	103.1	0.06	0.41	1.04	2.29	2.71
Beeswax	2.03	139.7	246.2	0.01	0.09	0.32	1.18	2.12
Vaseline	2.68	135.0	220.9	0.01	0.12	0.38	1.43	2.56
T600	2.73	100.3	193.6	0.01	0.22	0.64	1.69	2.44
Sasolwax C	2.59	85.5	182.6	0.01	0.22	0.65	1.78	2.5
M3M	3.04	77.6	163.6	0.01	0.24	0.80	2.13	2.98
Carnauba	2.84	64.2	133.4	0.01	0.25	0.82	2.20	2.79
Lanolin	2.66	52.1	131.4	0.03	0.37	0.91	1.94	2.61
p-value	0.003	0.002	0.004	0.70	0.04	< 0.001	0.01	0.09
LSD[‡]	0.45	47.32	62.85	0.02	0.17	0.29	0.56	0.55

* Total thickness swelling after 21 days of immersion in water

[†] Rate of thickness swelling as time to reach 25% or 50% of total thickness swelling

[‡] Least significant difference (α = 0.05)

4.3.1 Wax application and physical appearance of wax-treated samples

There were noticeable differences in the way different wax types atomized and sprayed onto OSB surfaces. When carnauba wax was sprayed, for example, some of the molten wax droplets solidified in the air, before they struck the surface of the OSB. The solid wax droplets briefly remained on the hot surface of the OSB as a powder before they melted and later re-solidified. Carnauba wax did not appear to penetrate the surface of OSB; instead it formed a thick coating that later fractured and developed large cracks. The fractured areas did not adhere well to the surface and tended to flake off when the wax-coated OSB was handled or immersed in water. Lanolin did not appear to penetrate the surface either, even when small quantities were applied. Most of the other waxes also formed visible coatings on OSB surfaces, but only when more than approximately 170 g / m^2 of wax was applied to samples. Sasolwax C did not form a visible coating on any of the sample surfaces, and Vaseline only formed a coating when more than approximately 260 g / m^2 of it was applied onto OSB samples. Differences in the hardness of the waxes were apparent. Beeswax felt softer than carnauba wax. Coatings formed by beeswax were also smoother and contained less cracks than those formed by carnauba wax.

Coatings formed by Sasolwax M3M also appeared to be harder than beeswax coatings, whereas those formed by Tekniwax 600 appeared to be softer. Unlike carnauba wax, none of the other wax coatings flaked off as easily when handled, or when coated OSB samples were immersed in water. Waxes other than carnauba wax and lanolin, appeared to penetrate the surface of OSB when less than approximately 170 g / m^2 of wax was sprayed onto the samples. Once coated, wax-treated OSB samples were conditioned at 20 ± 1°C and 65 ± 5 % r.h. for a minimum of one week. Those samples with no visible coatings were slightly darker, but otherwise indistinguishable from the untreated controls.

Figure 4.6. Close up of the surface of OSB sprayed with approximately 270 g /m^2 of molten carnauba (left) wax and Vaseline (right). Note that the high application rate caused surface coatings to form, even though the OSB samples were hot (170°C) when the waxes were sprayed onto them. Carnauba wax coatings cracked and flaked off when touched, while Vaseline formed a defect-free coating that filled the surface voids

4.3.2 Effect of wax type on total thickness swelling

The average TTS of all OSB samples immersed in water for 21 days was 2.66 mm. There was no significant difference between the mean TTS of the wax-treated samples (2.65 mm) and the untreated control samples (2.74 mm). There were, however, significant differences ($p = 0.003$) between the TTS of samples treated with different wax types (Figure 4.7). Samples treated with beeswax had an average TTS of 2.03 mm; significantly less than untreated samples, as well as samples treated with other wax types (Figure 4.7). Samples treated with Sasolwax M3M swelled the most (3.04 mm); significantly more than beeswax and Sasolwax C (2.59 mm) treated samples.

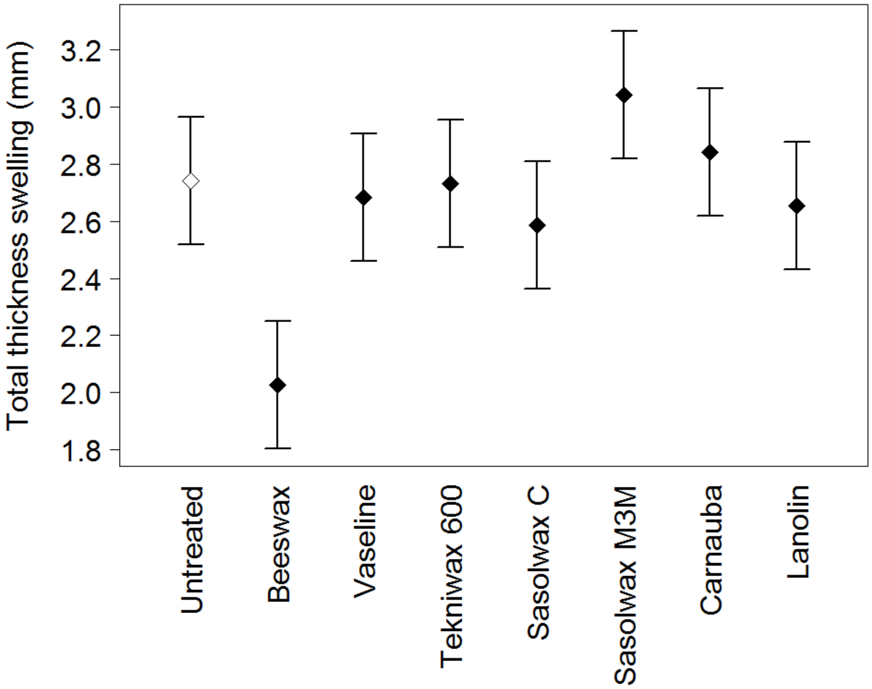


Figure 4.7. Effect of wax type on the total thickness swelling of wax-treated OSB samples after 21 days of immersion in water Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant difference (LSD) is 0.45 mm

4.3.3 Effect of wax treatment and wax type on the rate of thickness swelling

Over the first 24 hours all samples treated with wax, except for those treated with lanolin, increased in thickness at a slower rate than untreated samples (Figure 4.8). Beeswax and Vaseline treated samples swelled markedly less than samples treated with other wax types. Beeswax was the only wax type which significantly reduced total thickness swelling after 21 days, as mentioned above.

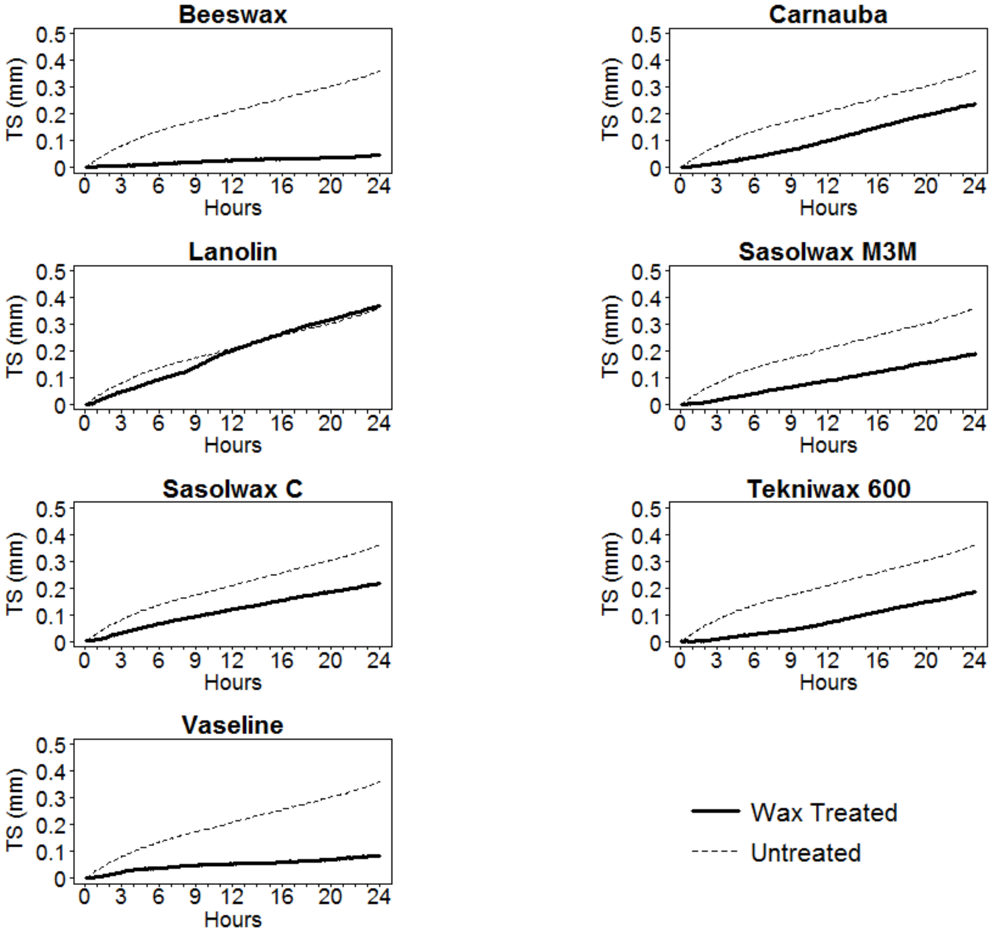


Figure 4.8. The average thickness swelling of untreated and wax-treated OSB samples that were immersed in water for 24 h (n = 7). Refer to attached CD for numerical values

The long term TS curves for beeswax and Vaseline treated samples were noticeably different from those of other treated samples. This was because these two wax types were more effective than other waxes at reducing TS of samples during short-term water exposure (Figure 4.9).

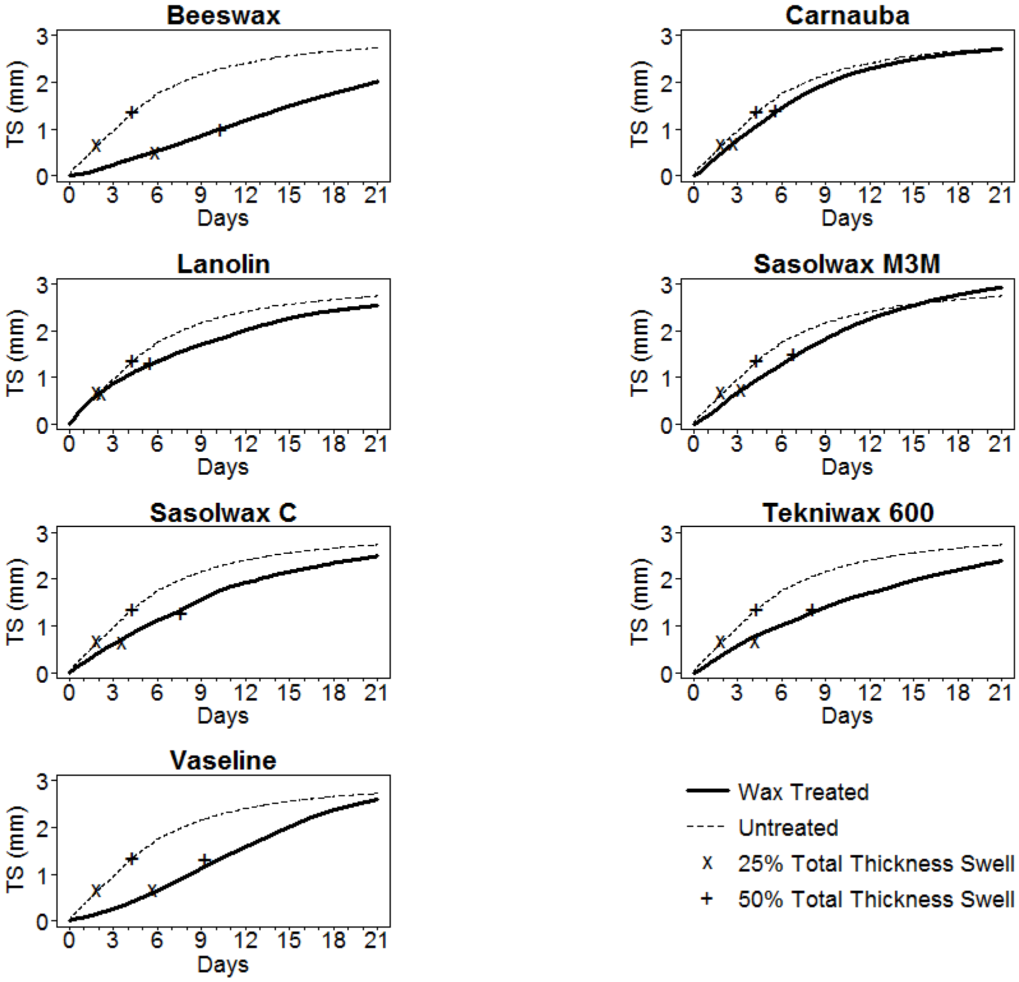


Figure 4.9. The average thickness swelling of untreated and wax-treated OSB samples that were immersed in water for 21 days (n = 7). Refer to attached CD for numerical values

Overall, wax treatments had a highly significant effect on the time it took samples to reach 25% ($p = 0.008$) and 50% ($p = 0.002$) of their total thickness swelling (TTS) (Figure 4.10). Untreated OSB samples took on average of 44 h to swell to 25% of TTS and 103 h 6 min to swell to 50% of TTS. In contrast, wax treated samples remained below 25% of TTS for 96 h 30 min and below 50% TTS for 181 h 42 min. It therefore took 2.2 times longer for wax treated samples to swell to 25% of TTS and 1.76 times longer to swell to 50% of TTS.

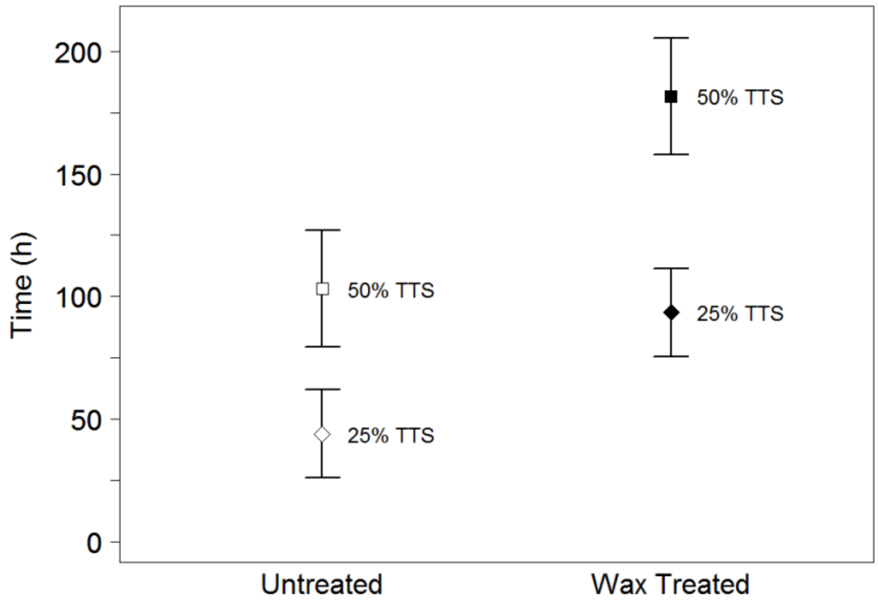


Figure 4.10. Effect of wax treatments on the time it took OSB to reach 25% and 50% total thickness swelling (TTS). Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant difference (LSD) for 25% TTS is 35.7 h and the LSD for 50% TTS is 47.5 h

The type of wax sprayed onto OSB samples also had a highly significant effect on the time to reach 25% ($p = 0.002$) and 50% ($p = 0.004$) of TTS (Figure 4.11). Samples treated with beeswax, Vaseline, or Tekniwax-600 remained below both 25% and 50% of TTS for significantly ($p < 0.005$) longer than untreated samples. Beeswax treated samples remained below 25% of TTS for 3.18 times longer; Vaseline treated samples for 3.07 times longer; and Tekniwax 600 treated samples for 2.28 times longer. Similarly, beeswax samples remained below 50% of TTS for 2.39 times longer than untreated samples; Vaseline for 2.14 times longer; and Tekniwax 600 for 1.88 times longer. Sasolwax C treated samples, which also took longer to swell to 50% of TTS than untreated samples, took 1.77 times longer to reach 50% of TTS than untreated samples.

Samples treated with beeswax or Vaseline remained below 25% of TTS for longer than those of samples treated with the other wax types, except for those treated with Tekniwax 600. Samples treated with Tekniwax 600 remained below 25% of TTS for longer than untreated samples and those treated with lanolin, but not significantly longer than those of samples treated with other wax types. Beeswax samples remained below 50% of TTS for longer than any of the other types of wax-treated samples. Furthermore, the rate of swelling of samples treated with beeswax was lower than those of all of the other types of wax-treated samples; except for those treated with Vaseline or Tekniwax-600. Vaseline treated samples took longer to reach 50% of TTS than untreated samples or those treated with carnauba wax and lanolin, but not significantly longer than those of samples treated with other wax types.

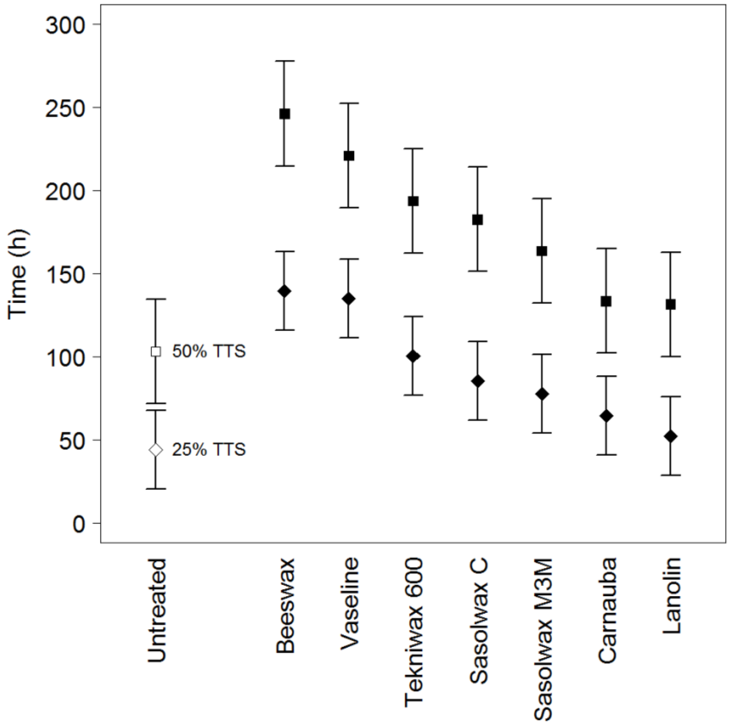


Figure 4.11. Effect of wax type on the time it took wax-treated OSB samples to reach 25% and 50% of total thickness swelling (TTS). Non-overlap of error bars indicates that means are significantly different at the 5% level. The least significant difference (LSD) for 25% TTS is 47.3 h and the LSD for 50% TTS is 62.8 h

4.3.4 Effect of wax treatment and wax type on thickness swelling

Wax treatments, on average, had a significant effect on the TS of OSB samples after they were immersed in water for 2 h ($p<0.001$), 24 h ($p = 0.003$), 72 h ($p<0.001$) and 240 h ($p = 0.017$); but not after 480 h of immersion (Figure 4.12).

After 2 h the thickness of untreated samples had increased by 0.056 mm (0.4%), while the thickness of wax-treated samples increased by 0.012 mm (0.08%). Wax treatments had therefore reduced TS by 78.7% after 2 h of immersion in water. After 24 h, the thickness of untreated samples had increased by 0.41 mm (2.58%) and wax-treated samples had increased by 0.22 mm (1.36%); a 47.8% reduction in TS. After 72 h, the thickness of untreated samples had increased by 1.04 mm (6.5%) and treated samples had increased by 0.65 mm (4.1%); a 37.9 % reduction in TS. After 240 h, the thickness of untreated samples had increased by 2.3 mm (14.3 %) and treated samples had increased by 1.8 mm (11.1 %); a 22.9% reduction in TS as a result of wax treatment.

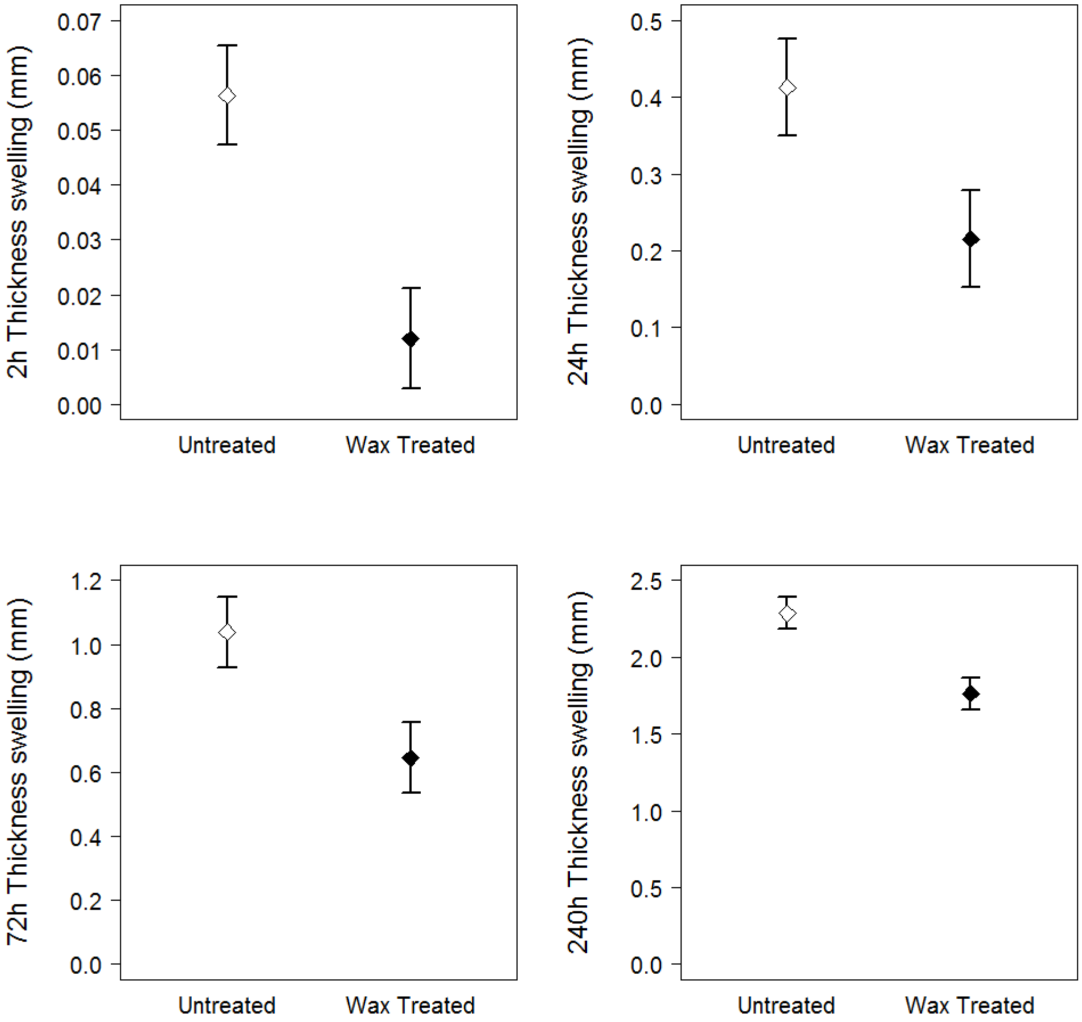


Figure 4.12. Effect of wax treatments on the thickness swelling of OSB after 2 h, 24 h, 72 h, and 240 h. Non-overlap of error bars indicates that means are significantly different at the 5% level. The least signficant differences (LSD) for 2 h, 24 h, 72 h and 240 h are 0.02 mm, 0.13 mm, 0.22 mm, and 0.42 mm, respectively. Note the different y-axis scales for each plot, always starting at zero

There were no significant differences in the swelling of different types of wax-treated samples after 2 h and 480 h. There were, however, significant differences between wax-treated samples after 24 h ($p = 0.036$), 72 h ($p < 0.001$), and 240h ($p = 0.007$) (Figure 4.13).

Untreated samples swelled significantly more than any of the wax-treated samples during the first 24 h, except for samples treated with carnauba wax or lanolin. Beeswax was the most effective treatment followed by Vaseline. Treatment with beeswax reduced the TS of OSB after 24 h by 79.2 % and treatment with Vaseline reduced swelling by 70.2 %. Both beeswax and Vaseline treated samples also swelled significantly less than lanolin treated samples.

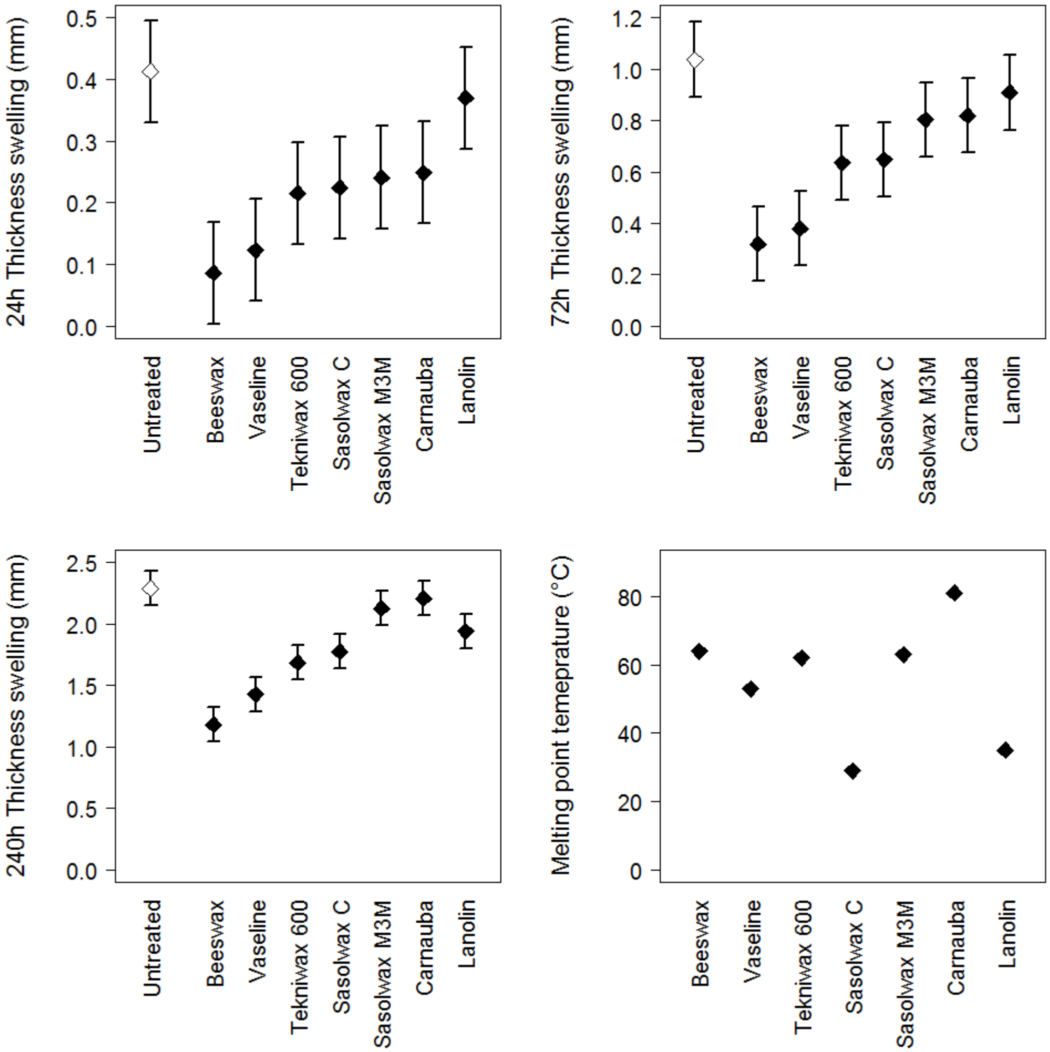


Figure 4.13. Effect of individual wax types on the thickness swelling of OSB samples after 24 h, 72 h, and 240 h of immersion in water. Also included (bottom right) are the melting point temperatures of the different waxes. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant differences (LSD) for 24 h, 48 h, and 240 h are 0.17 mm, 0.29 mm, and 0.56 mm, respectively

After 72 h, the TS of samples treated with beeswax, Vaseline, Tekniwax 600 or Sasolwax C were significantly less than that of the untreated controls. Samples treated with beeswax swelled significantly less than those of samples treated with all other wax types, except for samples treated with Vaseline. Treatment of samples with beeswax reduced TS of OSB after 72 h by 69.3% and treatment with Vaseline reduced swelling by 63.5%. Samples treated with Vaseline also swelled significantly less than samples treated with carnauba wax, lanolin, or Sasolwax M3M. Treatment with Tekniwax 600 reduced TS by 38.7 % and Sasolwax C treatment reduced TS by 37.5% after 72 h.

After 240 h, the TS of untreated samples was significantly greater than those of samples treated with beeswax, Vaseline, or Tekniwax 600. Treatment with beeswax reduced TS by 48.4% and beeswax treated samples swelled significantly less than samples treated with other wax types; except for those treated with Tekniwax 600 or Vaseline. Samples treated with Vaseline swelled 37.52% less than untreated samples and also significantly less than samples treated with carnauba wax or Sasolwax M3M. Treatment of samples with Tekniwax 600 reduced TS by 26.32% after 240 h of immersion in water.

4.3.5 Relationship between wax melting point and thickness swelling

There was no correlation between the melting point temperatures of different wax types and TS of OSB samples treated with those waxes. Furthermore, there was no relationship between the TS of wax-treated samples and the viscosities of the waxes at 95°C.

4.4 Discussion

In the introduction to this chapter suggested that low melting (LM) point waxes might be more effective than high melting (HM) point waxes at creating a water-repellent barrier when they are sprayed molten onto hot OSB surfaces.

There was little correlation between the melting point temperatures of the waxes and the TS of wax-treated OSB samples. HM waxes were more likely to form coatings on top of the surface, rather than penetrate into OSB as envisioned. LM waxes rarely formed surface coatings. Instead they likely pretreated the top layer of the OSB panels, and the wax was invisible to the naked eye. HM waxes, such as beeswax, may have formed coatings that were more effective water repellent barriers than the sub-surface barriers created by most of the LM waxes. This supposition could partly explain why there was no clear relationship between melting point temperature of waxes and TS of wax-treated samples. The results from the previous chapter suggested that the water repellency of wax-treated OSB increased as wax melting point temperatures increased. This supposition could also partly explain why some of the HM waxes performed better than the LM waxes. It appears that the ability of a molten wax to form an effective water-repellent barrier in OSB is affected by a complex combination of its physical and chemical properties.

The most obvious reason why some HM waxes did not penetrate into the board, but rather solidified on top of the surface, was because the spray temperature was kept constant, at 100°C, regardless of the melting point of the wax which was sprayed. Some HM waxes were only sprayed a few degrees higher than their congealing point temperatures, while LM waxes were discharged from the spray gun at temperatures far higher than their congealing points. Carnauba wax, for example, was sprayed at only 19°C (100°C - 81°C) above its congealing point, while Sasolwax C was sprayed at 69°C (100°C - 31°C) above its congealing point. Given this temperature difference, it is very likely that LM waxes took longer to cool down and solidify than HM waxes. When molten wax cools down and its temperature approaches congealing point its viscosity and resistance to flow increases dramatically (Hsu and Bender 1988). Thus, HM waxes were more likely to solidify on top of the surface than penetrate into the sample. In support of this suggestion Grigsby and Thumm (2012a) showed that when wax is used during the manufacture of medium density fibreboard (MDF), it spreads more readily over the MDF fibres when the temperature of the wax is far above its congealing point. According to Maloney (1993) molten wax that is sprayed onto OSB strands during blending, seldom travels more than 300 – 450 mm through the air before solidifying. Lanolin was not able to effectively penetrate the surface of OSB, even when small quantities were applied. This is probably because of its high viscosity when its temperature is close to its congealing point and also possibly due to the presence of wool fibres in the wax.

Wax treatments in general decreased the rate of TS, but there was no significant difference in the extent of TS of wax-treated samples and untreated samples after 21 days of immersion in water. Therefore, according to the categories that Rowell and Banks (1985) defined for water-repellents for solid wood (Section 2.4), the wax treatments used in this study can be defined as a Type-I water repellent treatment. In other words: spraying the surface of OSB with molten wax reduces the board's the rate of liquid water uptake, but not its extent of TS. Beeswax was the only wax that reduced the extent of swelling after 21 days, however, it is possible that if beeswax treated samples were immersed in water for longer they would have swelled to the same extent as untreated samples. The definition by Rowell and Banks (1985) does define the time period for testing and characterization of water repellents, since it is not necessary for solid wood. However, for OSB, and other particleboards, a (defined) testing time should be specified, since it is likely that most OSB treated with water repellents will "swell to the same extent" as untreated controls if left immersed in water for long enough.

During building construction, when OSB panels are exposed to rain and high humidity, Type-I water repellent treatments might be able to slow the rate of liquid WA, until construction is complete and the building envelope is sealed. Thus, the mechanical strength of the boards should be preserved and any other unwanted effects caused by water will also be reduced. In practice OSB panels are rarely totally immersed in water, as was the case in this study. It is far more likely that the panels will only be exposed to alternating periods of rain and sunshine. Thus, the test methods used here are relatively severe (Taylor et al. 2008) and any treatment that can significantly reduce OSB's rate of TS during a 24 h water immersion test may be useful in practice.

It should be noted that the rate of TS for samples treated with beeswax or Vaseline was different to that of samples treated with other wax types (Figure 4.9). The slower rate of swelling was possibly the result of a combination of effects: (1) the water repellent properties of the waxes; (2) the softness of the waxes; and (3) the unexpected defect-free coatings that Vaseline and particularly beeswax formed when high spread rates were used. Soft waxes, similar to beeswax and Vaseline, have provided flexibility to water-repellent coatings for more than half a century (Hilditch 1965). Harder coatings, such as those formed by carnauba wax and Sasolwax M3M, cracked and flaked off as the samples swelled. Evidence for such cracking of carnauba wax coatings was seen in the SEM photomicrographs in Chapter 3. Such cracks, if present in carnauba wax treated samples, may have opened pathways for moisture ingress into OSB samples. In contrast, there was also evidence from Chapter 3 that beeswax coatings had greater integrity and this may, in part, explain why the molten beeswax treatment was more effective at restricting swelling than the other treatments, particularly when OSB samples were first immersed in water.

Another possible explanation for the slower rate of swelling of samples treated with beeswax could be related to the polarity of the wax, which may have caused it to adhere more strongly to the OSB surfaces than other wax types. According to Adam (1963), water repellents with polar functional groups are more attracted to wood than those without such groups. Finally, it may also be that the presence of propolis in beeswax, allowed the wax to adhere more strongly to the OSB surface. Propolis is a type of resin that is produced by bees to protect and seal the honeycomb. A study, which looked at the possibilities of using propolis for wood finishing concluded that, although there were only limited opportunities for its direct use as a wood finish, propolis was, nevertheless, hydrophobic and could be an effective component of coatings when combined with other natural water repellents, such as wax (Budija et al. 2008).

Although wax treatments significantly reduced the TS of OSB, the extent of TS of all samples, including the untreated controls, was probably restricted by the epoxy resin that was used to edge-seal samples prior to the immersion test. For this reason it is not possible to directly compare the swelling results to industry standards. The literature, however, contains two comparable studies that also measured the dimensional stability of OSB samples that were edge sealed with epoxy resin (Semple et al. 2009, Evans and Cullis 2008). Semple et al. (2009) sprayed linseed oil-wax solutions onto the surface of hot OSB and found that treatments were most effective at reducing the short-term TS of OSB when the linseed oil hardened to form a coating that covered the surface voids of the boards. They also found that linseed oil coatings that contained beeswax were less effective than those that contained carnauba wax. These results are contrary to my results, however, they support the suggestion that beeswax and Vaseline treated samples here may have performed well because of the presence of coatings which sometimes formed on the surface, rather than as a result of other factors, such as the hydrophobicity of the wax. Evans and Cullis (2008) used a roller coater to coat the surfaces of OSB samples with UV-cured finishes, as mentioned above. They reported that, after 72 h of immersion in water, the thickness swelling of uncoated control samples was approximately 1.2 mm, while the thickness of surface-coated OSB samples had increased by approximately 0.3 mm. These findings agree well with my results and also support the suggestion that beeswax and Vaseline treated samples performed well because they tended to form surface coatings.

Other properties, which were not examined in this study, but which may also affect the water repellency of wax-treated OSB, include the oil content of wax and its hardness. The oil content of wax can be measured according to ASTM D721 – 06, while wax hardness can be measured according to the needle penetration test ASTM D1321 -10. Rodríguez-Valverde et al. (2006) investigated the effect of oil content on the water repellency of paraffin wax emulsions and found that oil contents below 14% increase the water-proofing capacity of wax emulsions, but that higher percentages decrease water repellency. In contrast, Hsu and Bender (1988) concluded that oil content does not directly affect the water repellency of wax. Hsu et al. (1990) also reached the same conclusion. The measured the TS of waferboard that contained slack wax sizing with different oil contents ranging from 0 - 30%. Further research is therefore necessary to determine whether the oil content and hardness of wax has an effect on the ability of molten wax treatments to dimensionally stabilize OSB. Slack wax, for example, may be a relatively inexpensive option to use as hot wax spray treatment, since it is readily available and is already used by the wood composite industry. Its oil content, however, is known to be 5 – 12% (Wolfmeier et al. 2000), and therefore it may not be the most effective wax at stabilizing OSB.

Lastly, I suggest that to compare different wax treatments more accurately the difference between the spray temperature and the wax melting point temperature must remain constant for all waxes. I suggest that the maximum amount of wax that can be applied to an OSB surface, without forming an unwanted surface coating, will depend on: (1) the melting temperature of the wax; (2) the temperature at which the wax is sprayed; (3) the rate at which the discharged wax cools before it comes in contact with the OSB surface; and (4) the surface temperature of the OSB. I propose a maximum spread rate of less than 170 g / m^2 for most waxes; however, this will depend on the wax being sprayed and the spraying conditions, as described above.

4.5 Conclusion

Molten wax spray treatments can reduce the TS rate of OSB in the absence of a surface coating, as hypothesized in the introduction. The formation of surface coatings, however, made it difficult to draw conclusions about whether there is a relationship between the melting point temperatures of waxes and their ability to dimensionally stabilize OSB. I conclude that the ability of a molten wax to penetrate the surface of OSB and form an effective water-repellent barrier is affected by a complex combination of its physical and chemical properties.

Molten wax treatment effectively reduced the rate of WA of treated OSB, but not the extent of TS. Therefore, I conclude that wax treatments can provide OSB with enhanced protection during short periods of exposure to liquid water, but they will not be suitable for OSB exposed outdoors.

Finally, I conclude that to compare the ability of molten waxes to dimensionally stabilize OSB, the spray temperatures should be tailored and adjusted according to the type of wax being sprayed. A sliding scale system is proposed, whereby the difference between the spray temperature and wax melting point temperature remains constant for all wax types. I propose to employ this method in the next chapter.

Chapter 5. Effects of wax polarity and melting point temperature on water absorption and thickness swelling

5.1 Introduction

In Chapter 4, I observed that samples treated with beeswax swelled significantly less than untreated and some wax-treated samples, especially when samples were first immersed in water. I suggested that this was mainly because beeswax formed defect-free surface coatings at the surface of treated OSB. I examined whether the polarity of waxes had an effect on their performance. My results were inconclusive. Beeswax performed well, but the other two polar waxes performed poorly. One of the latter waxes, carnauba wax, tended to form surface coatings that cracked, and the other polar wax, raw lanolin, was contaminated by wood fibres and was one of the least hydrophobic waxes.

In this chapter I seek to better test the hypothesis that polar waxes will be more effective wax treatments for OSB than nonpolar waxes. To do this 16 different waxes, including nine polar waxes, were sprayed in a molten state onto the surfaces of OSB samples and samples were floated face down on water for 72h. It has been suggested that waxes with polar groups have a higher affinity for wood than those without such groups (Adam 1963; Borgin 1965; Rowell and Banks 1985). Stamm and Hansen (1935) impregnated solid wood with various types of wax and found that those that contained polar groups were more effective water repellents than nonpolar waxes. The hydrophobicity of wax, however, decreases as the number and the size of polar functional groups increases (Holloway 1969). This, in turn, may reduce the effectiveness of wax as a water-repellent treatment for OSB. Borgin (1965) suggested that effective water repellents for solid wood should consist of a combination of hydrophobic components that repel water, and hydrophilic components that increase the attraction of the water repellent to wood. Accordingly, I hypothesize that polar waxes that are strongly hydrophobic will be more effective at dimensionally stabilizing OSB than nonpolar waxes or polar waxes with lower hydrophobicity.

In Chapter 4, I also concluded that waxes should be compared by spraying them at temperatures high above their individual melting points so that each one could penetrate into the surface of OSB rather than forming a surface coating. For this purpose I also suggested that less than 170 g / m^2 of wax should be applied onto the surface of OSB samples. The waxes that are tested in this chapter have a large range of melting point temperatures and the spray temperatures for each wax type was adjusted so that the difference between the spray temperatures and the wax melting points remain constant for all waxes. Spray temperatures were kept high enough to avoid the formation of thick surface coatings on OSB. In Chapter 4 the formation of surface coatings with some of the higher melting point waxes made it difficult to establish whether there was a clear relationship between the melting point temperatures of waxes and their ability to dimensionally stabilize OSB. In this chapter, using the refined methodology described above, I again tested the hypothesis that low melting point waxes will be more effective at dimensionally stabilizing OSB than high melting point waxes.

To better test these hypotheses (effects of polarity and melting point temperature) five wax blends were prepared by combining polar waxes with waxes that had large range of melting point temperatures. Two of these wax blends, one based on beeswax and another based on a Fischer-Tropsch wax (Sasolwax M3M), each contained a 25% ethylene maleic anhydride (EMA), by weight. EMA was added to increase the melting point temperature and polarity of the waxes. The other three wax blends were prepared at a 1:1 weight ratio. One of them consisted of the two best performing waxes from Chapter 4, beeswax (polar) and Vaseline (nonpolar). The other two were similar blends of beeswax and paraffin wax (nonpolar and high melting point), as well as beeswax and a Fischer-Tropsch wax (Sasolwax C, nonpolar and low melting point).

5.2 Materials and methods

5.2.1 Experimental design

A randomized block design was used to determine the effect of a single fixed factor (wax type) on water absorption (WA) and thickness swelling (TS) of OSB. Sixteen waxes were chosen based on their melting points and polarity (Table 5.1). Each wax was individually sprayed onto OSB samples. Untreated samples and a commercially available "moisture resistant" OSB acted as controls. Each experimental block consisted of 18 samples (16 wax-treated + 1 untreated control + 1 "moisture resistant" sample). The experiment was replicated seven times, each time using samples cut from independent panels (as in Chapter 4). The total sample population for the experiment was therefore 126 (18 treatments x 7 panels).

Analysis of variance for a randomized block design was used to examine the effect of wax type on the following response variables: (1) water absorption (WA) after 2 h, 24 h, 48 h and 72 h; and (2) thickness swelling (TS) after 2 h, 24 h, 48 h and 72 h. The hierarchical design of the experiment accounted for random variation between panels, as well as the fixed effect of wax type. The amount of wax applied to each sample was included as a covariant. The statistical program Genstat 12.1 (VSN International 2009) was used to analyze the data with a 95% confidence interval ($\alpha = 0.05$) and to check the assumptions of ANOVA (as described in Chapter 3). A sub-routine (convsstrt), within Genstat, was used to compare the response variables of untreated OSB samples with those of all wax-treated samples, as well as samples treated with each individual wax type. The same sub-routine was used for a second analysis, which compared the performance of all wax-treated samples and individual wax types with those of untreated "moisture resistant" OSB. Results are presented in graphs and error bars on each graph (± standard error of difference, $p < 0.05$) can be used to estimate whether differences between individual means are statistically significant. Stepwise linear regression was used to establish relationships between WA and TS measurements and the wax properties reported in Chapter 3. The free statistical analysis software "RStudio" was used for this purpose (RStudio 2014).

5.2.2 Waxes

Sixteen waxes were chosen based on their melting point temperatures and polarity (Table 5.1). Supplier details and methods used to prepare wax blends are provided in Section 3.2.1. The congealing point of each wax was determined according to ASTM D938-12 and the drop melting point temperature was determined according to ASTM D127-08, as described in Section 3.2.5. The apparent viscosity of each wax was measured using the standard test method ASTM D2669 – 06, as described in Section 3.2.6.

Table 5.1. The names, abbreviations, origin, melting point, and viscosity of 16 waxes

Wax	**Abbrev**	**Origin**	**MP (°C)†**	**Viscosity (cP) at MP + 25°C**	**Acid value (mg KOH/g)**
Sasolwax C	Sc	F-T ‡	31	5.30	0
Tekniwax 801	T801	F-T	44	7.50	0
Soy wax	Soy	Vegetable	54	15.8	31.5
Merkur 300	M300	Petroleum	55	6.00	0
Beeswax + Sasolwax C (1:1)	Bee+Sc	Blend	59	10.2	9.2
Vaseline	Vas	Petroleum	59	9.50	0
Beeswax + Vaseline (1:1)	Bee+Vas	Blend	62	11.4	9.2
Stearic acid	Stearic acid	Vegetable	63	7.70	215.3
Beeswax	Bee	Animal	65	14.5	18.5
Sasolwax M3M	M3M	F-T	68	8.10	0
Beeswax + Synthetic Beeswax (1:1)	Bee+Synth	Blend	73	16.2	9.2
Microcrystalline wax	Micro	Petroleum	73	17.5	0
Synthetic Beeswax	Synth	Petroleum	77	8.40	0
Carnauba wax	Car	Vegetable	81	22.2	6.8
Sasolwax M3M + EMA*(3:1)	M3M+EMA	Blend	85	29.5	8.6
Beeswax + EMA* (3:1)	Bee+EMA	Blend	87	51.3	22.4

† MP = Drop melting point temperature

‡ F-T = Fischer-Tropsch

* Ethylene maleic anhydride

5.2.3 Oriented strandboard

Seven independent OSB panels, measuring 2440 x 1220 x 18 mm^3, were supplied by Tolko Industries, Canada. These samples are sometimes referred to as “regular OSB” samples, or simply as “untreated OSB”. A single panel was used for each experimental replication (block).

The panels were sampled from the production line at different times, as mentioned above. More information on the composition of the OSB panels can be found in Section 4.2.3.

Each experimental replication also included a single commercially available, “moisture resistant” OSB sample (150 x 150 mm^2), manufactured by a U.S. company. These samples are referred to as “MR” hereafter. Seven independent MR panels were provided by the Centre for Advanced Wood Processing, at UBC. A single 150 x 150 mm^2 sample was cut from a random location on each panel, using a table saw (Altendorf F45 ELMO).

5.2.4 Sample preparation

The preparation of samples for each seven experimental replications (blocks) occurred at different times. All samples (except for the MR samples) in each block were cut from a single board. A table saw (Altendorf F45 ELMO) was used to trim off 100 mm from one end of each board. Seven strips, 1220 x 150 mm^2 each, were then sawn from the freshly-cut side. A cross-cut saw (Omga T55-300) was used to trim off 50 mm from the ends of each strip and the remaining lengths were cross-cut into fifty-six 150 x 150 mm^2 samples.

All OSB samples were placed in an oven, at 105 ± 2°C for a minimum of 24 h or until they reached equilibrium moisture content. The oven dry weight of each sample was measured and 17 samples with the most similar weights were selected to reduce the strong effect that density has on WA and TS. A wax treatment (wax type or control) was randomly assigned to each of the selected samples. The average oven dry thickness of the Tolko samples in the sample population was 18.7 mm, with a standard deviation of 0.4 mm, and the average dry density was 597 kg / m^3, with a standard deviation 19 kg / m^3. The average oven dry thickness of the MR samples was 17.6 mm and the average density was 649 kg / m^3.

The 18 oven dried samples in each block (16 wax-treated + 1 untreated control + 1 MR sample) were placed in a vacuum oven at 90 ± 1°C and were individually removed and placed in a second oven (170°C), between two heated metal plates (1 kg each), for 10 min before wax application (as in Chapter 4).

5.2.5 *Wax application*

Wax was sprayed onto the surface of each sample using a pneumatic hot wax spray gun, as described in Section 4.2.5. Each wax was applied at 25°C above its melting point, and the gun had a constant chamber pressure of 300 kPa and spray pressure of 200 kPa.

To determine how much wax was applied to each sample, the mass of each sample was recorded immediately after wax application (Table 5.2). Samples were sprayed with an average of 76 g / m^2 wax (or 0.7% by weight), with a standard deviation of 21 g / m^2. The minimum amount applied onto a single sample was 45 g / m^2 and the maximum was 138 g / m^2 (or 0.4% and 1.2% by weight, respectively).

Table 5.2. Summary of the amount of each wax type applied to seven samples

Wax Type	Wax applied per sample (g / m^2)			
	Mean	**σ**	**Min**	**Max**
Beeswax + Synthetic Beeswax (1:1)	80.44	25.92	55.56	131.11
Beeswax + Vaseline (1:1)	78.60	28.07	51.11	138.22
Beeswax	79.68	21.54	55.56	118.67
Beeswax + EMA* (3:1)	81.52	20.68	46.67	105.33
Microcrystalline wax	72.44	15.97	46.67	93.33
Synthetic Beeswax	75.11	24.91	50.67	128.89
Sasolwax M3M + EMA* (3:1)	75.62	14.75	59.11	96.44
Tekniwax 801	72.13	14.07	56.44	100.89
Stearic acid	84.44	25.84	47.11	129.33
Vaseline	81.71	25.94	54.22	129.78
Carnauba wax	68.63	20.10	45.33	104.44
Sasolwax M3M	72.38	27.90	50.22	133.33
Beeswax + Sasolwax C (1:1)	75.94	17.88	45.78	96.00
Merkur 300	70.41	17.01	49.78	99.56
Soy wax	75.68	16.73	54.67	95.56
Sasolwax C	76.13	23.74	54.22	124.44

*EMA = Ethylene maleic anhydride

Treated samples were placed in a climate controlled room at 20 ± 1 °C and 65 ± 5% r.h. for a minimum of five days. All conditioned samples were reweighed before and after their edges were sealed with a white silicone sealant (GE Silicone II 100% Silicone # P-WGH291). The mass of the silicone applied to samples was calculated. The sealed samples were conditioned for two additional days to allow the silicone to cure. All samples were therefore conditioned for a minimum of seven days. The initial mass of each sample before liquid water exposure was calculated by subtracting the mass of the wax and the silicone from the total mass of the sample. The initial mass was then used to calculate the initial moisture content of samples based on the oven dry weight that was measured upon sample selection (Section 5.2.4).

The oven dry mass and the oven dry thickness of the untreated and wax-treated samples were not significantly different ($p > 0.05$). In contrast, after conditioning, there were significant ($p = 0.006$) differences in the initial moisture content of samples that were treated with different types of wax. The average initial moisture content of the sample population was 6.2%, with a standard deviation of 1.4%. Untreated control samples had the highest average initial moisture content (6.5%), while samples treated with microcrystalline wax, had the lowest (5.8%).

5.2.6 Water absorption and thickness swelling measurement

For this experiment a water float test was used, instead of the conventional soak test (NIST 2004, ASTM 2012b). Water float tests are commonly used to determine the liquid water permeability of surface coatings for solid wood (EN 2005), but a float test was also recently employed by Evans et al (2013) to test the differential edge swelling of OSB. Approximately 150 L of fresh tap water was poured into a 257 L water tank, which measured 1840 x 930 x 150 mm^3. Once the water temperature stabilized at room temperature (20 ± 3°C), the samples were carefully placed on the surface of the water, where they floated for three days. The water in the tank was refreshed once a day to reduce the negative effects that changes in water pH levels have on WA and TS (Blau, K., personal communication, February 4, 2013). Samples were removed from the tank after 2 h, 24 h, 48 h, and 72 h. Once the samples were removed, they were then placed on a flat surface, lightly blotted with tissue paper to remove excess water and left to dry for 10 min. Samples were weighed and their thicknesses were measured using a digital laboratory micrometer (Evans et al. 2013). Four thickness measurements were taken per sample, midway along and 15 mm from each edge. The four measurements were averaged and the averages were recorded. After the 72 h measurements, the samples were placed in a climate controlled room at 20 ± 1°C at 65 ± 5% r .h. for a minimum of two and a maximum of four weeks. All the conditioned samples were then reweighed and their thicknesses were measured using a digital micrometer, as above. All samples from each individual experimental replication were measured at the same time, regardless of the conditioning period.

Figure 5.1. Samples were floated face down on water for 72 h. The weight and the thickness of each sample was measured after 2 h, 24 h, 48 h, and 72 h

5.3 Results

The overall effects of wax treatments on the WA and TS of OSB are summarized in Table 5.3. This table also compares the WA and TS of wax-treated samples with those of commercial MR samples. Wax treatments had a significant effect on WA, as well as the degree of TS of samples for all exposure periods when results are compared to those of untreated controls. WA was significantly different at all time periods: 2 h ($p < 0.001$); 24 h ($p < 0.001$); 48 h ($p = 0.006$); and 72 h ($p = 0.037$). Similarly, TS was significantly different at 2 h ($p < 0.001$), 24 h ($p = 0.008$), 48 h ($p = 0.042$), and 72 h ($p = 0.043$). Samples treated with wax consistently absorbed less water and swelled less than the untreated controls. When compared to the MR samples there were significant differences in WA at 2 h ($p < 0.001$), 48 h ($p = 0.002$), and 72 h ($p < 0.001$), but not at 24 h. There were also significant differences in TS at 2 h ($p = 0.005$), 24 h ($p < 0.001$), 48 h ($p < 0.001$), and 72 h ($p < 0.001$).

Table 5.3. The effects of wax treatments on the water absorption and thickness swelling of OSB samples, and a comparison between wax-treated samples and "moisture resistant" samples. All samples were floated face down on water for 72 h and measured at 2 h, 24 h, 48 h and 72 h (α = 0.05)

	Water absorption (mL)				**Thickness swelling (mm)**			
	2 h	**24 h**	**48 h**	**72 h**	**2 h**	**24 h**	**48 h**	**72 h**
Wax-treated samples (n = 112)	3.68	16.78	30.39	46.33	0.16	0.63	1.02	1.41
Untreated controls (n = 7)	*6.4*	*21.87*	*36.49*	*53.51*	*0.25*	*0.77*	*1.17*	*1.6*
p-value †	< 0.001	< 0.001	0.006	0.037	< 0.001	0.008	0.042	0.043
Least significant difference ‡	0.66	2.57	4.63	7.32	0.04	0.11	0.16	0.19
Untreated MR (n = 7)	*4.79*	*14.32*	*22.53*	*30.29*	*0.09*	*0.31*	*0.54*	*0.6*
p-value †	< 0.001	0.095	0.002	< 0.001	0.005	< 0.001	< 0.001	< 0.001
Least significant difference ‡	0.69	2.46	4.61	7.4	0.04	0.12	0.17	0.2

† Wax-treated samples are significantly different to control samples if $p < 0.05$

‡ Any difference larger than the least significant difference is significantly different ($p < 0.05$)

The WA and TS of untreated and the different types of wax-treated samples was significantly different for all recorded time periods (Table 5.4.). Similarly, when wax-treated samples are compared with MR samples there were also significant differences in TS at all recorded time periods. However, for WA there were only significant differences at 2 h, 24 h, and 48 h ($p < 0.001$).

Table 5.4. The effect of individual wax on the water absorption and thickness swelling of OSB samples that were floated face down on water for 2 h, 24 h, 48 h and 72 h, as well as a comparison between wax-treated samples and "moisture resistant" samples

	Water absorption (mL)				**Thickness swelling (mm)**			
	2 h	**24 h**	**48 h**	**72 h**	**2 h**	**24 h**	**48 h**	**72 h**
Beeswax + Synth Beeswax	2.26	11.73	23.3	37.11	0.12	0.46	0.78	1.12
Beeswax + Vaseline	1.98	11.57	24.72	42.08	0.09	0.45	0.79	1.19
Beeswax	2.45	14.13	26.46	43.15	0.10	0.52	0.83	1.27
Beeswax + EMA*	2.57	14.78	29.00	46.3	0.11	0.49	0.87	1.27
Microcrystalline wax	2.68	14.54	27.08	41.73	0.13	0.52	0.93	1.32
Synthetic Beeswax	2.50	14.65	28.44	46.44	0.10	0.55	0.91	1.22
Sasolwax M3M + EMA*	3.29	18.07	32.89	49.97	0.12	0.6	1.00	1.43
Tekniwax 801	4.03	16.92	29.84	43.97	0.21	0.62	1.00	1.36
Stearic acid	3.85	15.03	25.73	37.99	0.18	0.62	0.93	1.28
Vaseline	3.53	16.33	31.05	48.36	0.16	0.62	1.06	1.50
Carnauba wax	2.76	15.24	28.30	43.53	0.16	0.65	1.07	1.44
Sasolwax M3M	3.93	18.18	32.16	48.14	0.17	0.68	1.08	1.52
Beeswax + Sasolwax C	4.01	17.95	32.18	48.26	0.16	0.73	1.17	1.62
Merkur 300	5.10	19.95	33.52	48.37	0.21	0.76	1.13	1.50
Soy wax	5.96	21.63	36.49	53.29	0.24	0.80	1.20	1.64
Sasolwax C	6.49	22.78	37.97	53.34	0.28	0.81	1.29	1.65
Untreated controls	*6.40*	*21.87*	*36.49*	*53.51*	*0.25*	*0.77*	*1.17*	*1.60*
p-value†	< 0.001	< .001	< 0.001	0.047	< 0.001	< 0.001	< 0.001	< 0.001
Least significant difference ‡	0.91	3.53	6.35	10.04	0.06	0.15	0.22	0.27
Untreated "moisture resistant"	*4.79*	*14.32*	*22.53*	*30.29*	*0.09*	*0.31*	*0.54*	*0.60*
p-value †	< 0.001	< 0.001	< 0.001	0.054	< 0.001	< 0.001	< 0.001	0.002
Least significant difference ‡	0.94	3.37	6.32	10.15	0.06	0.16	0.23	0.28

† Wax-treated samples were significantly different to control samples if $p < 0.05$

‡ Any difference larger than the least significant difference was significantly different ($p < 0.05$)

* EMA = Ethylene maleic anhydride

5.3.1 Relationship between water absorption and thickness swelling

There was a very strong linear relationship between the WA and TS of OSB samples over a 72 h period (Figure 5.2).

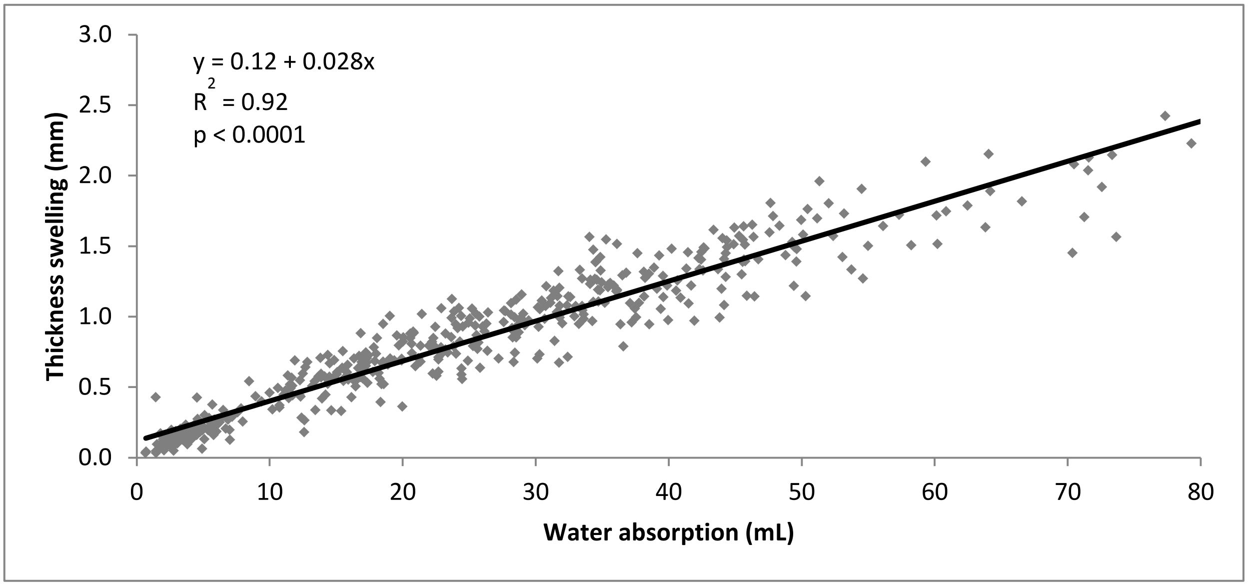


Figure 5.2. The relationship between water absorption and thickness swelling of untreated and wax-treated OSB samples that were floated face down on water for 72 h. Moisture resistant samples not included

The relationship between WA and TS was strongly affected by the length of time that samples were floated on water (Figure 5.3), with the positive correlation becoming stronger after longer exposure periods. After 2 h, the coefficient of determination (R^2) was 0.51, but this increased to $R^2 = 0.6$ after 24 h, and $R^2 = 0.62$ after 48 h. After 72 h hours the R^2 was 0.71 or, in other words, 71% of the variation in TS could be explained by the amount of water that samples absorbed. It can also be seen that the slope of the trend lines decreased with increasing exposure to water. This finding indicates that similar amounts of water caused more TS during initial exposure periods than they did after longer exposure periods. It also suggests that the relationship between WA and TS of OSB may be curvilinear and not linear.

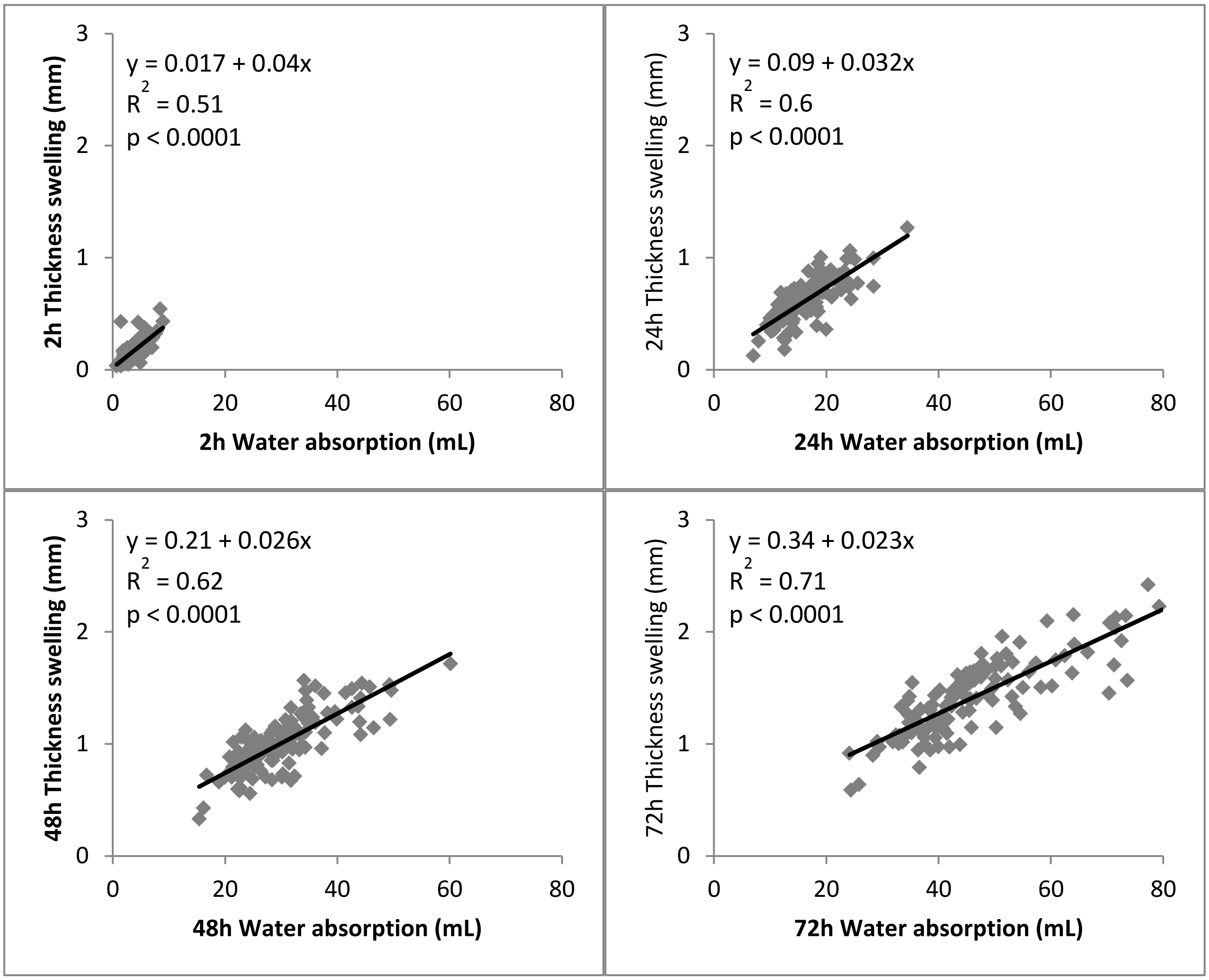


Figure 5.3. Relationships between water absorption and thickness swelling of untreated and wax-treated OSB samples that were floated face down on water for 72 h. Measurements were made after 2 h (top left), 24 h (top right), 48 h (bottom left) and 72 h (bottom right)

5.3.2 Wax application and physical appearance of wax-treated samples

After samples were treated with wax they appeared slightly darker, but otherwise they were indistinguishable from untreated samples. Unlike the treatments in Chapter 4, lower application rates and adjusted spray temperatures prevented the formation of any thick surface coatings. I noted, however, that some of the most polar waxes, particularly stearic acid, tended to agglomerate on top of large strands, before seeping into the surface. Such behaviour was also noticed during contact angle measurements in Chapter 3.

5.3.3 Effect of wax treatments and wax type on water absorption

On average, OSB samples absorbed more water during the first 24 h period than during any of the subsequent time-periods (Table 5.5).

Table 5.5. Average water absorption of all OSB samples*

	Water absorption (mL)			
	2 h	**24 h**	**48 h**	**72 h**
Mean	3.8	16.8	30.5	46.5
σ	1.7	4.6	7.8	12.8

* Sample population includes "moisture resistant" samples, untreated controls, and all wax-treated samples

On average, wax-treated samples absorbed less water than untreated water during water exposure time periods (Figure 5.3). One of the best performing wax types was a blend of beeswax and synthetic beeswax. OSB samples treated with this wax type absorbed less water than those of MR samples after 2h and 24 h of exposure to water, but not after 48 h and 72 h.

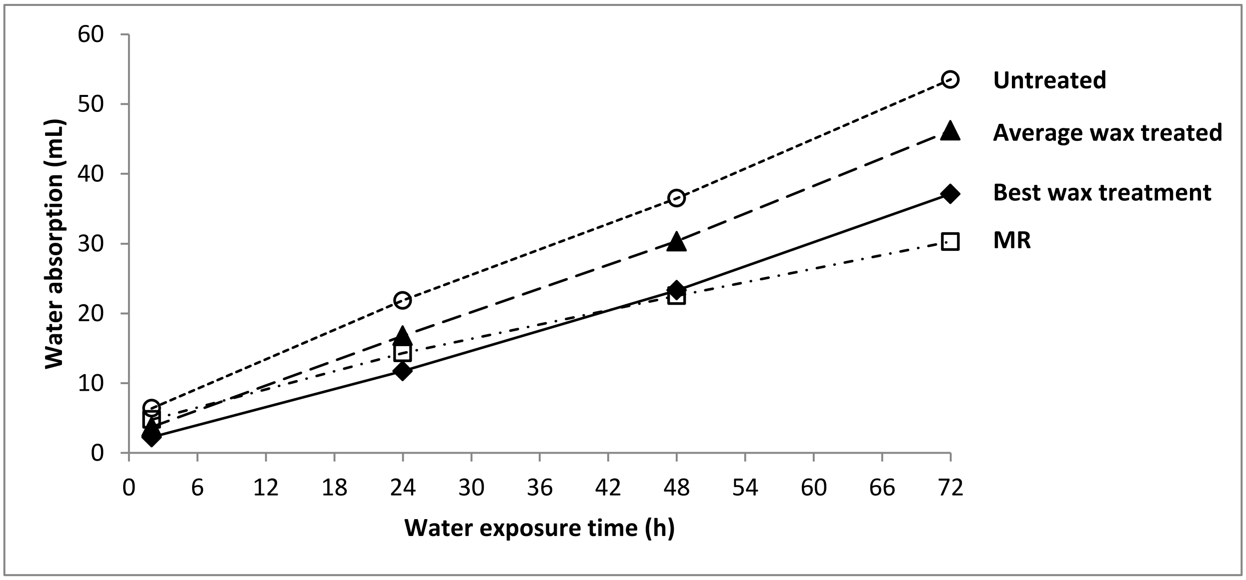


Figure 5.4. Average water absorption of: (1) untreated OSB (n = 7); (2) all wax-treated samples (n = 112); (3) OSB samples treated with a blend of beeswax and synthetic beeswax (n = 7); and (4) "moisture resistant" OSB (n = 7). All samples were floated on water for 72 h and measurements were taken after 2 h, 24 h, 48 h, and 72 h

Wax treatments had a significant ($p > 0.05$) effect on WA of OSB samples for all time periods (Figures 5.4 – 5.5). When wax-treated samples are compared with MR samples, significant differences are apparent for WA at 2 h ($p < 0.001$), 48 h ($p = 0.002$) and 72 h ($p < 0.001$), but not after 24 h.

After 2 h, wax-treated samples had, on average, absorbed 44% less water than untreated samples; untreated samples absorbed 6.4 mL of water, while wax-treated samples absorbed 3.6 mL (Figure 5.4, left). MR samples absorbed 4.8 mL of water after 2 h of floating on water; 25% more water than the average wax-treated samples.

After 24 h, wax-treated samples absorbed 24.7% less water than untreated samples; untreated samples absorbed 22 mL of water, in total, while wax-treated samples absorbed 16.5 mL of water in total (Figure 5.4, right). There was no significant ($p > 0.05$) difference in the amount of water absorbed by wax-treated samples and MR samples after 24 h of floating on water.

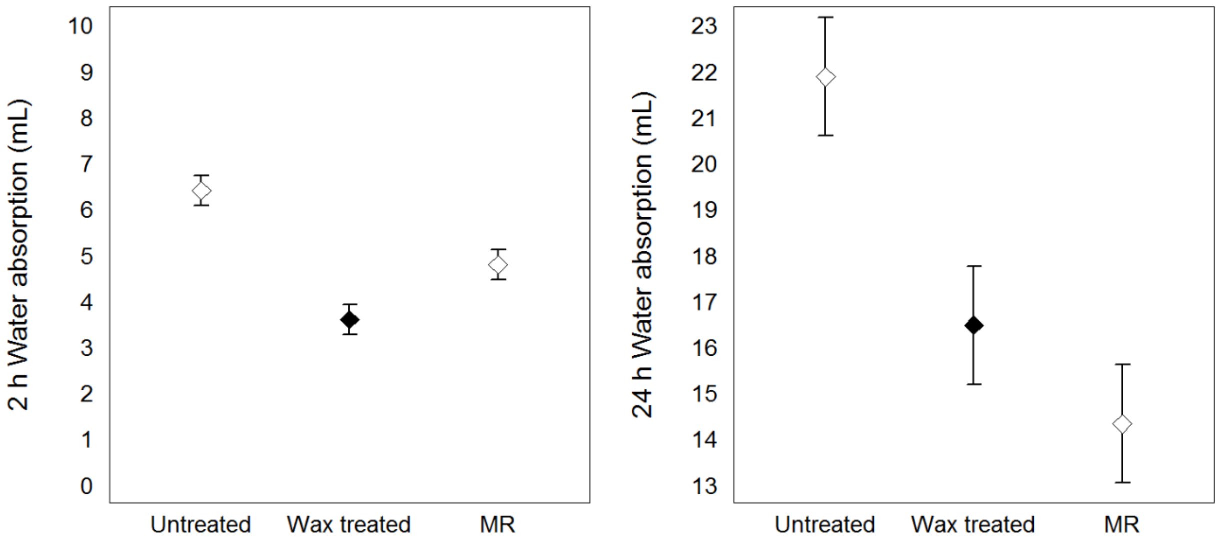


Figure 5.5. Average effect of wax treatments on the water absorption of OSB samples that were floated face down on water for 2 h (left) and 24 h (right), as well as comparison between the water absorption of these samples and those of "moisture resistant" (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 2 h and 24 h was 0.66 mL and 2.57 mL, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.69 mL and 2.46 mL, respectively (not drawn)

After 48 h, wax-treated samples absorbed only 18% less water than untreated samples; untreated samples absorbed 36.5 mL of water, in total, while wax-treated samples absorbed 30 mL of water (Figure 5.6, left). Furthermore, after 48h, wax-treated samples absorbed 25% more water than MR samples, which had absorbed 22.5 mL of water in total.

Finally, after 72 h, wax-treated samples absorbed 14.5% less water than untreated samples; untreated samples absorbed 53.5 mL of water, in total, while wax-treated samples absorbed 45.8 mL of water (Figure 5.6, right). MR samples absorbed 30.3 mL of water after 72 h; 34% less water than wax-treated samples.

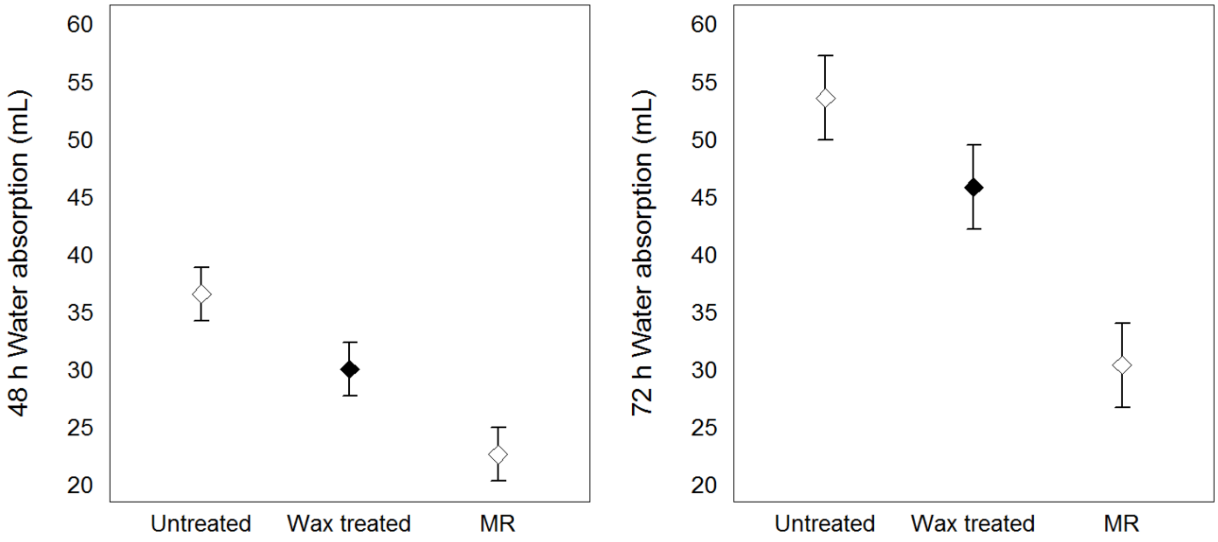


Figure 5.6. Average effect of wax treatments on the water absorption of OSB samples that were floated face down on water for 48 h (left) and 72 h (right), as well as comparison between the water absorption of these samples and those of "moisture resistant" (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (48 h and 72 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 48 h and 72 h was 4.63 mL and 7.32 mL, respectively (error bars drawn). The LSD between untreated samples and MR samples after 48 h and 72 h was 4.61 mL and 7.4 mL, respectively (not drawn)

There were significant differences in the WA of untreated samples and different types of wax-treated samples for all time periods, as well as significant differences in the WA of MR samples and different types of wax-treated samples at 2 h, 24 h, and 48 h ($p < 0.001$). There were also significant differences in WA of different types of wax-treated samples at each of the time periods (Figures 5.6 – 5.9). After 2 h, untreated samples had absorbed 6.4 mL of water, significantly more than most of the other wax-treated samples; except for those treated with Sasolwax C (6.5 mL) or soy wax (6 mL) (Figure 5.7). Samples treated with a blend of beeswax and Vaseline absorbed the lowest amount of water after 2 h (2 mL); 69% less than untreated samples. Samples treated with a blend of beeswax and Vaseline, however, did not absorb significantly ($p > 0.05$) less water than six of the other waxes types. MR samples absorbed 4.8 mL of water after 2 h; significantly ($p < 0.001$) more than nine of the different types of wax-treated samples, but significantly less than samples treated with Sasolwax C or soy wax.

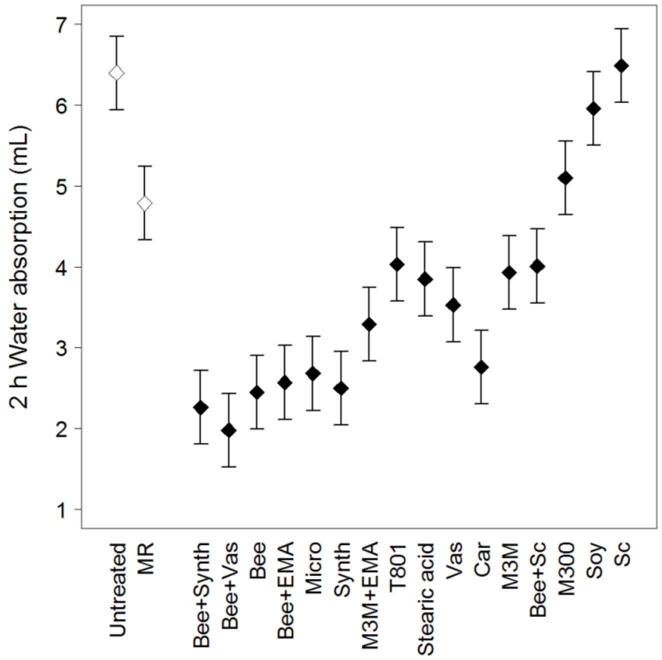


Figure 5.7. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 2 h, as well as a comparison between the water absorption of these samples and "moisture resistant" (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.91 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.94 mL (not drawn)

After 24 h, untreated samples absorbed 22 mL of water in total; significantly ($p < 0.001$) more than most of the wax-treated samples (Figure 5.7). However, there was no significant ($p > 0.05$) difference between the amounts of water absorbed by untreated samples after 24 h and samples treated with Sasolwax C (22.8 mL), soy wax (21.6 mL), or Merkur 300 (20 mL). Once again, samples treated with a blend of beeswax and Vaseline absorbed the least amount of water. After 24 h these samples absorbed 11.57 mL of water in total; 47% less than untreated samples, and significantly ($p < 0.001$) less than most of the other types of wax-treated samples. Samples treated with a blend of beeswax and Vaseline, however, did not absorb significantly ($p > 0.05$) less water after 24 h than six of the different types of wax-treated samples. These included all samples treated with any beeswax combination, except for those treated with a blend of beeswax and Sasolwax C. MR samples absorbed 14.3 mL of water after 24 h and there were no wax-treated samples that absorbed significantly ($p < 0.001$) less water than these MR samples at this time. However, there were six of the different types of wax-treated samples that absorbed significantly ($p < 0.001$) more water.

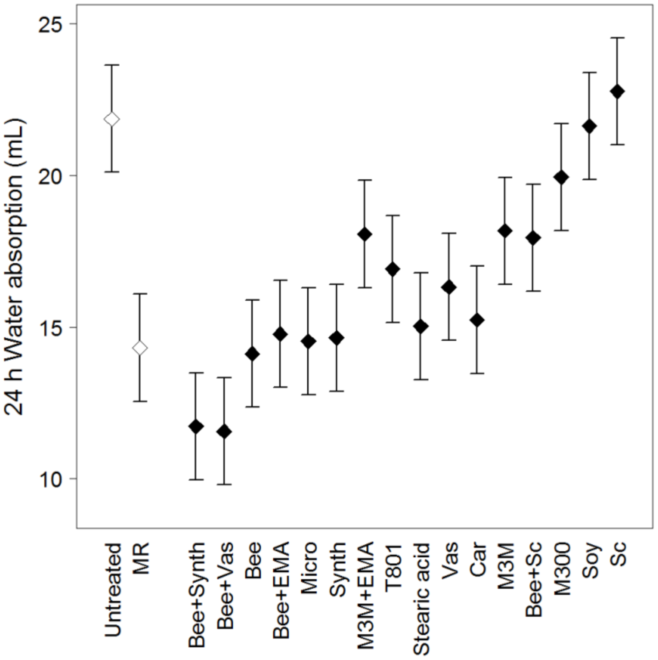


Figure 5.8. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 24 h, as well as a comparison between the water absorption of these samples and "moisture resistant" (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 3.53 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 3.37 mL (not drawn)

After 48 h, untreated samples absorbed 36.5 mL of water in total; significantly ($p < 0.001$) more than many of the wax-treated samples (Figure 5.9). However there was no significant difference in the WA of untreated controls and those of seven of the different wax-treated samples. Samples that absorbed the lowest amount of water after 48 h, were those treated with a blend of beeswax and synthetic beeswax. These samples absorbed 23.3 mL of water in total; 36.1% less than that of untreated samples, and significantly less than most of the other wax-treated samples. The WA of samples treated with a blend of beeswax and synthetic beeswax, however, was not significantly ($p > 0.05$) different from those of samples treated with seven of the other wax types. Once again, these wax types included all those containing beeswax, except a blend of beeswax and Sasolwax C. MR samples absorbed a total of 22.5mL of water after 48 h; significantly ($p < 0.001$) less than nine of the different types of wax-treated samples. There were no wax-treated samples that absorbed significantly ($p < 0.001$) less water than MR samples.

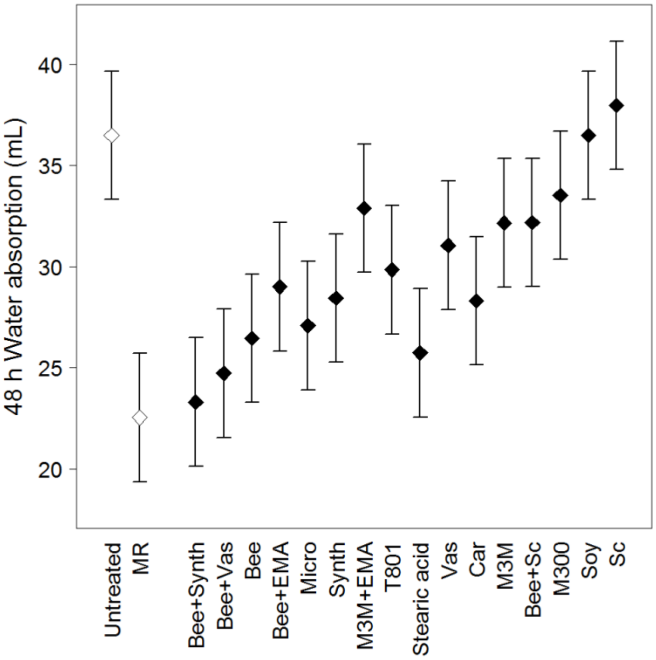


Figure 5.9. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 48 h, as well as a comparison between the water absorption of these samples and "moisture resistant" (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 6.35 mL (error bars drawn), while the LSD between MR samples and wax-treated samples is 6.32 mL (not drawn)

After 72 h, untreated samples absorbed 53.5 mL of water in total, significantly ($p = 0.047$) more than samples treated with any of the following five wax types: beeswax (43.2 mL); a blend of beeswax and Vaseline (42 mL); microcrystalline wax (41 mL); stearic acid (38 mL); or a blend of beeswax and synthetic beeswax (37.11 mL) (Figure 5.10). Samples treated with a blend of beeswax and synthetic beeswax once again absorbed the least amount of water after 72 h.

They absorbed significantly less water than untreated samples (31% less), as well as less than those of samples treated with seven of the different types of wax.

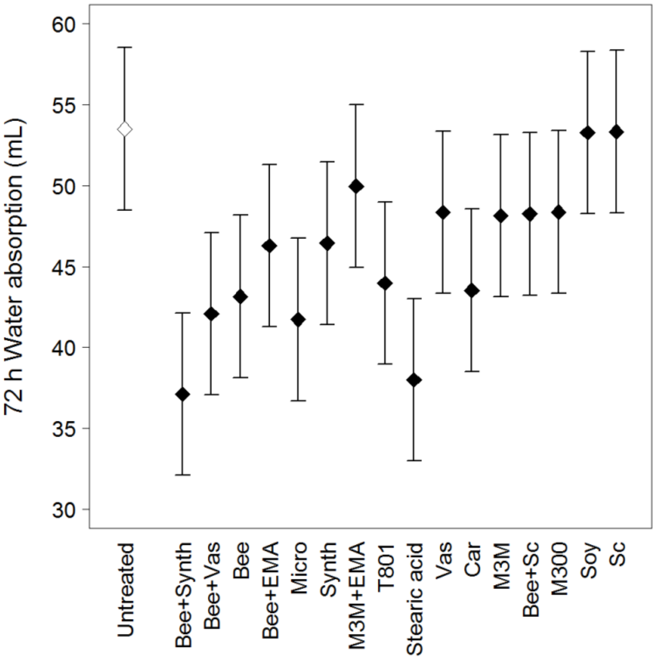


Figure 5.10. Effect of wax type on the water absorption of wax-treated OSB samples that were floated face down on water for 72 h. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 10 mL

5.3.4 Effect of wax treatments and wax type on thickness swelling

On average, OSB samples swelled more during the first 24 h of the float test than during any of the subsequent 24 h periods (Table 5.6).

Table 5.6. Average thickness swelling of all OSB samples*

	Thickness swelling (mm)			
	2 h	**24 h**	**48 h**	**72 h**
Mean	0.17	0.63	1.02	1.42
σ	0.10	0.19	0.26	0.36

* Sample population includes “moisture resistant” samples, untreated controls, and all wax-treated samples

On average wax-treated OSB samples swelled less than untreated OSB samples for all time periods (Figure 5.10). One of the best performing wax types was a blend of beeswax and synthetic beeswax. OSB samples treated with this wax type swelled much less than untreated OSB samples at all time periods, but never less than those of MR samples.

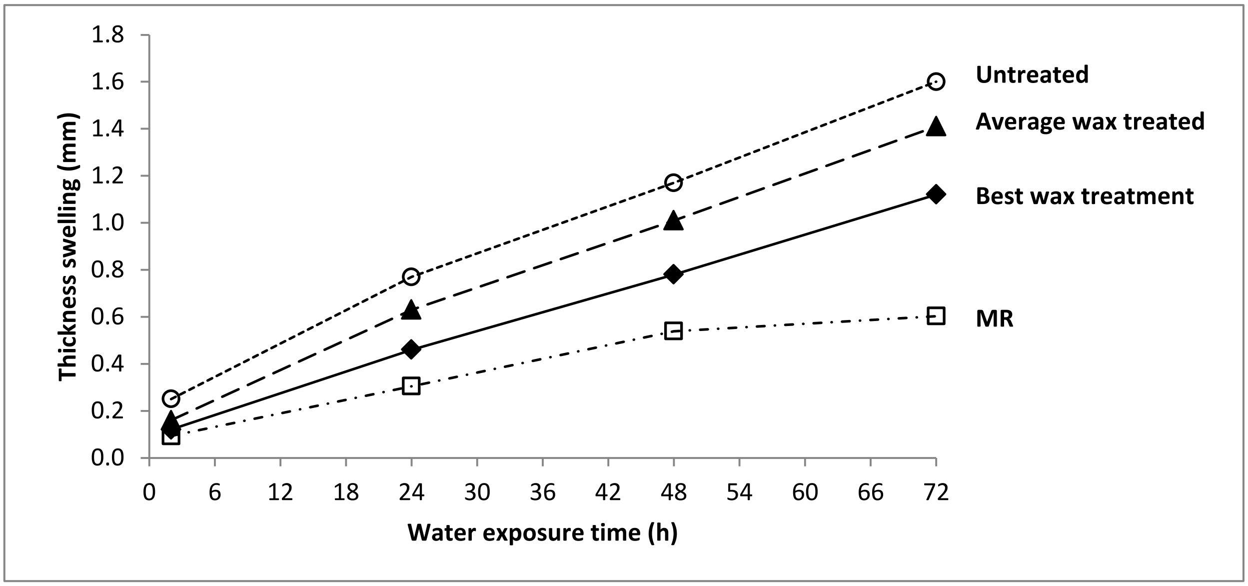


Figure 5.11. Average thickness swelling of: (1) untreated OSB (n = 7); (2) all wax-treated samples (n = 112); (3) OSB samples treated with a blend of beeswax and synthetic beeswax (n = 7): and (4) "moisture resistant" OSB (n = 7). All samples were floated on water for 72 h and measurements were taken after 2 h, 24 h, 48h, and 72 h

Wax treatments had a significant ($p < 0.05$) effect on the TS of OSB for all time periods (Figures 5.11 - 5.12). When wax-treated samples are compared with MR samples there were also significant differences for all the time periods.

After 2 h of floating on water, the average TS of wax-treated samples was 37% less than that of untreated samples (Figure 5.12, left). The thickness of untreated samples had increased by 0.25 mm, while the thickness of wax-treated samples had increased by only 0.16 mm. The thickness of MR samples had increased by 0.09 mm, 41% less than the average wax-treated samples.

After 24 h, the TS of wax-treated samples, on average, was 20% less than that of untreated samples (Figure 5.12, right). The thickness of untreated samples had increased by 0.77 mm in total, while the thickness of wax-treated samples had increased by 0.62 mm. The thickness of MR samples had increased by 0.31 mm in total;, 52% less than that of untreated samples.

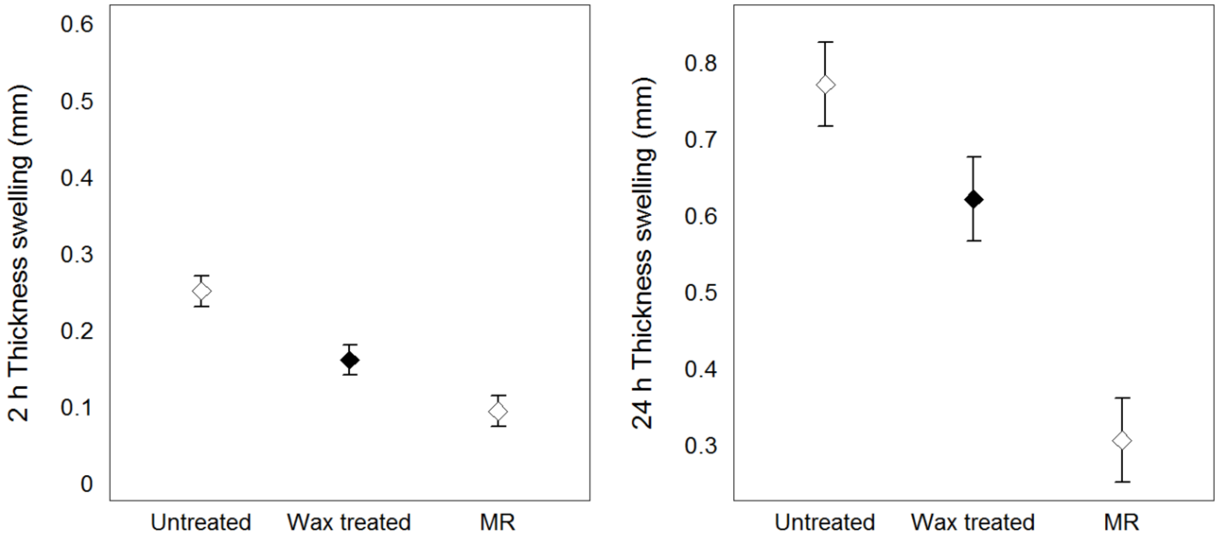


Figure 5.12. Average effect of wax treatments on the thickness swelling of OSB samples that were floated face down on water for 2 h (left) and 24 h (right), as well as a comparison between the water absorption of these samples and those of "moisture resistant" (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24 h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 2 h and 24 h was 0.04 mm and 0.11 mm, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.04 mm and 0.12 mm, respectively (not drawn)

After 48 h, the TS of wax-treated samples, on average, was 15% less than that of untreated samples (Figure 5.13, left). The thickness of untreated samples had increased by 1.17 mm in total, while the thickness of wax-treated samples had increased by 1 mm. The thickness of MR samples had increased by 0.54 mm in total, 46% less than that of untreated samples.

After 72 h, the average TS of wax-treated samples was 13% less than that of untreated samples (Figure 5.13, right). The thickness of untreated samples had increased by 1.6 mm in total, while the thickness of wax-treated samples had increased by 1.4 mm. The thickness of MR samples had increased by 0.6 mm in total, 57% less than that of untreated samples.

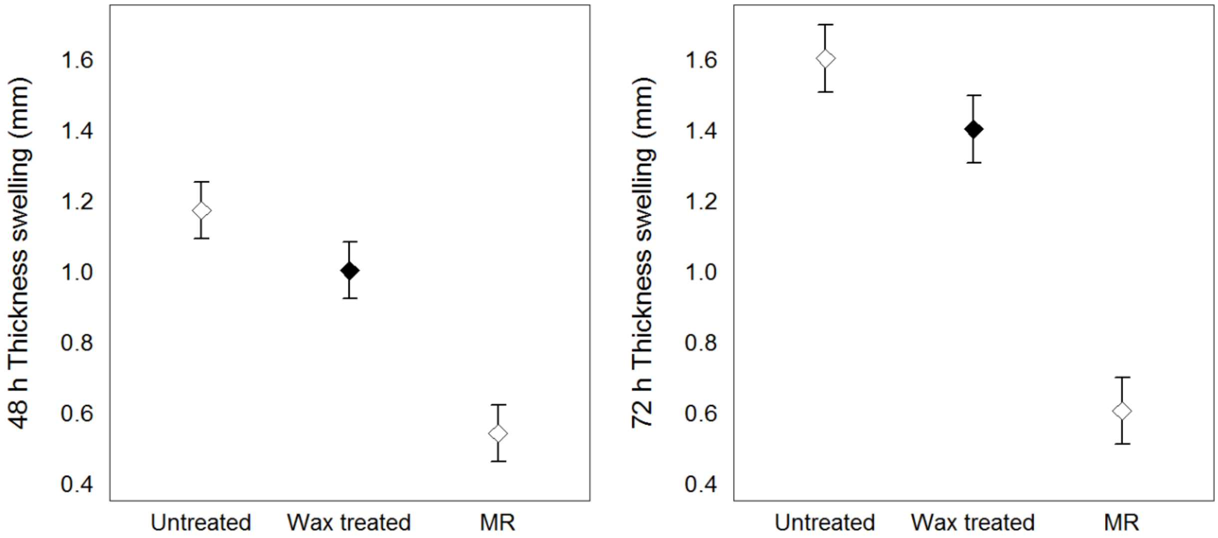


Figure 5.13. Average effect of wax treatments on the thickness swelling of OSB samples that were floated face down on water for 48 h (left) and 72 h (right), as well as a comparison between the water absorption of these samples and those of “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted for each water exposure period (2 h and 24h), each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples after 48 h and 72 h was 0.16 mm and 0.19 mm, respectively (error bars drawn). The LSD between untreated samples and MR samples after 2 h and 24 h was 0.17 mm and 0.2 mm, respectively (not drawn)

There were significant differences in the TS of untreated OSB samples and the different types of wax-treated samples for all time periods, as well as significant differences in the TS of the different wax-treated samples and MR samples for all time periods. There were also significant differences in TS of samples treated with different wax types for all time periods (Figures 5.13 – 5.16). After 2 h, the thickness of untreated samples had increased by 0.25 mm; significantly more than that of most of the wax-treated samples (Figure 5.14). There was, however, no significant ($p < 0.001$) difference between the TS of untreated samples, after 2 h, and that of samples treated with any of the following four wax types: (1) Sasolwax C (0.28); (2) soy wax

(0.24 mm); (3) Tekniwax 801 (0.21 mm); or (4) Merkur 300 (0.21 mm). Samples treated with a blend of beeswax and Vaseline swelled the least (0.09 mm); about 65% less than untreated samples and significantly ($p < 0.001$) less than those of most of the other wax-treated samples. Samples treated with a blend of beeswax and Vaseline, however, did not swell significantly ($p > 0.05$) more than those of six of the other wax treated samples. This group of six included all waxes that contained beeswax, except for samples treated with a blend of beeswax and Sasolwax C. The group of six also included both wax types that contained ethylene maleic anhydride. The TS of MR samples was significantly ($p < 0.001$) less than those of most of the different wax-treated samples. MR samples, however, did not swell significantly less than samples treated with a blend of beeswax and Vaseline or any of the samples treated with the waxes in the group of six mentioned above.

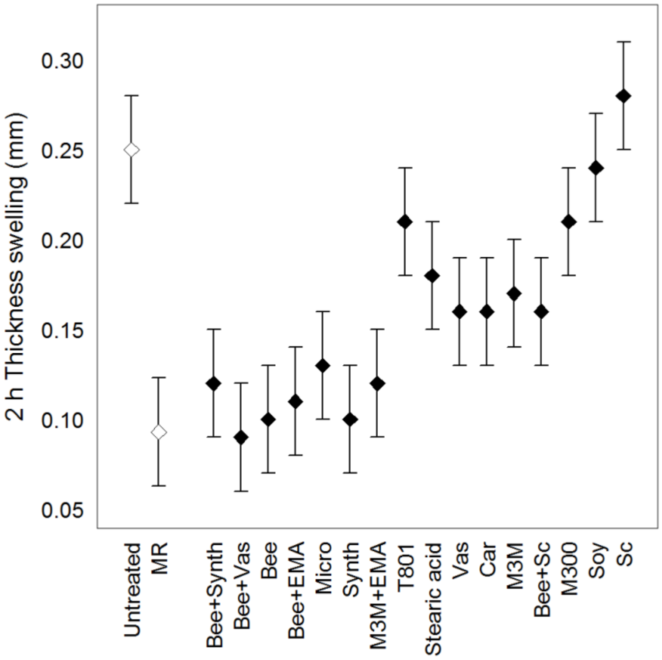


Figure 5.14. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 2 h, as well as a comparison between the thickness swelling of these samples and "moisture resistant" (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) for both statistical analyses is 0.06 mm (error bars drawn)

After 24 h, the thickness of untreated samples had increased by 0.77 mm in total (Figure 5.15). The TS of samples treated with the following seven wax types was significantly ($p < 0.001$) less than that of untreated samples: (1) a blend of Sasolwax M3M and ethylene maleic anhydride (0.60 mm); (2) synthetic beeswax (0.55 mm); (3) beeswax (0.52 mm); (4) microcrystalline wax (0.52 mm); (5) a blend of beeswax and ethylene maleic anhydride (0.49 mm); (6) a blend of beeswax and synthetic beeswax (0.46 mm); and (7) a blend of beeswax and Vaseline (0.45 mm). Samples treated with a blend of beeswax and Vaseline had the smallest thickness increase after 24 h; about 41% less than that of untreated samples and significantly less than those of nine of the other types of wax-treated samples. MR samples had significantly ($p < 0.001$) less TS than most of the different wax-treated samples after 24 h, except for samples treated with: (1) a blend of beeswax and synthetic beeswax; or (2) a blend of beeswax and Vaseline.

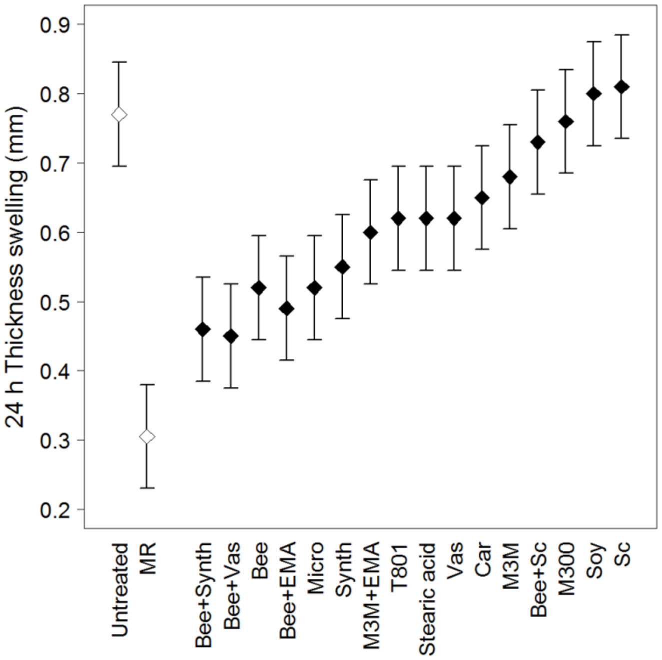


Figure 5.15. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 24 h, as well as a comparison between the thickness swelling of these samples and “moisture resistant” (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.15 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.16 mm (not drawn)

After 48 h, the thickness of untreated samples had increased by 1.17 mm in total; significantly ($p < 0.001$) more than those of seven of the different types of wax-treated samples (Figure 5.16). These seven wax types, once again, included all beeswax containing waxes, except for a blend of beeswax and Sasolwax C. Samples treated with a blend of beeswax and synthetic beeswax had the smallest thickness increase after 48 h; about 34% less than that of untreated samples and significantly ($p < 0.001$) less than those of nine of the other types of wax-treated samples. After 48 h, the TS of MR samples was significantly ($p < 0.001$) less than those of any of the samples treated with wax.

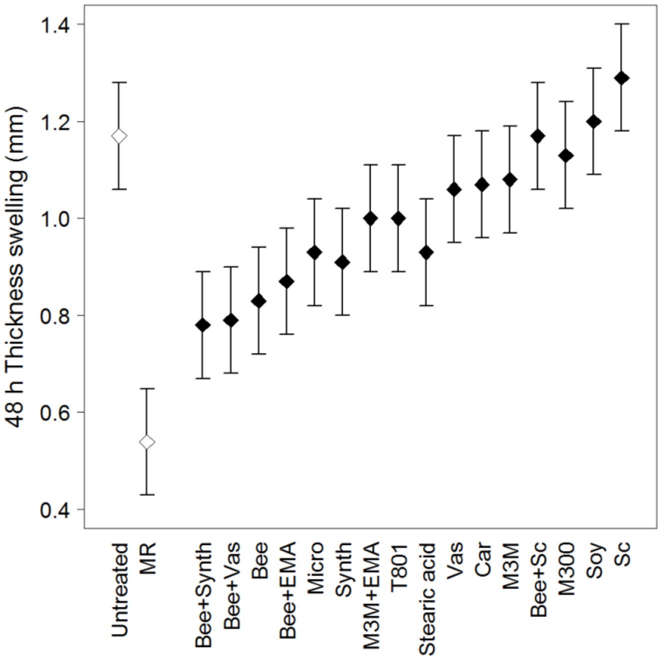


Figure 5.16. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 48 h, as well as a comparison between the thickness swelling of these samples and "moisture resistant" (MR) OSB samples. Two independent statstical analyses were conducted, each time comparing the wax treaments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.22 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.23 mm (not drawn)

After 72 h, the thickness of untreated samples had increased by 1.6 mm; significantly ($p < 0.001$) more than those of seven of the other types of wax-treated samples, including most of the wax types containing beeswax (Figure 5.17). Samples treated with a blend of beeswax and synthetic beeswax had the smallest thickness increase; about 30% less than that of untreated samples and significantly less than those of eight of the other types of wax-treated samples. After 72 h, the TS of MR samples was significantly ($p = 0.002$) less than those of any of the samples treated with wax.

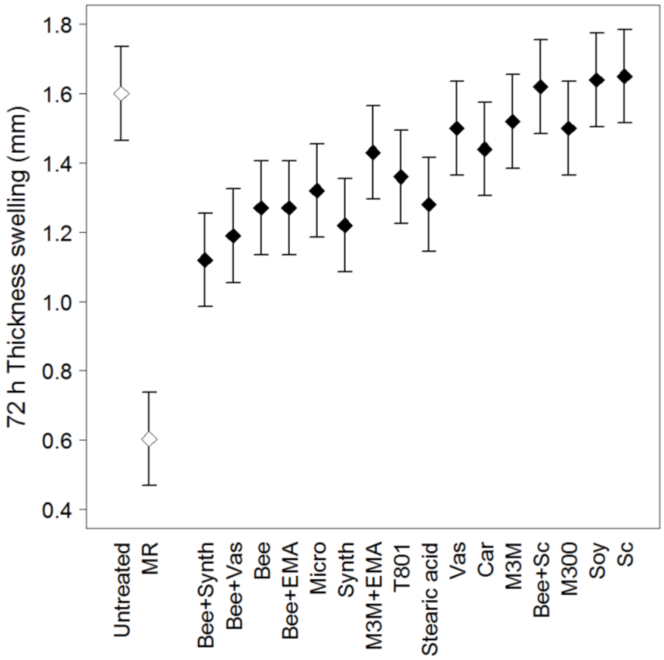


Figure 5.17. Effect of wax type on the thickness swelling of wax-treated OSB samples that were floated face down on water for 72 h, as well as a comparison between the thickness swelling of these samples and "moisture resistant" (MR) OSB samples. Two independent statistical analyses were conducted, each time comparing the wax treatments to a different control. The two controls (Untreated and MR) have clear data points. Non-overlap of error bars indicates that means are significantly different at a 5% level. The least significant difference (LSD) between untreated samples and wax-treated samples is 0.27 mm (error bars drawn), while the LSD between MR samples and wax-treated samples is 0.28 mm (not drawn)

After floating on water for 72 h and conditioning at 20 ± 1°C and 65 ± 5% r .h. for a minimum of two weeks and a maximum of four, the average moisture content of all OSB samples (excluding MR samples) was 11.9%. The standard deviation in moisture content was 0.3%. There were significant ($p = 0.003$) differences between the moisture contents of samples treated with different wax types, as well as between wax-treated and untreated samples. Untreated samples had a conditioned moisture content of 11.9%. Samples treated with Sasolwax C had the highest conditioned moisture content (12.58%), while samples treated with a blend of beeswax and synthetic beeswax had the lowest (11.45%).

Both the wax-treated and untreated OSB samples that were floated on water for 72 h continued to swell when they were removed and placed in a conditioning room for 2 – 4 weeks (Figure 5.18). This continued swelling will henceforth be termed as “time-delayed thickness swelling”. There were significant ($p = 0.01$) differences in the time-delayed TS of untreated samples and wax-treated samples. On average, untreated OSB samples swelled by 0.125 mm, while wax-treated samples swelled by 0.25 mm. Thus, the time-delayed TS of wax-treated samples was approximately 103% more than that of untreated samples. There were also significant ($p = 0.023$) differences between the time-delayed TS of samples treated with different types of waxes. Samples treated with carnauba wax had the lowest amount of time-delayed TS (0.146 mm), approximately 16.8% more than untreated samples. Samples treated with microcrystalline wax had the highest amount of time-delayed TS (0.4 mm), approximately 218.4% more than that of untreated samples. The time-delayed TS of samples treated with petroleum jellies, Vaseline and Merkur 300, was 164% and 140% more than that of untreated samples, respectively. Samples treated with a blend of beeswax and Vaseline swelled 145.6% more than untreated samples, while samples treated with a blend of beeswax and synthetic beeswax swelled 132.8% more. The average time-delayed TS of MR samples (0.27 mm) was comparable to that of the different wax-treated samples.

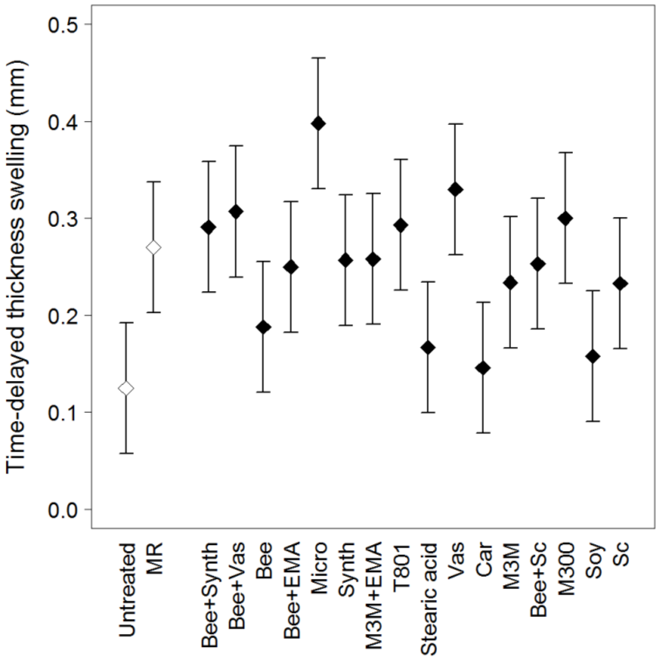


Figure 5.18. The time-delayed thickness swelling of OSB samples treated with different wax types. Measurements were taken after the samples were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two weeks and a maximum of four weeks. Non-overlap of error bars indicates that means are significantly different at a 5% level. All samples from each individual experimental replication were measured at the same time, irrelevant of their conditioning period

There was no significant difference ($p = 0.58$) between the total thickness swelling of untreated and wax-treated OSB samples after they were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks. There were, however, significant ($p = 0.005$) differences between the TS of samples treated with different wax types, as well as between those samples and untreated samples (Figure 5.19). Untreated samples had a total thickness swelling of 1.72 mm. Samples treated with two of the different types of wax-treatments swelled significantly less than this ($p = 0.005$); the samples treated with a blend of beeswax and synthetic beeswax had a total thickness swelling of only 1.41 mm, while samples treated with stearic acid had a total thickness swelling of 1.45 mm. The average total thickness swelling of MR samples (0.87 mm) was significantly less than those of untreated and wax-treated OSB samples.

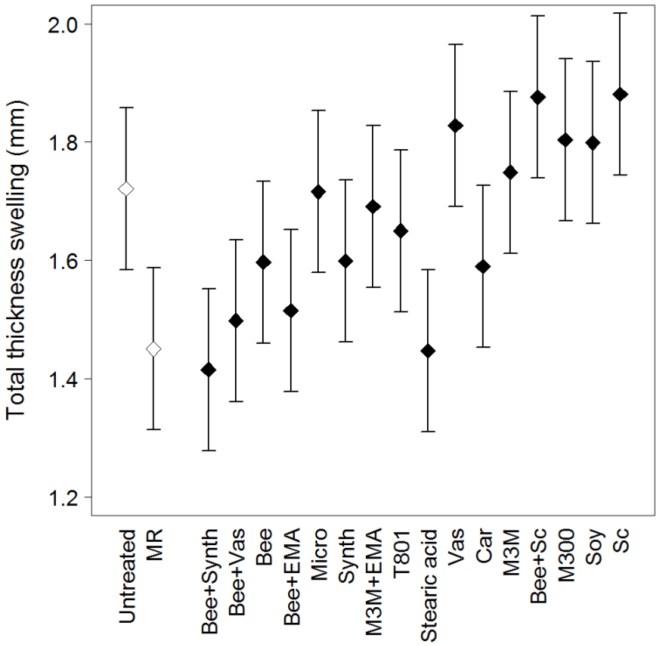


Figure 5.19. Total thickness swelling of untreated and wax-treated OSB samples after they were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks. Non-overlap of error bars indicates that means are significantly different at a 5% level. All samples from each individual experimental replication were measured at the same time, irrelevant of their conditioning period

5.3.5 Effects of initial moisture content on water repellency, water absorption and thickness swelling

There was a weak negative correlation ($p = 0.019$; $R^2 = 0.34$) between the initial moisture content of samples (untreated and wax treated) and the time it took for 5 μL water droplets to spread over wax-treated OSB surfaces and form contact angles of less than 90° (t<90°) (Figure 5.20). Samples treated with wax types with long t<90° times, therefore, generally adsorbed less water vapour while stored in the conditioning room than samples treated with wax types with short t<90° times.

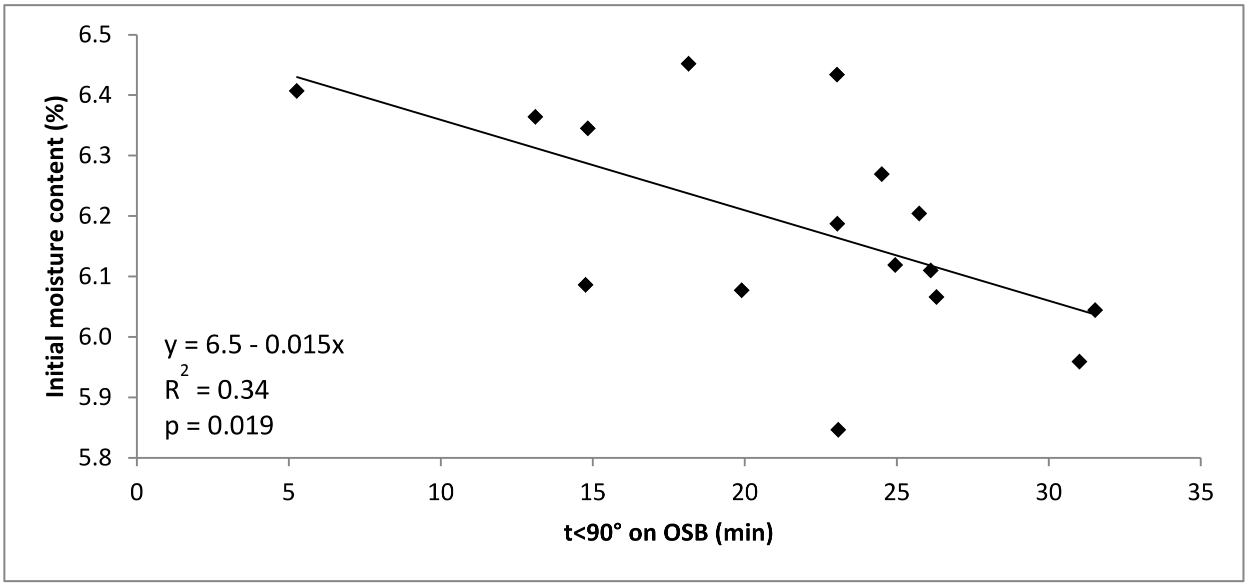


Figure 5.20. Relationship between (1) the initial moisture content of wax-treated samples that were oven dried, wax treated and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the time it took for 5 µL water droplets to spread over wax-treated OSB surfaces and form contact angles of less than 90°

There were weak positive correlations between the initial moisture content of OSB samples (untreated and wax treated) and the WA of the same samples, after they were floated face down on water for 2 h ($p = 0.01$; $R^2 = 0.34$) and 24 h ($p = 0.03$; $R^2 = 0.27$) (Figure 5.21). There were no significant ($p > 0.05$) relationships between the initial moisture content of wax-treated samples and WA at 48 h and 72 h. In general, samples that had low initial moisture contents, when exposed to water for the first time, absorbed less water during the first 24 h than samples that had high initial moisture contents.

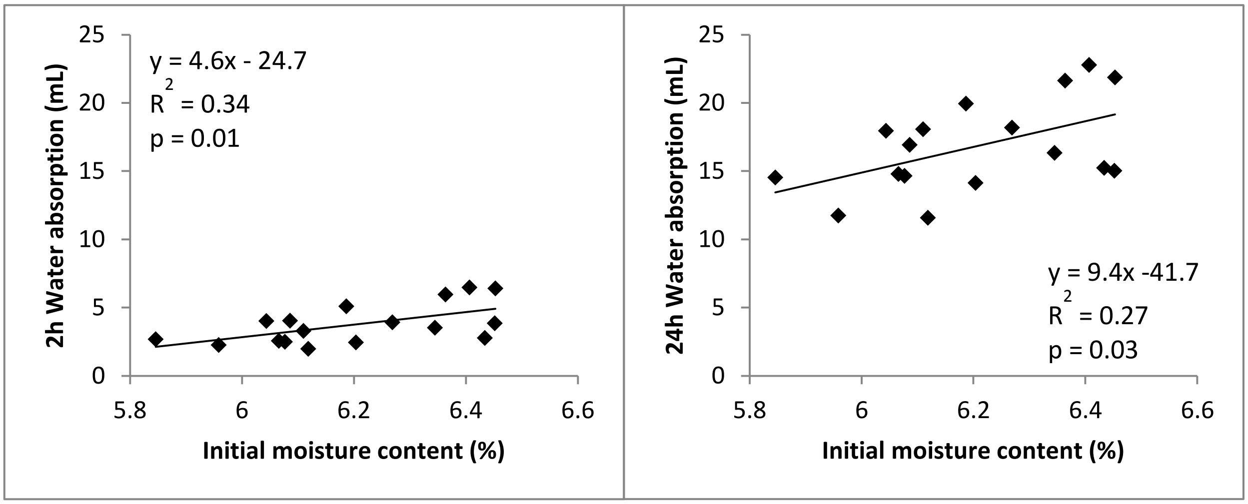


Figure 5.21. Relationships between (1) the initial moisture content of wax-treated samples that were oven dried, wax treated and conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the water absorption of the samples after they were floated face down on water for 2 h (left) and 24 h (right)

There were moderate to weak correlations between the initial moisture content of the OSB samples and the TS of the same samples, after they were floated face down on water for 2 h ($p = 0.002$; $R^2 = 0.47$), 24 h ($p = 0.009$; $R^2 = 0.38$), 48 h ($p = 0.027$; $R^2 = 0.29$), and 72 h ($p = 0.031$; $R^2 = 0.27$) (Figure 5.22). The positive correlation was affected by the length of exposure time, becoming weaker after longer floatation periods. Similar relationships to those between water absorption and initial moisture content were present between thickness swelling and initial moisture content. In general, samples that had low initial moisture content, when exposed to water for the first time, swelled less over 72 h than samples that had high initial moisture contents.

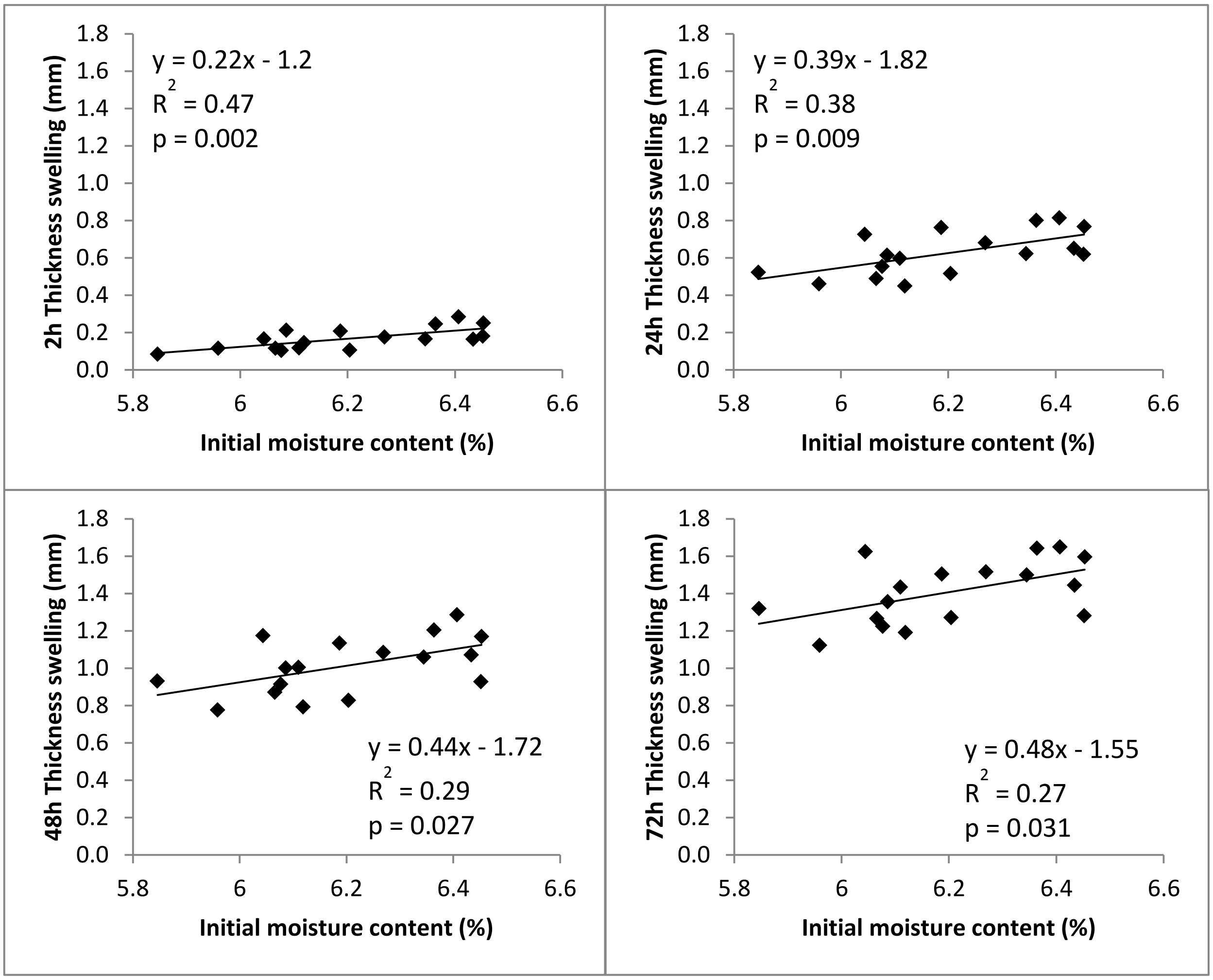


Figure 5.22. Relationships between (1) the initial moisture content of wax-treated samples that were oven dried, wax-treated and conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of seven days, and (2) the thickness swelling of the samples after they were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)

5.3.6 Effects of water repellency of wax-treated surfaces on water absorption and thickness swelling

There were moderate to weak negative correlations between the times it took for 5µL water droplets to spread and form contact angles of less than 90° on wax-treated OSB surfaces (t<90°), and the amount of water absorbed by wax-treated OSB samples that were floated face down on water for 2 h ($p < 0.001$; $R^2 = 0.55$), 24 h ($p = 0.005$; $R^2 = 0.43$), 48 h ($p = 0.008$; $R^2 = 0.38$), and 72 h ($p = 0.024$; $R^2 = 0.3$) (Figure 5.23).

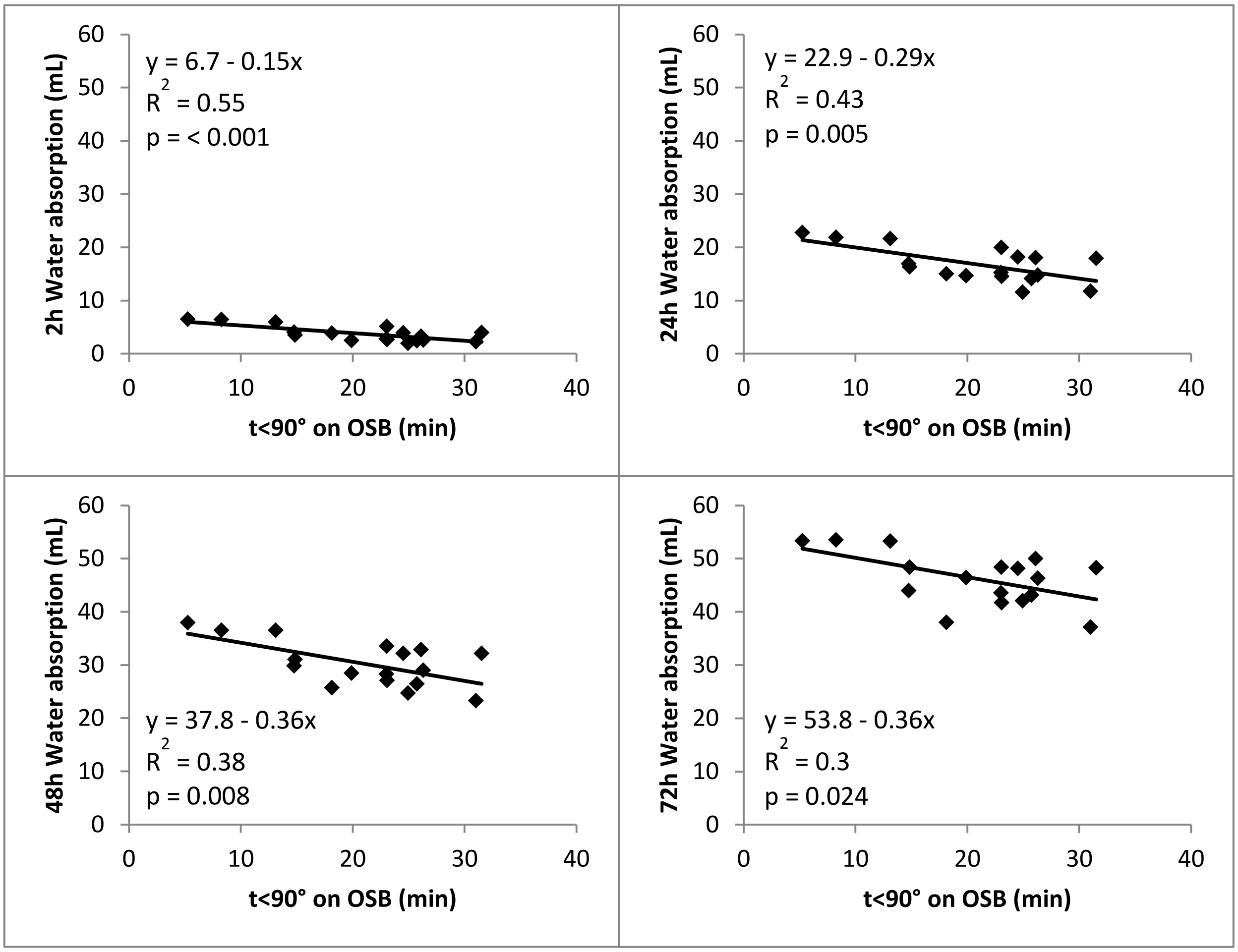


Figure 5.23. Relationships between (1) the times it took for 5 µL water droplets to spread over wax-treated surfaces and form a contact angles of less than 90° (t<90°), and (2) the water absorption of wax-treated OSB samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)

There were also moderate to weak negative correlations between the times it took for 5µL water droplets to spread and form contact angles of less than 90° on wax-treated OSB surfaces (t<90°), and the TS of wax-treated OSB samples that were floated face down on water for 2 h ($p < 0.001$; $R^2 = 0.58$), 24 h ($p = 0.012$; $R^2 = 0.35$), 48 h ($p = 0.016$; $R^2 = 0.33$), and 72 h ($p =0.043$; $R^2 = 0.25$) (Figure 5.24).

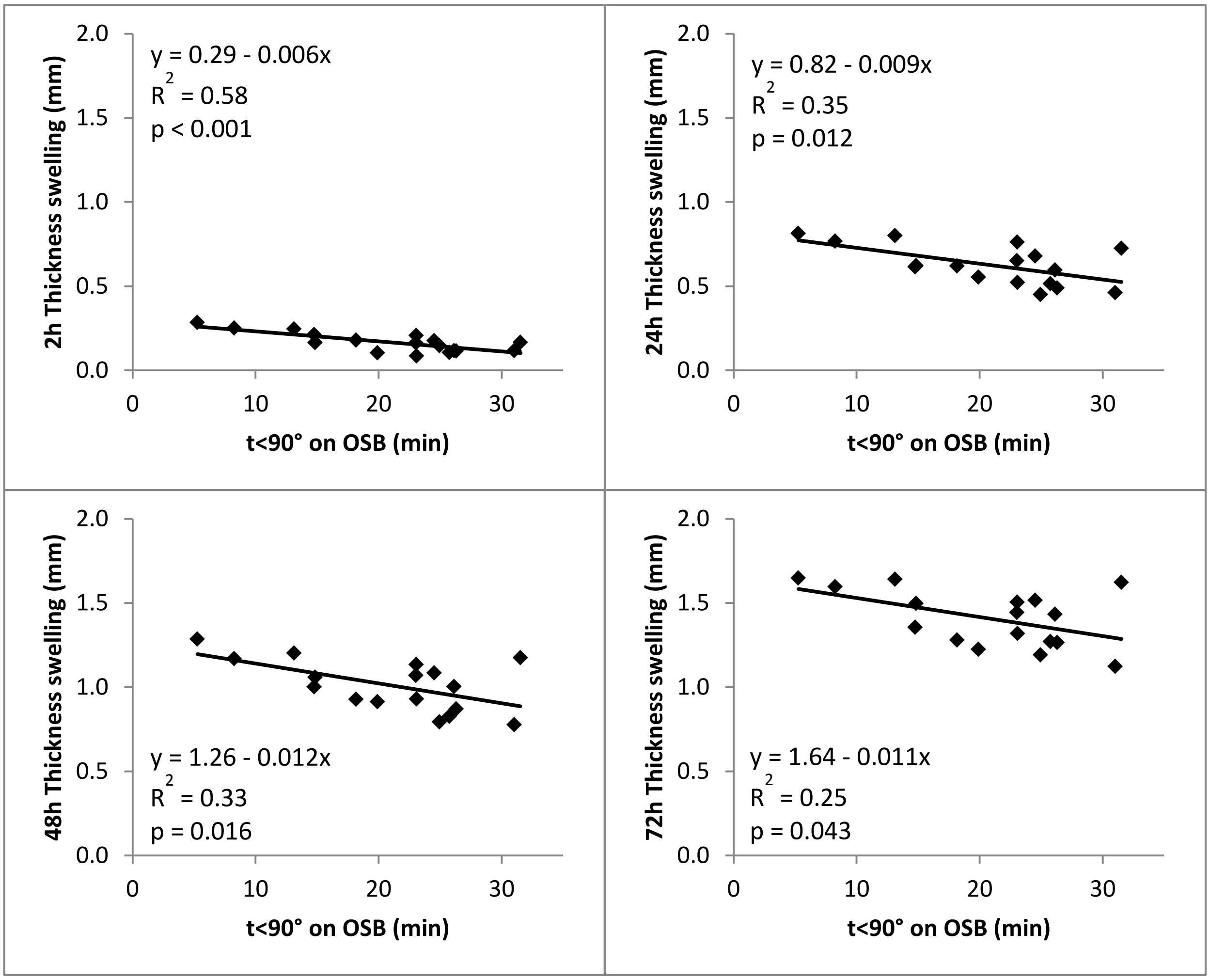


Figure 5.24. Relationships between (1) the times it took for 5µL water droplets to spread over wax-treated surfaces and form a contact angles of less than 90° (t<90°) and (2) the thickness swelling of wax-treated OSB samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)

5.3.7 Effects of melting point temperatures on water absorption and thickness swelling

There were moderate and weak negative correlation between the melting point temperatures of waxes applied to samples and WA after 2 h ($p = 0.001$; $R^2 = 0.55$) and 24 h ($p = 0.02$; $R^2 = 0.32$), respectively (Figure 5.25). However, there were no statistically significant relationships between the melting point temperatures of the different waxes and WA of wax-treated samples after 48h ($p = 0.055$) and 72 h ($p = 0.2$).

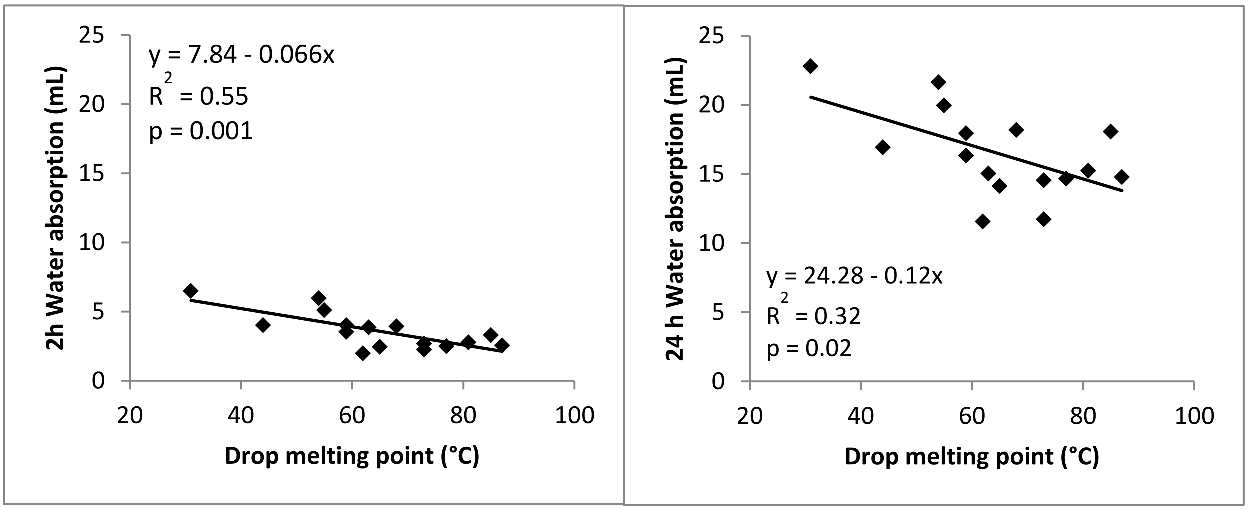


Figure 5.25. Relationships between the melting point temperatures of the waxes sprayed onto OSB surfaces and the water absorption of wax-treated samples that were floated face down on water for 2 h (left) and 24 h (right)

There were also negative correlations between the melting point temperatures and TS of wax-treated samples that were floated face down on water for 2 h ($p < 0.001$; $R^2 = 0.67$), 24 h ($p = 0.014$; $R^2 = 0.36$), 48 h ($p = 0.026$; $R^2 = 0.31$), and 72 h ($p = 0.049$; $R^2 = 0.25$) (Figure 5.26). The length of exposure to water had a strong effect on the correlations; with correlations being strong at 2 h and weaker at 24 h, 48 h and 72 h.

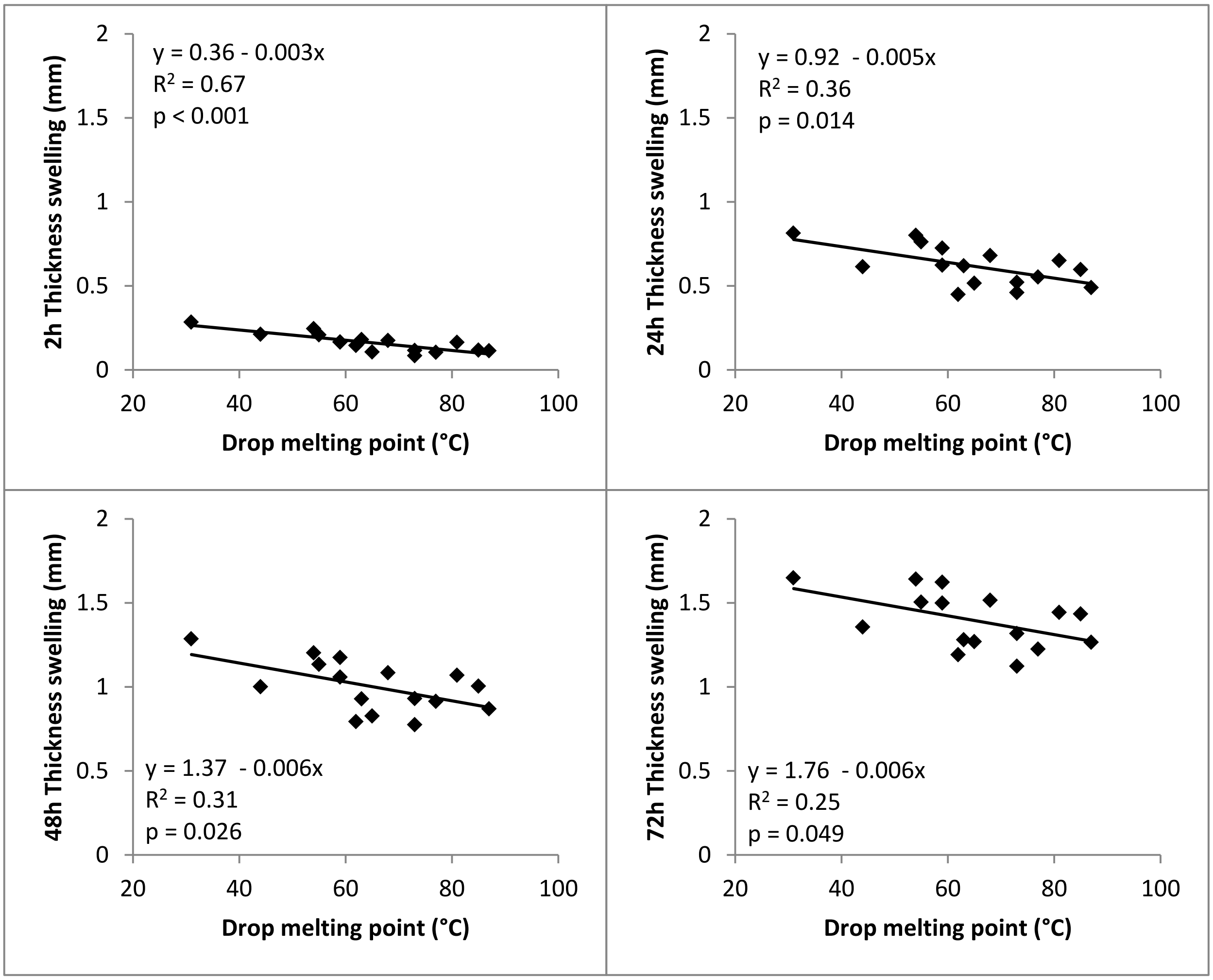


Figure 5.26. Relationships between the melting point temperatures of the waxes sprayed onto the surface of OSB and the thickness swelling of wax-treated samples that were floated face down on water for 2 h (top left), 24 h (top right), 48 h (bottom left), and 72 h (bottom right)

Finally, there was also a weak correlation ($p = 0.04$; $R^2 = 0.26$) between the melting point temperatures of different wax types and the time-delayed TS of wax-treated samples that were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks (Figure 5.27).

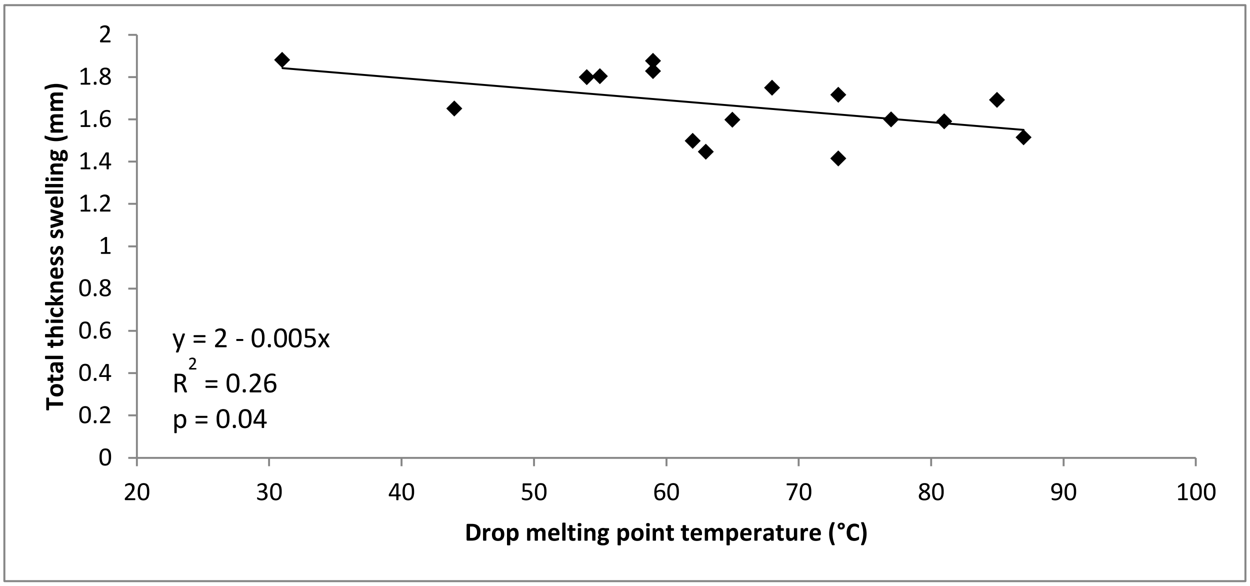


Figure 5.27. Relationship between the melting point temperatures of different wax types and the total thickness swelling of wax-treated OSB samples that were floated face down on water for 72 h and then conditioned at 20 ± 1°C and 65 ± 5% r.h. for a minimum of two and a maximum of four weeks

5.4 Discussion

In the introduction to this chapter I hypothesized that polar waxes with strong hydrophobic properties would be more effective at dimensionally stabilizing OSB than nonpolar waxes or polar waxes with low hydrophobicity. I also restated the hypothesis developed in Chapter 4, which argued that low melting (LM) point waxes would be more effective at stabilizing the dimensions of OSB than high melting (HM) waxes.

Results in this chapter confirm those described in Chapter 4 and allow me to reject the hypothesis, that LM point waxes are more effective than HM point waxes at dimensionally stabilizing OSB. Contrary to expectations, there was a negative correlation between melting point temperature of waxes and the TS of wax-treated samples for all water exposure periods, as well as for the time-delayed TS after samples were removed from the water tank and conditioned in a climate controlled room. This negative correlation was strongest for short periods of exposure to liquid water and became weaker as the length of exposure increased. There were also moderate to weak negative correlations between the melting point temperatures of waxes and the WA of wax-treated samples during the first 24 h of liquid water exposure.

There were no statistically significant relationships between the acid value numbers of the wax types and the WA or TS of wax-treated samples. Since the polarity of wax increases as its acid value number increases, polarity did not appear to influence the ability of wax to dimensionally stabilize OSB. Upon closer examination, however, it was noted that the best performing waxes, during both short and long term exposure of OSB to water, were those that contained both beeswax (polar) and a nonpolar wax. Of these beeswax blends, the best ones were blends of beeswax and paraffin waxes (Vaseline or synthetic beeswax), although beeswax also performed well on its own. Samples treated with only beeswax, or only Vaseline, consistently swelled more than samples treated with a blend of the two waxes. Similarly, samples treated with only beeswax, or only synthetic beeswax, consistently swelled more than samples treated with a blend of the two waxes. Waxes with high polarity and strong affinity to wood, but low hydrophobicity, such as soy wax and stearic acid were less effective particularly in the short term. Two strongly hydrophobic, nonpolar paraffin waxes, microcrystalline wax and synthetic beeswax, provided excellent protection against TS. Fischer-Tropsch waxes, on the other hand, were some of the least effective waxes. For example, a Fischer-Tropsch and beeswax blend (beeswax + Sasolwax C) did not perform well even though, as noted above, the other beeswax blends were some of the most effective water repellents for OSB. Beeswax has polar functional groups that may have allowed it to bond well to wood strands, whereas paraffin wax, with its saturated hydrocarbon structure, may have provided additional hydrophobicity. This agrees with the suggestions of Borgin (1965) and the findings of Borgin and Corbertt (1970; 1974), that water repellents for solid wood need to contain both hydrophobic and hydrophilic components. Hilditch (1965) and Borgin (1965) also reported that paraffin wax imparted excellent dimensional stability to solid wood. These observations partially support the hypothesis that polar waxes with strong hydrophobic properties will be more effective at dimensionally stabilizing OSB than nonpolar waxes, or polar waxes with low hydrophobicity.

In this chapter I used a water float test, instead of the conventional soak test, to test the effectiveness of the molten wax treatments at dimensionally stabilizing OSB. Water float tests are commonly used to determine the liquid water permeability of coatings on solid wood (EN 2005). In Chapter 4, I used a water immersion test and based on a previous study by Evans et al. (2013). I expected the TS of samples floated on water in this chapter to be lower than those that were immersed in the previous chapter. The opposite was the case. My results showed that TS measured in the water float test was greater than that measured in Chapter 4. This may be because more wax was applied to the samples in Chapter 4, which created more effective barriers against moisture ingress. The edges of samples in Chapter 4 were also sealed using epoxy resin, which probably restricted TS even further. In this chapter, samples were edge sealed with less restrictive, more elastic, silicone sealer. The silicone may have restricted swelling less than the epoxy sealant used in Chapter 4.

The majority of the WA and TS measured in this chapter most likely occurred in the exposed face layers of the OSB samples, since the samples were floated on water and because the rate and extent of TS of OSB is known to be highest in the surface layers (Winistorfer and Xu 1996; Wang and Winistorfer 2003; Gu et al. 2005; Tackie et al. 2008). Wang and Winistorfer (2003) reported that the two surface layers of OSB may account for 74.36% of the overall swelling after 2 h and for 57.3% after 24 h. Any wax treatment that can effectively reduce TS of samples floated on water should, therefore, also be effective at reducing the swelling of the entire board.

In a report by Taylor and Wang (2007), it was shown that the edge swelling of the same brand of MR OSB that was used as a control in this chapter was approximately half that of regular OSB panels after 24 h and 72 h of immersion in water. In a later paper it was reported that the TS of the same brand of MR boards was 2.35% after 24 h, while the swelling of regular OSB panels was 8.3% (Taylor et al. 2008). After 72 h, the TS of MR boards was 12.14%, while the TS of regular OSB was 24.5%. In accord with the results of Taylor et al. (2008), my results also indicate that MR samples swelled roughly half as much as regular OSB after 24 h. In contrast, however, my results showed more TS for the MR samples after 72 h than the results of Taylor et al. (2008).

The time-delayed thickness swelling and final moisture content results suggested that wax-treated samples dried at a slower rate than untreated samples. In accord with this suggestion, Feist (1982) coated waferboard surfaces with various film-forming finishes and exposed them to natural weathering for 21 – 43 months. He observed that fungal growth occurred in many of the samples because the coatings were unable to prevent water ingress. Furthermore, the coatings appeared to trap the absorbed water within the panels. My results also suggest that wax treatments may have trapped water inside the board and slowed the rate of drying, as mentioned above.

The majority of studies that have examined the water repellent effects of wax on solid wood or OSB almost exclusively looked at paraffin wax. Furthermore, no previous studies have examined the use molten wax treatments for dimensionally stabilizing OSB. Therefore, it is difficult to compare my results with those of other researchers. However, my results are partially supported by Borgin and Corbertt's (1970) work. They used various waxes as water repellents for radiata pine wood. Their water repellents contained 2.5%, 10%, 25% or 50% of wax dissolved in mineral turpentine. The waxes included some of the waxes I tested, such as paraffin waxes, petroleum jelly, beeswax, and carnauba wax. They did, however not blend any of their waxes as I did. They found that all of the waxes were effective at preventing water uptake and swelling, but the best performing waxes were paraffin waxes. A number of waxes which included the prefix "Sasolwaks" in their name were less effective than the other wax types. It is assumed that these waxes were Fischer-Tropsch waxes, similar to the Fischer-Tropsch waxes I sourced from Sasolwax, South Africa. Borgin and Corbertt also showed that beeswax's ability to prevent swelling improved over time and it was consistently better than that of carnauba wax and petroleum jelly at dimensionally stabilizing wood. From their results they concluded paraffin waxes could perform even better if they contained hydrophilic groups. Many of their results agree with my findings.

The study that is the most relevant to mine is one by Semple et al. (2009). They sprayed unheated water-based wax emulsions or linseed oil-wax solutions onto the surface of hot OSB. The waxes in their study included soy wax, beeswax, carnauba wax, and paraffin wax. They found that linseed oil-wax solutions containing beeswax rarely performed better than those containing paraffin or soy wax, and almost never performed better than those containing carnauba wax. This discrepancy between their results and mine may be explained by the fact that their waxes were sprayed as oil based solutions and not as neat molten wax, as was the case here.

The very strong positive relationship between the WA and TS of wax-treated OSB was strongly affected by the length of time samples were exposed to water. As mentioned, the positive correlation was stronger after longer exposure periods. This supports the concept that liquid water first enters the inter-strand voids within OSB, where it does not directly lead to TS (Wu and Piao 1999; Semple et al. 2009). This suggestion also accords with the research of van Houts et al. (2004) who used nuclear magnetic resonance imaging to show that WA by OSB occurs via inter-strand voids. The correlation between TS and WA strengthens over time, because as the inter-strand voids become saturated with water, water will only be able to diffuse into wood cell walls where it causes swelling. Wax treatments that are effective at blocking inter-strand voids within OSB will therefore be able to limit initial water uptake and slow the rate of TS, but not the ultimate amount of TS.

Although the linear relationship between WA and TS occurred for all exposure periods, the varied slopes and intercepts of the regression lines at different time periods suggest that absorption of similar amounts of water caused more TS during initial exposure periods than it did during later periods. Thus the relationship between WA and TS might be curvilinear and not linear. Greater swelling during initial periods is probably caused by wood swelling and recovering strains developed when flakes were compressed and densified during hot-pressing (Neusser et al. 1965; Halligan 1970; Hsu et al. 1988; Kelly 1977; Wu and Suchsland 1997).

The hydrophobicity of wax-treated surfaces and the differences in the initial moisture content were correlated with the WA and TS of the wax-treated samples that were floated on water. However, contrary to expectations, samples with low initial moisture contents absorbed less water and swelled less during the first 24 h than samples with high initial moisture content. A similar relationship was observed between initial moisture content and TS after 72 h. The correlation between the water repellency of wax-treated OSB surfaces and the WA and TS of wax-treated OSB samples also displayed a similar relationship. Thus, the same wax types which slowed the rate of water vapour adsorption during the conditioning period also slowed the rate of liquid WA during the water float test. This observation suggests, that strongly hydrophobic waxes are more effective water-repellent treatments for OSB.

An unexpected finding was that the TS of samples treated with stearic acid was quite high relative to WA. This may have been because stearic acid tended to agglomerate around one area when it was applied to OSB, thus reducing WA and TS in certain areas only. These areas, where the wax agglomerated, swelled noticeably less than the surrounding “untreated” areas and caused variable TS across the sample.

Lastly, it seems that the hardness and flexibility of wax is not important for wax treatments that do not form surface coatings. There was, for example, no evident trend between the WA and TS of OSB samples treated with soft waxes, such as Vaseline or Merkur 300, and those treated with hard waxes, such as carnauba wax, Sasolwax M3M or stearic acid.

5.5 Conclusion

Wax treatments were able to reduce the rate of WA and TS of OSB for short periods of exposure to water, but not the extent of TS after long periods of exposure. I therefore conclude that the wax treatments are useful water-repellent treatments for OSB exposed to water for short periods of time, but not for boards immersed in water for a long time.

HM waxes performed better than LM. Strongly hydrophobic, nonpolar waxes, such as paraffin wax, were also effective treatments. However, my results suggest that the addition of polar waxes may improve their performance. I therefore conclude that molten wax treatments that contain both polar and nonpolar waxes will be more effective at dimensionally stabilizing OSB than waxes that contain only hydrophobic nonpolar waxes or polar waxes on their own.

Chapter 6. General discussion, suggestions for further research and conclusions

6.1 General discussion

The wax treatments developed and tested in this thesis significantly reduced the WA and TS of OSB, as hypothesized in Chapter 1. Results in Chapter 4 supported my overall hypothesis, but some of the high melting (HM) point waxes formed coatings on the surface of the OSB, rather than acting as a penetrating water repellent as desired. Wax coatings can be easily removed from surfaces by abrasion and are therefore undesirable from a practical standpoint. Subsequent research in Chapter 5 used an application method that minimized the occurrence of such surface coatings. The results in Chapter 5 showed that such wax treatments significantly reduced the WA and TS of OSB. The treatments were very effective when treated OSB samples were first exposed to liquid water, but their effectiveness decreased with further exposure to water. Thus the molten wax treatments can be classified as Type-I treatments, according to the definitions of dimensional stabilizing treatments for solid wood proposed by Rowell and Banks (1985). Results from Chapter 5 also showed that HM waxes were more effective water repellents for OSB than LM waxes, contrary to expectations. According to contact angle measurements in Chapter 3, HM waxes were more hydrophobic than LM waxes, which may partly explain why they performed better than LM waxes. It appears that in the absence of a surface coating, the hydrophobicity of wax is more important than its ability to flow into and penetrate OSB surfaces; contrary to what was speculated in Chapter 4. This suggestion is also supported by studies which observed that wax emulsions with long n-alkanes chain are more effective at reducing the WA and TS of MDF and particleboard than those made with short n-alkanes chain (Roffael and May 1983; Schriever and Roffael 1984; Hague 1995; Roffael et al. 2005).

Results from Chapter 3 and 5 suggested that wax treatments that contained both polar and nonpolar waxes were more effective at dimensionally stabilizing OSB than treatments that contained only polar wax or only nonpolar wax. Molten blends of beeswax and paraffin wax performed very well and improved the stability of regular OSB samples to a level where their short term resistance to water matched that of highly moisture resistant OSB, which commands a premium in the market place. For example, after 24 h of exposure to water there was no significant difference between the TS of OSB treated with a blend of beeswax and synthetic beeswax (a paraffin wax) and that of the “moisture resistant” samples. However, after 24 h the rate of swelling of “moisture resistant” samples slowed, whereas the regular OSB samples treated with wax continued to swell. These results suggest that it may be possible for OSB manufacturers to improve the short-term thickness stability (but not the long-term stability) of their product by directly spraying wax blends onto the surface of their hot, freshly-pressed, OSB. Molten wax treatments for OSB may be a cost effective way of improving the dimensional stability of OSB, considering that premium “moisture resistant” OSB panels (1.2 m x 2.44 m) can cost up to three times more than regular OSB (Evans, P.D., personal communication, March 5, 2014).

My results also suggest that the water repellency of wax-treated OSB surfaces is correlated with the WA and TS of wax-treated samples . In Chapter 3, I found that the t<90° times of water droplets on wax-treated OSB surfaces can be used to indicate the water repellency of the surface. Wax-treated OSB surfaces with long t<90° times appeared to be more hydrophobic than those with short t<90° times. My results in Chapter 5 suggest that the rate of water vapour adsorption of wax-treated OSB samples decreased as the hydrophobicity of the wax-treated surface increased. All OSB samples were oven dried directly before wax application, and were immediately placed in a climate controlled room for a minimum of seven days thereafter. Some of the experimental blocks remained in the conditioning room for as long as 28 days before they were exposed to liquid water. According to the average initial moisture contents that were measured at the end of these conditioning periods (before first exposure liquid water), wax-treated samples which were treated with wax types that had long t<90° times absorbed significantly less water vapour, while being stored in the climate controlled room, than those treated with waxes that had short t<90° times. This result was surprising, since the bottom surfaces of the OSB samples were unsealed and the edges were only sealed after five days of conditioning. It is known that the rate of water vapour uptake by solid wood is not affected by the hydrophobic properties of a water repellent, but rather by its ability to block voids which provide pathways for water vapour (Gibson 1965). It appears, therefore, that the ability of wax to block ingress of water vapour in OSB increases as its hydrophobicity increases. This suggests that strongly hydrophobic waxes are better at blocking sorption sites in OSB than less hydrophobic waxes. Further research would be necessary to confirm this suggestion.

The technology necessary to industrially to spray molten wax onto OSB already exists. In fact, the very first commercial waferboard plant sprayed its wafers with molten wax before hot pressing (Clarck 1980). Similar spray lines could be installed directly after an OSB press, so that the surfaces of the freshly pressed boards could be sprayed with wax while they are still hot. This setup should work particularly well in factories that use a continuous press, but it may also be suitable for those that use a batch press. Wax treatment can be applied as a separate process, to a fraction of the total production, without interfering with the production of commodity products.

Spraying molten wax onto OSB directly after pressing will also have benefits over other technologies currently available to dimensionally stabilize OSB, such as thermal and chemical modification. For example, no pre-treatment of the wood strands is necessary, thus the boards are more likely to retain their mechanical properties after being sprayed with wax. Wax treatments might be further improved by hot stacking the freshly-pressed boards after wax application. Maloney (1993) reported that wax sizing migrates when particleboards are hot stacked, thus improving the water repellency of the boards. Paraffin waxes, such as slack wax, are non-toxic and bio-degradable by-products of the petroleum industry (Wolfmeier et al. 2000). Unfortunately the use of renewable waxes, such as beeswax (which performed very well here), is often not economically viable, since these waxes are more expensive than paraffin or synthetic waxes because there are limited supplies of them (Wolfmeier et al. 2000).

One possible disadvantage of molten wax treatments for OSB is the increased risk of fires in production plants. According to Amthor (1972), wax sizing does not increase the inflammability of particleboard, but further research is needed to confirm whether this is the case for OSB treated with molten wax. Another possible limitation is that the treated surfaces may not be able to accept paints, varnishes, or other surface coatings. Structural OSB, however, is not usually used in applications where such surface coatings are required.

Spraying wax onto the surface of OSB might be a cost-effective way to produce dimensionally stable OSB products, which could compete with the expensive premium-grade OSB products currently available in the marketplace. Premium-grade OSB is bonded with pMDI resin, which costs approximately $ 567 (CAD) / ton, while wax is much cheaper, approximately $430 (CAD) / ton.

6.2 General conclusions

The pronounced thickness swelling that OSB undergoes when it is exposed to moisture is a major shortcoming of this type of structural panel. Many available technologies, such as thermal and chemical treatments, are able to reduce the thickness swelling of OSB, however, few of them have proven to be commercially viable, except for speciality products. Most of the available dimension-stabilizing technologies for OSB have negative effects on board properties, such as loss of internal bond strength and a decrease in modulus of rupture. Spraying molten wax onto the surface of OSB offers a new approach to improve the dimensional stability of OSB, with many advantages and few disadvantages over those that have been used in the past.

Molten wax can, under the right conditions, be sprayed onto the surface of hot OSB without forming a thick surface coating. When wax was applied in this manner, it increased the water repellency of OSB and effectively slowed the rate of water absorption and thickness swelling of samples exposed to water for short periods of time. I conclude that molten wax treatments can be an effective way of protecting OSB from the adverse effects of short-term water exposure.

The hydrophobicity of wax increases as its melting point temperature increases. There was a negative correlation between the melting point temperatures of waxes and the TS of wax-treated samples that were exposed to water. Waxes with long, unbranched carbon chains therefore provided good protection to OSB during short periods of exposure to water. The addition of a more polar wax appeared to increase the effectiveness of such molten wax treatments. I conclude that the best performing wax treatments were those that were strongly hydrophobic and contained both polar and nonpolar waxes components. It may therefore be possible to improve the performance of waxes, which are currently used by industry to dimensionally stabilize OSB, by blending them with polar waxes or additives that increase their polarity.

6.3 Suggestions for further research

Additional research is required to determine how the water-repellent barriers formed by wax treatments prevent moisture ingress and egress. If they prevent moisture egress then the practical implications would be undesirable, as high moisture contents in OSB may favour fungal decay. Wax is known to restrict the rate of diffusion of water in wood strands (Neimsuwan et al. 2008). According to Ye et al. (2006), however, moisture content is not a reliable indicator of mold susceptibility of OSB. Additional research is therefore required to determine whether wax treatments of OSB might increase the risk of fungal decay.

Additional research is also required to determine if the performance of the best wax blends can be improved by further optimizing spraying parameters and the quantities of wax applied to OSB. It is possible that wax blends may be more effective if they are sprayed at higher temperatures or if the OSB is hotter. Optimization of atomization parameters (droplet size and velocity) during the spraying of wax onto OSB may also influence the performance of the treatments and is an area worthy of further investigation. Further research is also necessary to determine the minimum application rate that is required for wax-treatment to be effective at reducing WA and TS.

Research is needed to better understand why beeswax blends performed better than other molten wax-treatments. It was not possible to explain their superior performance in terms of melting point temperature and polarity. Nor was it possible to recommend an ideal wax in terms of these two properties. Testing the effects of wax hardness and oil content on the performance of wax-treatments might provide some useful insights, but since all these basic properties are correlated and dependent on the chemical composition of the wax, further research using more refined materials (waxes and wood substrates) is needed.

Visualizing the location of the waxes within OSB may also provide insights as to how wax-treatments are able to affect water ingress into OSB. I recommend the use of fluorescent microscopy for this purpose. Scholz et al. (2010a) used a coloured wax to measure the penetration of wax that was impregnated into Scots pine and European beech. Waxes can also be labeled with a fluorescent dye before being sprayed onto the surface of wood (Ede et al. 1998; Grigsby and Thumm 2012b). Alternatively the wood strands may be labeled with a fluorescent stain before the board is pressed, thus visualising the wax location by using negative staining techniques (Kamke et al. 1996; Saunders and Kamke 1996). Both of these recommended methods will require destruction of the test sample. One possible non-destructive test method that may be used to locate wax in OSB is X-ray micro computed tomography. Due to the small density difference between wax and OSB, however, it may be difficult to create the required contrast between wax and wood. Nevertheless, one research group has used X-ray CT to visualize wax inside solid wood (Scholz et al. 2010b; Scholz et al. 2010c). Another non-destructive technique that could be used to visualize wax in OSB is autoradiography. For example, Levi et al. (1970) demonstrated how autoradiography could be used to visualize wax in solid wood and the same technique could be used to visualize wax in thin sections of OSB.

Molten wax spray treatments have obvious potential as an edge treatment for OSB. Thickness swelling of OSB is pronounced at the edges of the OSB panels and several North American companies have developed ways of restricting the edge swelling of OSB exposed to water (Evans et al. 2013). Commercially available edge seals are usually silicone or latex based and contain only small amounts of wax as a hydrophobic filler (Winterowd et al. 2003). Further research is required to determine whether molten wax treatments applied to the edges of panels can perform better than current commercial edge sealants.

According to standard methods that test the dimensional stability of OSB, samples should be immersed in water. In Chapter 5 a water float test was used as a more realistic way of comparing surface treatments. As a result I am unable to compare my results to those of previous studies. In Chapter 4, I used an immersion test, however, the presence of epoxy edge seals may have restricted swelling, thus also making it difficult to compare my results to those of previous studies. Therefore, additional research, using standard immersion tests are required to compare the effectiveness of molten wax treatments with other treatments that dimensionally stabilize OSB. In addition to standard immersion tests, it is also necessary to expose full-sized, wax-treated panels to cyclic wetting and drying and then measure the TS of the OSB panels in both wet and dry conditions. Cyclic water exposure tests will better simulate the rainy and sunny conditions that OSB panels experience when in service.

Lastly, the performance of wax treatments in general may be improved by adding small amounts of resin, polymer, or oil. Resins and polymers may act as a binder to hold the wax deposits in place, possibly increasing the long term water repellency of the wax-treated boards. Alternatively, drying oils may also be introduced as a potential binder. Further research is required to determine the effect of different resins or oils on the performance of molten wax spray treatments for OSB.

Bibliography

Adam, N. K. (1963). Waterproofing and water-repellency. In: J.L. Moilliet (Ed.), *Principles of Water Repellency* (pp. 1-23). New York, NY: Elsevier.

Adam, N.K., Jessop, G. (1925). Angles of contact and polarity of solid surfaces. *Journal of the Chemical Society*, Transactions 127, pp. 1863-1868.

Adam Y. S., Sites, L.S., Sellers Jr, T., Nicholas, D.D. (2000). Computerized dynamic swellometer evaluation of oriented strand products. *Forest Products Journal*, 50(3), 35-38.

ASTM (2007). D4442-07: Standard test methods for direct moisture content measurement of wood and wood-based materials. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2008). D127-08: Standard test method for drop melting point of petroleum wax, including petrolatum. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2009). D87-09*:* Standard test method for melting point of petroleum wax (cooling curve). West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2010). D1321-10: Standard test method for needle penetration of petroleum waxes. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2010). D1386-10: Standard test method for acid number (empirical) of synthetic and natural waxes. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2011). D721-06: Standard test method for oil content of petroleum waxes. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2012a). D2669-06: Apparent viscosity of petroleum waxes compounded with additives (hot melts). West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2012b). D1037-12: Standard test methods for evaluating properties of wood-based fiber and particle panel materials. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2013). D938-12: Congealing point of petroleum waxes, including petrolatum. West Conshohocken, PA: American Society for Testing and Materials.

Amthor, J. (1972). Paraffindispersionen zur hydrophobierung von spanplatten. *Holz Als Roh-und Werkstoff*, 30(11), 422-429.

Anonymous (2012). Global OSB Industry 2011/2012. *Wood Markets Monthly International Report*, 17(7), 2-3. Vancouver, BC: Wood Markets.

APA (2009). Oriented strand board product guide. Tacoma, WA: The Engineered Wood Association.

Arena, L., Mantha, P., Karagiozis, A.N. (2010). Monitoring of internal moisture loads in residential buildings, December. Retrieved March 2014 from SSRN: http://ssrn.com/abstract=1761413 (or http://dx.doi.org/10.2139/ssrn.1761413).

Ashori, A., Raverty, W.D., Vanderhoek, N., Ward, J.V. (2008). Surface topography of kenaf (*Hibiscus cannabinus*) sized papers. *Bioresource Technology*, 99(2), 404-410.

Avramidis, S., Smith, L.A. (1989). The effect of resin content and face-to-core ratio on some properties of oriented strand board. *Holzforschung*, 43(2), 131-133.

Banks, W.B., Voulgaridis, E.V. (1980). The performance of water repellents in the control of moisture absorption by wood exposed to the weather. In: *Record of the 1980 Annual Convention of the British Wood Preserving Association* (pp. 43-53).

Barbuta, C., Blanchet, P., Cloutier, A., Yadama, V., Lowell, E. (2012). OSB as substrate for engineered wood flooring. *European Journal of Wood and Wood Products*, 70(1-3), 37-43.

Bartell, F.E., Zuidema, H.H. (1936). Wetting characteristics of solids of low surface tension such as talc, waxes and resins. *Journal of the American Chemical Society*, 58(8), 1449-1454.

Barthlott, W., Neinhuis, C. (1997). Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta*, 202(1), 1-8.

Baştürk, M.A. (2007). Improving oriented strandboard properties with chitosan treatment of strands. *Journal of Applied Sciences Research*, 3(7), 507-510.

Beall, F.C., Eickner, H.W. (1970). Thermal degradation of wood components: a review of the literature. *USDA Forest Service Research Paper FPL 130.* Madison, WI: Forest Service, Forest Products Laboratory.

Bennett, H. (1963). *Industrial waxes. Vol. 2, Compounded waxes and technology*. New York, NY: Chemical Publishing Company Inc.

Berglund, L., Rowell. R.M. (2005). Wood composites. In: Rowell. R.M. (Ed.), *Handbook of Wood Chemistry and Wood Composites* (pp. 279-301). Boca Raton, FL: CRC Press.

Bhuiyan, T.R., Hirai, N., Sobue, N. (2001). Effect of intermittent heat treatment on crystallinity in wood cellulose. *Journal of Wood Science,* 47(5), 336-341.

Bhuiyan, T.R., Hirai, N. (2005). Study of crystalline behavior of heat-treated wood cellulose during treatments in water. *Journal of Wood Science*, 51(1), 42-47.

Biblis, E.J. (1990). Performance of southern OSB overlaid with resin-impregnated paper. *Forest Products Journal*, 40(4), 55-62.

Bolton, A.J., Humphrey, P.E. (1994). The permeability of wood-based composite materials, Part 1: A review of the literature and some unpublished work. *Holzforschung,* 48(1), 95-100.

Boonstra, M.J., Tjeerdsma, B. (2006). Chemical analysis of heat treated softwoods. *Holz Als Roh-und Werkstoff* 64(3), 204-211.

Borgin, K., Corbett, K. (1974). The hydrophobic and water-repellent properties of wattle bark extractives. *Wood Science and Technology* 8(2), 138-147.

Borgin, K., Corbett, K. (1970). Stability and weathering properties of wood treated with various oils, waxes and resins. *Plastics Paint Rubber*, 4, 69-72.

Borgin, K. (1965). The testing and evaluation of water repellents, In: *Record of the 1965 Annual Convention of the British Wood Preserving Association* (pp. 67-84).

Brochmann, J., Edwardson, C., Shmulsky, R. (2004). Influence of resin type and flake thickness on properties of OSB. *Forest Products Journal*, 54(3), 51-55.

Brown, F.L., Kenaga, D.L., Gooch, R.M. (1966). Impregnation to control dimensional stability of particle and fiberboards. *Forest Products Journal,* 16(1), 45-53.

Browning, B.L. (1963). *The chemistry of wood.* New York, NY: Interscience Publishers.

Budija, F., Kričej, B., Petrič, M. (2008). Possibilities of use of propolis for wood finishing. *Wood Research*, 53(2), 91-102.

Burmabaugh, J. (1960). Effect of flake dimensions on properties of particle boards. *Forest Products Journal,* 10(5), 243-246.

Burmester, A., Wille, W.E. (1975). Untersuchungen zur formbeständigkeit von teakholz. *Holz Als Roh-und Werkstoff*, 33(4), 147-150.

Burmester, A. (1970). Formbeständigkeit von holz gegenüber feuchtigkeit: grundlagen und vergütungsverfahren. *Bundesanstalt für Materialprüfung*.

Burmester, A. (1975). Zur dimensionsstabilisierung von holz. *Holz Als Roh-und Werkstoff*, 33(9), 333-335.

Cai, Z. (2012) Wood-based composite board. In: L. Nicolais, A. Borzacchiello (Eds.), *Wiley Encyclopedia of Composites* (pp. 1-11). Wiley Online Library.

Cai, Z., Ross, J. (2010). Mechanical properties of wood-based composite materials. In: *Wood Handbook, Wood as an Engineering Material: USDA General Technical Report FPL-GTR-190* (Centennial ed., pp. 1-12). Madison, WI: Forest Service, Forest Products Laboratory.

Carll, C., Wiedenhoeft, A.C. (2009). Moisture-related properties of wood and the effects of moisture on wood and wood products. In: H.R. Trechsel, M.T. Bomberg (Eds.), *Moisture control in buildings: the key factor in mold preventions* (2nd ed., pp. 54-79). West Conshohocken, PA: American Society for Testing and Materials.

Chapman, K.M. (2006). Wood-based panels: particleboard, fibreboards and oriented strand board. In: J.C.F. Walker (Ed.), *Primary Wood Processing: Principles and Practice* (2nd ed., pp. 427-475). Dordrecht, Netherlands: Springer.

Chesebrough, R.A. (1872). Improvement in products from petroleum. *Patent No. 127,568.* Washington, DC: U.S. Patent and Trademark Office.

Clarck, J.d'A. (1980). How it all started: The history of waferboard. In: *Canadian Waferboard Symposium* (pp. 4-14).

Coates, J.P. (2000). Interpretation of infrared spectra, a practical approach. In: R.A. Meyers (Ed.), *Encyclopedia of Analytical Chemistry (*pp. 10815–10837). Chichester, UK: John Wiley and Sons Ltd.

Coulson, J. (2012). *Wood in Construction: How to Avoid Costly Mistakes*. Ames, IA: Wiley-Blackwell.

Dai, C.P. (2004). Strand quality and geometry pertaining to OSB manufacturing and product properties [PowerPoint slides]. In: *Proceedings of the 38th International Particleboard/Composite Materials Symposium*. Seattle, WA: Washington State University. Retrieved March 2014 from http://www.woodsymposium.wsu.edu/ sessions.2004/technical%20workshop/Dai-TW.pdf.

Dai, C., Yu, C., Zhou, X. (2005). Heat and mass transfer in wood composite panels during hot pressing, Part II: Modeling void formation and mat permeability. *Wood and Fiber Science*, 37(2), 242-257.

de Meijer, M., Haemers, S., Cobben, W., Militz, H. (2000). Surface energy determinations of wood: comparison of methods and wood species. *Langmuir*, 16(24), 9352-9359.

Debye, P., Cleland, R. L. (2004). Flow of liquid hydrocarbons in porous Vycor. *Journal of Applied Physics*, 30(6), 843-849.

Del Menezzi, C.H.S., Tomaselli, I. (2006). Contact thermal post-treatment of oriented strandboard to improve dimensional stability: A preliminary study. *Holz Als Roh-und Werkstoff*, 64(3), 212-217.

Del Menezzi, C.H.S., Tomaselli, I., Okino, E.Y.A., Teixeira, D. E., Santana, M.A.E. (2009). Thermal modification of consolidated oriented strandboards: effects on dimensional stability, mechanical properties, chemical composition and surface color. *European Journal of Wood and Wood Products*, 67(4), 383-396.

Derbyshire, H., Miller, E.R. (1996). Moisture conditions in coated exterior wood, Part 1: An investigation of the moisture transmission characteristics of exterior wood coatings and the effect of weathering on coating permeability. *Journal of the Institute of Wood Science*, 14(79), 40-47.

Derbyshire, H., Robson, D.J. (1999). Moisture conditions in coated exterior wood, Part 4: Theoretical basis for observed behaviour, A computer modelling study. *Holz Als Roh-und Werkstoff*, 57(2), 105-113.

Dullien, F.A. (1991). *Porous Media: Fluid Transport and Pore Structure*. San Diego, CA: Academic Press.

Dullien, F.A., Zarcone, C., Macdonald, I.F., Collins, A., Bochard, R.D. (1989). The effects of surface roughness on the capillary pressure curves and the heights of capillary rise in glass bead packs. *Journal of Colloid and Interface Science*, 127(2), 362-372.

Eckert, J.R., Edwardson, C.F. (1998). The development of an optimal wax emulsion for oriented strandboard. In: *Proceedings of the 32nd International Particleboard/Composite Materials Symposium* (pp. 135-142). Pullman, WA: Washington State University.

Ede, R.M., Thumm, A., Coombridge, B.A., Brookes, G.S. (1998). Visualization and quantification of wax on MDF panels: a comparison of emulsion and molten waxes. In: *Proceedings of the 32nd International Particleboard/Composite Materials Symposium* (pp 143-149). Pullman, WA: Washington State University.

Ellis, S. (1993). Effect of resin particle size on waferboard adhesive efficiency. *Wood and Fiber Science*, 25(3), 214-219.

Elmendorf, A. (1950). Wood fibres from veneer waste. *Paper Trade Journal*, 130(6), 29-31.

Elmendorf, A. (1965). Oriented strand board. *Patent No. 3164511*. Washington, DC: U.S. Patent and Trademark Office.

EN (2005). EN 927-5:2005. Paints and varnishes - Coating materials and coating systems for exterior wood. Brussels, Belgium: European Committee of Standardization.

EN (2006). BS EN 300:2006. Oriented strand board (OSB): Definitions, classification and specifications. Brussels, Belgium: European Committee of Standardization.

Esteves, B.M., Pereira, H.M. (2009). Wood modification by heat treatment: a review. *BioResources*, 4(1), 370-404.

Evans, P.D., Cullis, I. (2008). Effect of sanding and coating with UV-cured finishes on the surface roughness, dimensional stability and fire resistance of oriented strandboard. *Holz Als Roh-und Werkstoff*, 66(3), 191-199.

Evans, P.D., Miesner, M., Rogerson, D. (2013). Machined tapers reduce the differential edge swelling of oriented strand board exposed to water. *Composites Part B: Engineering,* 50, 15-21.

Feist, W.C. (1982). Weathering characteristics of finished wood-based panel products. *Journal of Coatings Technology*, 54(686), 43-50.

Feist, W.C., Mraz, E.A. (1978). Protecting millwork with water repellents. *Forest Products Journal*, 28(5), 31-35.

Fengel, D., Wegener., G. (1989). Influence of temperature. In: *Wood: chemistry, ultrastructure, reactions* (pp. 319-344). New York, NY: Walter de Gruyter.

Forintek Canada Corp. (1998). *Wood-based panel products: special report*. Sainte-Foy, QC: Industry Canada.

Furuno, T., Hse, C.Y., Côté, W.A. (1983). Observation of microscopic factors affecting strength and dimensional properties of hardwood flakeboard. In: *Proceedings of the 17th International Particleboard/Composite Materials Series Symposium* (pp. 297-312). Pullman, WA: Washington State University.

Garai, R.M., Sánchez, I.C., García, R.T., Rodríguez Valverde, M.A., Cabrerizo Vílchez, M.A., Hidalgo-Álvarez, R. (2005). Study on the effect of raw material composition on water-repellent capacity of paraffin wax emulsions on wood. *Journal of Dispersion Science and Technology*, 26(1), 9-18.

Garay, R., Poblete, H., Karsulovic, J. (2009). Evaluation of oriented strandboard and plywood subjected to severe relative humidity and temperature conditions. *Forest Products Journal*, 59(3), 84-90.

Gatchell, C.J., Heebink, B.G., Hefty, F.V. (1966). Influence of component variables on properties of particleboard for exterior use. *Forest Products Journal*, 16(4), 46-59.

Geimer, R.L., Kwon, J.H. (1999). Flakeboard thickness swelling, Part II: Fundamental response of board properties to steam injection pressing. *Wood and Fiber Science*, 31(1), 15-27.

Geimer, R.L. (1976). Flake alignment in particleboard as affected by machine variables and particle geometry. *USDA Forest Service Research Paper FPL 275*. Madison, WI: Forest Service, Forest Products Laboratory.

Geimer, R.L. (1982). Dimensional stability of flakeboards as affected by board specific gravity and flake alignment. *Forest Products Journal*, 32(8), 44-52.

Geimer, R.L., Montrey, H.M., Lehmann, W.F. (1975). Effects of layer characteriztics on the properties of three-layer particleboards. *Forest Products Journal*, 25(3), 19-29.

Generalla, N.C., Biblis, E.J., Carino, H.F. (1989). Effect of two resin levels on the properties of commercial southern OSB. *Forest Products Journal*, 39(6), 64-68.

Gérardin, P., Petrič, M., Petrissans, M., Lambert, J., Ehrhrardt, J.J. (2007). Evolution of wood surface free energy after heat treatment. *Polymer Degradation and Stability*, 92(4), 653-657.

Gibson, E.J. (1965). Measuring the effectiveness of water repellents - some basic considerations. In: *Report of a Symposium on Water Repellents and Wood* (pp. 1-4). Princes Risborough, UK: Ministry of Technology, Forest Products Research Laboratory.

Gillespie, R.H. (1984). *Adhesives for Wood: Research, Applications and Needs*. Park Ridge, NJ: Noyes Publications.

Gindl, M., Sinn, G., Gindl, W., Reiterer, A., Tschegg, S. (2001). A comparison of different methods to calculate the surface free energy of wood using contact angle measurements. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 181(1), 279-287.

Go, A., Laplante, A., Pettersen, W.S. (2000). Dimensionally stable oriented strand board (OSB) and method for making the same. *Patent No. 6,098,679*. Washington, DC: U.S. Patent and Trademark Office.

Gomez-Bueso, J., Haupt, R. (2010). Wood composite adhesives. In: L. Pilato (Ed.), *Phenolic Resins: A Century of Progress* (pp. 155-187). Heidelberg, Germany: Springer.

Goroyias G.J., Hale M.D. (2002). Heat treatment of wood strands for OSB production: Effect on the mechanical properties, water absorption and dimensional stability. In: *The 33rd Annual Meeting of the International Research Group on Wood Preservation*. Cardiff, Wales: IRGWP.

Grant, D. R. (1995). A literature review of alternate species in oriented strand board and waferboard. Edmonton, AB: Canadian Forest Service, Land and Forest Service. Retrieved April 2014 from http://www.cfs.nrcan.gc.ca/bookstore_pdfs/21260.pdf.

Grauman N.N. (2013). Wax-based emulsifiers for wax emulsions for use in engineered wood products. *Open Access Dissertations and Theses,* Paper 7621. MSc. dissertation, McMaster University. Retrieved April 2014 from http://digitalcommons.mcmaster.ca/opendissertations/7621.

Green, D.W., Hernandez, R. (1998). Standards for structural wood products and their use in the United States. *Wood Design Focus*, Fall (9)3. Retrieved from http://128.104.77.228/documnts/pdf1998/green98a.pdf.

Greener-Donhowe, I., Fennema, O. (1993). Water vapor and oxygen permeability of wax films. *Journal of the American Oil Chemists' Society*, 70(9), 867-873.

Grigsby, W.J., Thumm, A. (2012a). Resin and wax distribution and mobility during medium density fibreboard manufacture. *European Journal of Wood and Wood Products*, 70(1-3), 337-348.

Grigsby, W., Thumm, A. (2012b). The interactions between wax and UF resin in medium density fibreboard. *European Journal of Wood and Wood Products*, 70(4), 507-517.

Grossman, L.M. (1992). Expanding your OSB market with protective coatings. In: *Proceedings of the 26th International Particleboard/Composite Materials Symposium* (pp. 227-235). Pullman, WA: Washington State University.

Grozdits, G.A., Bibal, J.N. (1983). Surface-activated wood bonding systems: accelerated aging of coated and uncoated composite boards. *Holzforschung*, 37(4), 167-172.

Gu, H., Wang, S., Neimsuwan, T., Wang, S. (2005). Comparison study of thickness swell performance of commercial oriented strandboard flooring products. *Forest Products Journal*, 55(12), 239-245.

Hague, J. 1995. New developments with wax emulsions for the wood-based panels industry. In: *Proceedings of the 29th International Particleboard/Composite Materials Series Symposium*. Pullman, WA: Washington State University.

Hakkou, M., Pétrissans, M., Zoulalian, A., Gérardin, P. (2005). Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. *Polymer Degradation and Stability*, 89(1), 1-5.

Halligan, A.F. (1970). A review of thickness swelling in particleboard. *Wood Science and Technology*, 4(4), 301-312.

Hann, R.A., Black, J.M., Blomquist, R.F. (1962). How durable is particleboard? *Forest Products Journal*, 12(12), 577-584.

Hartley, I.D., Wang, S., Zhang, Y. (2007). Water vapor sorption isotherm modeling of commercial oriented strand panel based on species groups and resin type. *Building and Environment*, 42(10), 3655-3659.

Haygreen, J.G., Gertjejansen, R.O. (1971). Improving the properties of particleboard by treating the particles with phenolic impregnating resin. *Wood and Fiber Science*, *3*(2), 95-105.

He, W., Xiaoxiang, L., Yukun, H. (2000). Study on waterproof performance of paint coated OSB. *China-Wood-Industry*, 14(6), 28-29.

Heebink, B.G. (1967). Wax in particleboards. In: *Proceedings of the 1st Symposium on Particleboard (pp. 251-268).* Pullman, WA: Washington State University.

Heebink, B.G., Hefty, F.V. (1969). Treatments to reduce thickness swelling of phenolic-bonded particleboard. *Forest Products Journal*, 19(11), 17-26.

Hetzler, B.H., Martin, H.V. (1983). Surface stabilized waferboard. *Patent No. 4,404,252*. Washington, DC: U.S. Patent and Trademark Office.

Hilditch, E.A. (1965). The relative effectiveness of different materials and methods of treatment. In: *Symposium on Water Repellents and Wood* (pp. 34-47). Princes Risborough, UK: Ministry of Technology, Forest Products Research Laboratory.

Hill, C.A.S. (2007). *Wood modification: chemical, thermal and other processes* (Vol. 5). Etobicoke, ON: John Wiley and Sons.

Holloway, P.J. (1969). Chemistry of leaf waxes in relation to wetting. *Journal of the Science of Food and Agriculture*, 20(2), 124-128.

Hosseinaei, O., Wang, S., Rials, T.G., Xing, C., Taylor, A.M., Kelley, S.S. (2011). Effect of hemicellulose extraction on physical and mechanical properties and mold susceptibility of flakeboard. *Forest Products Journal*, 61(1), 31-37.

Hosseinaei, O., Wang, S., Rials, T.G., Xing, C., Zhang, Y. (2011). Effects of decreasing carbohydrate content on properties of wood strands. *Cellulose*, 18(3), 841-850.

Howard, J.L., McKeever, D.B. (2012). U.S. forest products annual market review and prospects, 2008-2012. *USDA Research Note FPL-RN-0328*. Madison, WI: Forest Service, Forest Products Laboratory.

Howard, J. L., McKeever, D.B. (2013). U.S. forest products annual market review and prospects, 2009–2013. *USDA Research Note FPL-RN-0330*. Madison, WI: Forest Service, Forest Products Laboratory.

Hsu, O.H., Bender, H.S. (1988). Water repellent efficacy of wax used in hardboard. *Industrial and Engineering Chemistry Research*, 27(7), 1296-1300.

Hsu, W.E. (1987). A process for stabilizing waferboard/OSB. In: *Proceedings of the 21st International Particleboard/Composite Materials Symposium* (pp. 219-236). Pullman, WA: Washington State University.

Hsu, W.E., Melanson, R.J., Kozak, P.J., Maloney, T.M. (1990). The effect of wax type and content on waferboard properties. In: *Proceedings of the 24th International Particleboard/Composite Materials Symposium* (pp. 85-93). Pullman, WA: Washington State University.

Hsu, W.E., Schwald, W., Schwald, M.J., Shields, M.J. (1988). Chemical and physical changes required for producing dimensionally stable wood-based composites, Part 1: Steam pretreatment. *Wood Science and Technology*, 22(3), 281-289.

Hsu, W.E., Schwald, W., Shields, M.J. (1989). Chemical and physical changes required for producing dimensionally stable wood-based composites, Part 2: Heat post-treatment. *Wood Science and Technology*, 23(3), 281-288.

Hujanen, D.R. (1973). Comparison of three methods for dimensionally stabilizing wafer-type particleboard. *Forest Products Journal,* 23(6), 29-30.

Huldén, M., Hansen, C.M. (1985). Water permeation in coatings. *Progress in Organic Coatings*, 13(3), 171-194.

Impellizzeri, J.S., Etzold, R., Vaughan, T.W. (1976). Oriented strand board goes to western Massachusetts (Wood industry). In: *Proceedings of the 10th International Particleboard/Composite Materials Symposium*. Pullman, WA: Washington State University.

Irle, M., Barbu., M.C. (2010). Wood-based panel technology. In: T. Thoemen, M. Irle, M. Sernek (Eds.), *Wood-Based Panels: An Introduction for Specialist*s (pp. 1-94). London, UK: Brunel University Press.

Iwakiri, S., Mendes, L.M., Saldanha, L.K., Santos, J.D. (2004). Utilização da madeira de eucalipto na produção de chapas de partículas orientadas–OSB. *Cerne, Lavras*, 10(1), 46-52.

Johnson, J.W. (1964). Effect of exposure cycles on stability of commercial particleboard. *Forest Products Journal*, 14(7), 277-282.

Jorgensen, R.N., Murphey, W.K. (1961). Particle geometry and resin spread its effect on thickness and distribution of glueline in oak flakeboard. *Forest Products Journal* 11(12), 582-585.

Jorgensen, R.N., Odell, R.L. (1961). Dimensional stability of oak flakeboard as affected by particle geometry and resin spread. *Forest Products Journal*, 11(10), 463-466.

Kajita, H., Imamura, Y. (1991). Improvement of physical and biological properties of particleboards by impregnation with phenolic resin. *Wood Science and Technology*, 26(1), 63-70.

Kamke, F.A., Lenth, C.A., Saunders, H.G. (1996). Measurement of resin and wax distribution on wood flakes. *Forest Products Journal*, 46(6), 63-68.

Kelly, M.W. (1977). Critical literature review of relationships between processing parameters and physical properties of particleboard. *USDA General Technical Report FPL-10*. Madison, WI: Forest Service, Forest Products Laboratory.

Kline, D.E. (2005). Gate-to-gate life-cycle inventory of oriented strandboard production. *Wood and Fiber Science*, 37 Corrim Special Issue, 74-84.

Kolattukudy, P.E., Croteau, R., Buckner, J.S. (1976). Biochemistry of plant waxes. In: P.E. Kolattukudy (Ed.), *Chemistry and Biochemistry of Natural Waxes* (pp. 289-347). Amsterdam, Netherlands: Elsevier.

Kudo, K., Yoshida, E. (1957). The decomposition process of wood constituents in the course of carbonization. I. The decomposition of carbohydrate and lignin in Mizunara (*Quercus crispula*). *Journal of the Japan Wood Research Society*, 3(4), 125-127.

Kloeser, L., Kües, U., Schöpper, C., Hosseinkhani, H., Schütze, S., Dantz, S., Malik, I., Vos, H., Bartholme, M., Müller, C., Polle, A., Kharazipour, A. (2007). Panel Boards and Conventional Adhesives. In: U. Kües (Ed.), *Wood Production, Wood Technology, and Biotechnological Impacts (*pp. 297-346). Germany: Universitätsverlag Göttingen.

Lee, A.W., Bai, X., Peralta, P.N. (1996). Physical and mechanical properties of strandboard made from moso bamboo. *Forest Products Journal* 46 (11/12), 84-88.

Lehmann, W.F. (1964). Retarding dimensional changes of particle boards. *Information Circular 20*. Corvallis, OR: Forest Research Laboratory, Oregon State University.

Lehmann, W.F. (1974). Properties of structural particleboards. *Forest Products Journal,* 24(1), 19-26.

Lehmann, W.F. (1978). Cyclic moisture conditions and their effect on strength and stability of structural flakeboards. *Forest Products Journal*, 28(6), 23-31.

Lenth, C.A., Kamke, F.A. (1996). Investigations of flakeboard mat consolidation, Part I: Characterizing the cellular structure. *Wood and Fiber Science*, 28(2), 153-167.

Levi, M.P., Coupe, C., Nicholson, J. (1970). Distribution and effectiveness in *Pinus sp.* of a water repellent additive for water-borne wood preservatives. *Forest Products Journal*, 20(11), 32-7.

Levy, E.J., Doyle, R.R., Brown, R.A., Melpolder, F.W. (1961). Identification of components in paraffin wax by high temperature gas chromatography and mass spectrometry. *Analytical Chemistry*, 33(6), 698-704.

Li, P., Tao, Y., Wang, F. (2010). Research on macrovoids of bio-based strand composites using image processing technology. *Journal of Information and Computational Science*, 7(4), 1007–1012.

Li, P., Dai, C., Wang, S. (2009). A simulation of void variation in wood-strand composites during consolidation. *Holzforschung*, 63(3), 357-361.

Li, P., Wang, S., Chen, S., Wang, F. (2008). A three-dimensional solid model for OSB mat. *Forest Products Journal*, 58(1/2), 53-58.

Linville, J.D., Wolcott, M.P. (2001). Controlling thickness swell in oriented strand composites. In: *Proceedings of the 35th International Particleboard/Composite Materials Symposium* (pp 91-101). Pullman, WA: Washington State University.

Liu, H., Wang, J., Xie, Y., Ma, D., Shi, X. (2011). Flow characteriztics of heavy oil through porous media. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 34(4), 347-359.

Malanit, P., Barbu, M.C., Frühwald, A. (2011). Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (*Dendrocalamus asper* Backer). *European Journal of Wood and Wood Products*, 69(1), 27-36.

Maloney, T.M. (1993). *Modern Particleboard and Dry-process Fiberboard Manufacturing*. San Francisco, CA: Miller Freeman.

Mantanis, G.I., Papadopoulos, A.N. (2010). Reducing the thickness swelling of wood based panels by applying a nanotechnology compound. *European Journal of Wood and Wood Products*, 68(2), 237-239.

Mantanis, G.I., Young, R.A. (1997). Wetting of wood. *Wood Science and Technology*, 31(5), 339-353.

Maxwell, J.W., Kitazawa, G., Duncan, T., Hine, J.M. (1959). A search for better particleboard adhesive. *Forest Products Journal,* 9(10), 42A-46A.

Meiron, T.S., Marmur, A., Saguy, I.S. (2004). Contact angle measurement on rough surfaces. *Journal of Colloid and Interface Science*, 274(2), 637-644.

Mendes, R.F., Júnior, G.B., de Almeida, N.F., Surdi, P.G., Barbeiro, I.N. (2013). Effect of thermal treatment on properties of OSB panels. *Wood Science and Technology*, 47(2), 243-256.

Miniutti, V.P., Mraz, E.A., Black, J.M. (1961). Measuring the effectiveness of water-repellent preservatives. *Forest Products Journal*, 11(10), 453-462.

Mohammed-Ziegler, I., Oszlánczi, Á., Somfai, B., Hórvölgyi, Z., Pászli, I., Holmgren, A., Forsling, W. (2004). Surface free energy of natural and surface-modified tropical and European wood species. *Journal of Adhesion Science and Technology*, 18(6), 687-713.

Morrow, N.R. (1970). Physics and thermodynamics of capillary action in porous media. *Industrial and Engineering Chemistry*, 62(6), 32-56.

Mottet, A.L. (1967). The particle geometry factor in particleboard manufacturing. In: *Proceedings of the 1st Symposium on Particleboard* (pp. 23-73). Pullman, WA: Washington State University.

Moya, L., Tze, W.T., Winandy, J.E. (2009). The effect of cyclic relative humidity changes on moisture content and thickness swelling behavior of oriented strandboard. *Wood and Fiber Science*, 41(4), 447-460.

Moya, L., Winandy, J.E., Tze, W.T., Ramaswamy, S. (2008). Use of fire-impacted trees for oriented strandboards. *Forest Products Journal*, *58*(6), 45-52.

NIST (2004). Voluntary product standard PS 2–04: Performance standard for wood-based structural-use panels. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology.

Neimsuwan, T., Wang, S., Via, B.K. (2008). Effect of processing parameters, resin, and wax loading on water vapor sorption of wood strands. *Wood and Fiber Science*, 40(4), 495-504.

Neusser, H., Krames, U., Haidinger, K. (1965). Das verhalten von spanplatten gegeniiber feuchtigkeit unter besonderer beriicksichtigung der quellung. *Holzforschung und Holzverwertung,* 17(3), 43-69.

O'Halloran, M.R. (1989). Structural-use panels. In: A.P. Schniewind (Ed.), *Concise Encyclopedia of Wood and Wood-Based Materials* (Vol. 6). New York, NY: Pergamon Press.

Ohlmeyer, M. (2007). Heat treatment as an option for enhancement of OSB properties. In: *Proceedings of the 5th COST E34 International Workshop on Bonding Modified Wood* (pp. 21-29). Bled, Slovenia. Retrieved from http://zanran_storage.s3.amazonaws.com/www1.uni-hamburg.de/ContentPages/19222301.pdf#page=27.

Okino, E.Y., Teixeira, D.E., Del Menezzi, C.H. (2007). Post-thermal treatment of oriented strandboard (OSB) made from cypress (*Cupressus glauca* Lam.). *Maderas. Ciencia y tecnología*, 9(3), 199-210.

Orman, H.R. (1955). The response of New Zealand timbers to fluctuations in atmospheric moisture conditions. Technical Paper 8. Wellington, NZ: Forest Research Institute, New Zealand Forest Service.

Papadopoulos, A.N., Traboulay, E. (2002). Dimensional stability of OSB made from acetylated fir strands. *Holz Als Roh-und Werkstoff*, 60(2), 84-87.

Papadopoulos, A.N., Gkaraveli, A. (2003). Dimensional stabilisation and strength of particleboard by chemical modification with propionic anhydride. *European Journal of Wood and Wood Products*, 61(2), 142-144.

Paredes, J.J., Shaler, S.M., Edgar, R., Cole, B. (2010). Selected volatile organic compound emissions and performance of oriented strandboard from extracted southern pine. *Wood and Fiber Science*, 42(4), 429-438.

Paredes, J.J., Shaler, S.M., Jara, R., van Heiningen, A. (2008). Influence of hot water extraction on the physical and mechanical behavior of OSB. *Forest Products Journal*, 58(12), 56-62.

Paridah, M.T., Ong, L.L., Zaidon, A., Rahim, S., Anwar, U.M.K. (2006). Improving the dimensional stability of multilayered strand board through resin impregnation. *Journal of Tropical Forest Science*, 18(3), 166-172.

Paul, W., Ohlmeyer, M., Leithoff, H., Boonstra, M.J., Pizzi, A. (2006). Optimising the properties of OSB by a one-step heat pre-treatment process. *Holz Als Roh-und Werkstoff*, 64(3), 227-234.

Pelaez-Samaniego, M.R., Yadama, V., Lowell, E., Espinoza-Herrera, R. (2013). A review of wood thermal pretreatments to improve wood composite properties. *Wood Science and Technology*, 47(6), 1285-1319.

Pétrissans, M., Gérardin, P., Serraj, M. (2003). Wettability of heat-treated wood. *Holzforschung*, 57(3), 301-307.

Pettersen, R.C. (1984). The chemical composition of wood. In: R.M., Rowell (Ed.), *The Chemistry of Solid Wood (*pp. 57-126). Washington, DC: American Chemical Society.

Pizzi, A. (1993). The water sorption isotherm of crystalline cellulose I and II and amorphous cellulose. A molecular mechanics approach*. Cellul.: Chem., Biochem. Mater. Aspects*, 217-224.

Post, P.W. (1958). Effect of particle geometry and resin content on bending strength of oak flake board. *Forest Products Journal*, 8(10), 317-322.

Post, P.W. (1961). Relationship of flake size and resin content to mechanical and dimensional properties of flake board. *Forest Products Journal*, 11(1), 34-37.

Racota, M. (2007). Process for imparting water resistance to wood-based products. *Patent No.* 20070059509. Washington, DC: U.S. Patent and Trademark Office.

Rak, J. (1975). New evaluation of water repellency of wood by contact angle. *Wood and Fiber Science*, 7(1), 16-24.

Rice, J.T., Carey, R.H. (1978). Wood density and board composition effects on phenolic resin-bonded flakeboard. *Forest Products Journal,* 28(4), 21-28.

Richardson, B.A. (1993). *Wood Preservation* (2nd Ed.). New York, NY: E.&F.N. Spon.

Rodríguez-Valverde, M.A., Tejera-García, R., Cabrerizo-Vílchez, M.A., Hidalgo-Álvarez, R., Nolla-Anguera, J., Esquena-Moret, J., Solans-Marsa, C., Mujika-Garai, R., Aguilar- García, C., Juárez Arroyo, F., Covián-Sánchez, I. (2006). Influence of oil content in paraffins on the behavior of wax emulsions: wetting and rheology. *Journal of Dispersion Science and Technology*, 27(2), 155-163.

Roffael, E., May, H.A. (1983). Paraffin sizing of particleboards: chemical aspects. In: *Proceedings of the 17th International Particleboard/Composite Materials Series Symposium* (pp. 283-295). Pullman, WA: Washington State University.

Roffael, E., Schneider, T., Dix, B., Buchholz, T. (2005). On paraffin sizing of medium density fiberboards (MDF), Part 1: Influence of the chemical composition of paraffin and type of emulsifier on the hydrophobic properties of MDF. *Holz Als Roh-und Werkstoff*, 63(3), 192-203.

Rowell, R.M., Banks, W.B. (1985). Water repellency and dimensional stability of wood. *USDA General Technical Report FPL-50*. Madison, WI: Forest Service, Forest Products Laboratory.

Rowell, R.M., Youngquist, J.A., Sachs, I.B. (1987). Adhesive bonding of acetylated aspen flakes, Part 1: Surface changes, hydrophobicity, adhesive penetration and strength. *International Journal of Adhesion and Adhesives*, 7(4), 183-188.

Rowell, R.M., Tillman, A.M., Simonson, R. (1986). A simplified procedure for the acetylation of hardwood and softwood flaxes for flakeboard production. *Journal of Wood Chemistry and Technology*, 6(3), 427-448.

Rowell, R.M., Youngs, R.L. (1981). Dimensional stabilization of wood in use. *USDA Research Note FPL-0243*. Madison, WI: Forest Service, Forest Products Laboratory.

RStudio (2014). www.rstudio.com. Accessed on February 9, 2014.

Rudd, A., Henderson, H. (2007). Monitored indoor moisture and temperature conditions in humid-climate US residences. *ASHRAE Transactions*, 113(1), 435-449.

Runkel, R.O.H., Wilke, K.D. (1951). Zur kenntnis des thermoplastischen verhaltens yon holz, zweite mitteilung. *Holz Roh-Werkstoff*, 9(7), 260-270.

Sattler, C., Labbe, N., Harper, D., Elder, T., Rials, T. (2008). Effects of hot water extraction on physical and chemical characteriztics of oriented strand board (OSB) wood flakes. *CLEAN–Soil, Air, Water*, 36(8), 674-681.

Saunders, H.G., Kamke, F.A. (1996). Quantifying emulsified wax distribution on wood flakes. *Forest Products Journal*, 46(3), 56-62.

Scholz, G., Krause, A., Militz, H. (2010a). Exploratory study on the impregnation of Scots pine sapwood (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) with different hot melting waxes. *Wood Science and Technology*, 44(3), 379-388.

Scholz, G., van den Bulcke, J., Boone, M., Zauer, M., Bäucker, E., van Acker, J., Militz, H. (2010b). Investigation on wax-impregnated wood. Part 1: Microscopic observations and 2D X-ray imaging of distinct wax types. *Holzforschung*, 64(5), 581-585.

Scholz, G., Zauer, M., van den Bulcke, J., van Loo, D., Pfriem, A., van Acker, J., Militz, H. (2010c). Investigation on wax-impregnated wood. Part 2: Study of void spaces filled with air by He pycnometry, Hg intrusion porosimetry, and 3D X-ray imaging. *Holzforschung*, 64(5), 587-593.

Schriever, E., Roffael, E. (1984). Zur analyse von paraffinen in spanplatten und in reiner form. *Adhäsion*, 28(11), 13-18.

Sckeikl, M., Dunky, M. (1998). Measurement of dynamic and static contact angles on wood for the determination of its surface tension and the penetration of liquids into the wood surface. *Holzforschung*, 52(1), 89-94.

Sekino, N., Suzuki, M. (1984). Swelling and creep of isocyanate-bonded oriented-particle board. *Mokuzai Gakkaishi*, 30(1), 17-22.

Semple, K., Cullis, I., Evans, P. (2009). Improving the stability of oriented strand board manufactured from mountain pine beetle wood. *Mountain Pine Beetle Working Paper 2009-18*. Victoria, BC: Canadian Forest Service, Pacific Forestry Centre. Retrieved from http://www.cfs.nrcan.gc.ca/pubwarehouse/pdfs/31194.pdf.

Šernek, M., Kamke, F.A., Glasser, W.G. (2004). Comparative analysis of inactivated wood surfaces. *Holzforschung*, 58(1), 22-31.

Shaler, S.M., Blankenhorn, P.R. (1990). Composite model prediction of elastic moduli for flakeboard. *Wood and Fiber Science*, 22(3), 246-261.

Shaler, S.M. (1986). The usefulness of selected polymer composite theories to predict the elastic moduli of oriented flakeboard. Ph.D. Dissertation. University Park, PA: Pennsylvania State University.

Shen, K.C. (1980). The past headaches and future outlook of Canadian waferboard. In: *Canadian Waferboard Symposium Proceedings* (pp. 25-31). Vancouver, BC: Forintek Canada Corp.

Shmulsky, R., Jones, P.D. (2011). *Forest products and wood science*. Ames, IA: Wiley-Blackwell.

Shupe, T.F., Hse, C.Y., Price, E.W. (2001). Flake orientation effects on physical and mechanical properties of sweetgum flakeboard. *Forest Products Journal*, 51(9), 38-43.

Skaar, C. (1972). *Water in Wood*. New York, NY: Syracuse University Press.

Skaar, C. (1988). *Wood-Water Relations.* New York, NY: Springer-Verlag.

Snodgrass, J.D., Saunders, R.J., Syska, A.D. (1974). Particleboard of aligned wood strands. In: *Proceedings of the 7th Symposium on Particleboard* (pp. 415-448), Pullman, WA: Washington State University.

Spelter, H., McKeever, D.B., Alderman, M. (2006). Status and trends: Profile of structural panels in the United States and Canada. *USDA Research Paper FPL–RP–636*. Madison, WI: Forest Service, Forest Products Laboratory.

Stamm, A.J., Hansen, L.A. (1935). Minimizing wood shrinkage and swelling. *Industrial and Engineering Chemistry*, 27(12), 1480-1484.

Stamm, A.J., Seborg, R.M. (1936). Minimizing wood shrinkage and swelling. *Industrial and Engineering Chemistry*, 28(10), 1164-1169.

Stamm, A.J. (1964). *Wood and Cellulose Science*. New York, NY: Ronald Press Company.

Standfest, G., Petutschnigg, A., Dunky, M. (2009). 2D pore size distribution in particleboard and oriented strand board. In: *Proceedings of the 6th International Symposium on Image and Signal Processing and Analysis (*pp. 359-364). Salzburg, Austria.

Suchsland, O., Xu, H. (1991). Model analysis of flakeboard variables. *Forest Products Journal*, 41(11-12), 55-60.

Suchsland, O., Enlow, R.C. (1968). Heat treatment of exterior particleboard. *Forest Products Journal*, 18(8), 24-28.

Suchsland, O. (1959). An analysis of the particle board process. *Quarterly Bulletin. Michigan State University Agricultural Experiment Station*, 42(2), 350-372.

Suchsland, O. (1962). The density distributions in strand boards. *Quarterly Bulletin. Michigan State University Agricultural Experiment Station*, 45(1), 104-121.

Suchsland, O. (1973). Hygroscopic thickness swelling and related properties of selected commercial particleboards. *Forest Products Journal*, 23(7), 26-30.

Sumardi, I., Suzuki, S., Ono, K. (2006). Some important properties of strandboard manufactured from bamboo. *Forest Products Journal*, 56(6), 59-63.

Tackie, A.D., Wang, S., Bennett, R.M. (2008). Investigation of OSB thickness-swell based on a 3-D density distribution, Part II: Variations in thickness-swell and internal stresses. *Wood and Fiber Science*, 40(3), 352-361.

Talbott, J.W. (1959). Flapreg flakeboard-resin-impregnated, compressed wood flakes. *Forest Products Journal*, 9(2), 103-106.

Taylor, A., Wang, S. (2007). Properties of "enhanced" OSB subfloor panels. Knoxville, TN: The University of Tennessee, Tennessee Forest Products Center.

Taylor, A., Wang, S., Freitag, C., Morrell, J.J. (2008). Properties of "enhanced" OSB subfloor panels. *Forest Products Journal*, 58(5), 77-79.

Thomas, N.L. (1991). The barrier properties of paint coatings. *Progress in Organic Coatings*, 19(2), 101-121.

Tiemann, H.D. (1906). Effect of moisture upon the strength and stiffness of wood. *USDA Forest Service*, Bulletin 70.

Tjeerdsma, B.F., Boonstra, M., Pizzi, A., Tekely, P., Militz, H. (1998). Characterization of thermally modified wood: molecular reasons for wood performance improvement. *Holz Als Roh-und Werkstoff*, 56(3), 149-153.

Tulloch, A.P. (1970). The composition of beeswax and other waxes secreted by insects. *Lipids*, 5(2), 247-258.

Turner, H.D. (1954). Effect of particle size and shape on strength and dimensional stability of resin-bonded wood particles. *Forest Products Journal,* 4(5), 210-222.

UNECE/FAO (2012). Forest Products Annual Market Review 2011 - 2012. Geneva, Switzerland: United Nations Publications. Retrieved from http://www.unece.org/fileadmin/DAM/timber/publications/FPAMR_2012.pdf.

UNECE/FAO (2013). Forest Products Annual Market Review 2012 - 2013. Geneva, Switzerland: United Nations Publications. Retrieved from http://www.unece.org/fileadmin/DAM/timber/publications/FPAMR2013.pdf.

Unsal, O., Candan, Z., Buyuksari, U., Korkut, S., Babiak, M. (2010). Effects of thermal modification on surface characteriztics of OSB panels. *Wood Research*, 55(4), 51-58.

Vajda, P. (1974). Structural composition of boars in the wood products picture. In: *Proceedings of the 8th International Particleboard/Composite Materials Symposium* (pp. 13-29). Pullman, WA: Washington State University.

van Houts, J.H., Winistorfer, P.M., Wang, S. (2003). Analysis of OSB mat structure made from industrially manufactured strands using simulation modeling. *Wood and Fiber Science*, 35(3), 351-362.

van Houts, J.H., Wang, S., Shi, H., Kabalka, G.W. (2006). Moisture movement and thickness swelling in oriented strandboard, Part 2: Analysis using a nuclear magnetic resonance imaging body scanner. *Wood Science and Technology*, 40(6), 437-443.

van Houts, J.H., Wang, S., Shi, H., Pan, H., Kabalka, G.W. (2004). Moisture movement and thickness swelling in oriented strandboard, Part 1: Analysis using nuclear magnetic resonance microimaging. *Wood Science and Technology*, 38(8), 617-628.

Verrall, A.F. (1971). Durability of water-resisting treatments on wood siding. *Forest Products Journal*, 21(6), 57-58.

Vick, C.B., Krzysik, A., Wood Jr, J.E. (1991). Acetylated, isocyanate-bonded flakeboards after accelerated aging. *Holz Als Roh-und Werkstoff*, 49(6), 221-228.

Voulgaridis, E. (1986). Effect of water temperature and melting point of wax on water repellency in treated wood. *Holzforschung und Holzverwertung*, 38(6), 141-144.

Voulgaridis, E.V., Banks, W.B. (1979). The initial efficiency of water repellents applied to small pine and beech specimens. *The International Journal of Wood Preservation*, 1(2), 75-80.

Voulgaridis, E.V., Banks, W.B. (1983). Laboratory evaluation of the performance of water repellents applied to long wood specimens. *Holzforschung*, 37(5), 261-266.

Wagner, D., Schwarzinger, C., Leidl, M., Schmidt, H., Endesfelder, A. (2007). Particleboards from acetylated wood flakes. *Monatshefte für Chemie*, 138(4), 321-325.

Wan, H., Kim, M.G. (2006). Impregnation of southern pine wood and strands with low molecular weight phenol-formaldehyde resins for stabilization of oriented strandboard. *Wood and Fiber Science*, 38(2), 314-324.

Wang, S., Winistorfer, P.M. (2000). The effect of species and species distribution on the layer characteriztics of OSB. *Forest Products Journal*, 50(4), 37-44.

Wang, S., Winistorfer, P.M. (2003). An optical technique for determination of layer thickness swell of MDF and OSB. *Forest Products Journal*, 53(9), 64-71.

Watson, H.F. (1905). Composite board. *Patent No. 796,545*. Washington, DC: U.S. Patent and Trademark Office.

Wenzel, R.N. (1949). Surface roughness and contact angle. *The Journal of Physical Chemistry*, 53(9), 1466-1467.

Wikberg, H., Maunu, S.L. (2004). Characterization of thermally modified hard-and softwoods by ^{13}C CPMAS NMR. *Carbohydrate Polymers*, 58(4), 461-466.

Williams, R.S. (2000). Effect of water repellent preservatives and other wood treatments on restoration and durability of millwork. In: *Proceedings of the 97th Annual Meeting of the American Wood-Preservers' Association* (pp. 84 -103). Minneapolis, MN.

Williams, R.S., Winandy, J.E. (2008). Effect of flakeboard manufacturing variables on composite properties, Part 1: Effect of resin content, wax content, pressing conditions, and edge treatments on paint performance. In: *Proceedings of 104th Annual Meeting of the American Wood Protection Association* (pp. 146–160). Portland, ON.

Winistorfer, P.M., Xu,W. (1996). Layer water absorption of medium density fiberboard and oriented strandboard. *Forest Products Journal*, 46(6), 69-72.

Winistorfer, P.M., Wei, X., Helton, C.M. (1996). Influence of three wax formulations and three application rates on thickness swell performance of southern pine flakeboard. *Forest Products Journal*, 46(3), 63-67.

Winistorfer, P.M., McFarland, D.L., Slover, R.C. (1992). Evaluating the performance of ten wax formulations and three application rates on properties of oriented strand board. In: *Proceedings of the 26th International Particleboard/Composite Materials Symposium* (pp. 236-250). Pullman, WA: Washington State University.

Winterowd, J.G., Lewis, C.E., Izan, J.D., Shantz, R.M. (2003). Edge sealant formulation for wood-based panels. *Patent No. 6,608,131*. Washington, DC: U.S. Patent and Trademark Office.

Wolfmeier, U., Schmidt, H., Heinrichs, F.L., Michalczyk, G., Payer, W., Dietsche, W., Boehlke, K., Hohner, G., Wildgruber, J. (2000). Waxes. In: A. Hans-Jurgen (Ed.), *Ullmann's Encyclopedia of Industrial Chemistry* (5th ed., pp 112-155). Weinheim, Germany: Wiley-VCH.

Wu, Q., Lee, J.N. (2002). Thickness swelling of oriented strandboard under long-term cyclic humidity exposure condition. *Wood and Fiber Science*, 34(1), 125-139.

Wu, Q., Piao, C. (1999). Thickness swelling and its relationship to internal bond strength loss of commercial oriented strandboard. *Forest Products Journal*, 49(7/8), 50-55.

Wu, Q., Suchsland, O. (1997). Effect of moisture on the flexural properties of commercial oriented strandboards. *Wood and Fiber Science*, 29(1), 47-57.

Wu, Q., Zhang, B., Wang, L., Han, G. (2006). The application of 3-D X-ray tomography with finite element analysis for engineering properties of strand based composites. In: *Proceedings of the 8th Pacific Rim Bio-Based Composites Symposium* (pp. 200-209). Kuala Lumpur, Malaysia.

Ye, X., Wang, S., Ruan, R., Qi, J., Womac, A.R., Doona, C.J. (2006). Water mobility and mold susceptibility of engineered wood products. *Transactions of the ASABE*, 49(4), 1159-1165.

Young, T. (1805). An essay on the cohesion of fluids. *Philosophical Transactions of the Royal Society of London,* 95, 65 -87.

Youngquist, J.A., Rowell, R.M., Krzysik, A. (1986). Mechanical properties and dimensional stability of acetylated aspen flakeboard. *Holz Als Roh-und Werkstoff*, 44(12), 453-457.

Youngquist, J.A., Rowell, R.M. (1990). Adhesive bonding of acetylated aspen flakes. Part 3. Adhesion with isocyanates. *International Journal of Adhesion and Adhesives*, 10(4), 273-276.

Zabel, R.A., Morrell, J.J. (1992). *Wood Microbiology: Decay and its Prevention*. San Diego, CA: Academic Press.

Zeronian, S.H., Coole, M.L., Alger, K.W., Chandler, J.M. (1983). Studies on the water sorption isotherms of celluloses and their use for determining cellulose crystallinites. *Journal of Applied Polymer Science: Applied Polymer Symposium,* 37, 1053-1069.

Zhang, C., Smith, G.D. (2010a). In-plane permeability of oriented strand lumber, Part I: The effects of mat density and flow direction. *Wood and Fiber Science*, 42(1), 99-106.

Zhang, C., Smith, G.D. (2010b). In-plane permeability of oriented strand lumber. Part II: Microscopic investigation of void structure during compression. *Wood and Fiber Science*, 42(2), 121-129.

Zhang, M., Wong, E.D., Kawai, S., Kwon, J.H. (1998). Manufacture and properties of high-performance oriented strand board composite using thin strands. *Journal of Wood Science*, 44(3), 191-197.

Zhang, Y., Jin, J., Wang, S. (2007). Effects of resin and wax on the water uptake behavior of wood strands. *Wood and Fiber Science*, 39(2), 271-278.

Appendices

Appendix 1 - Chapter 3

Appendix Table 1.1. Raw data for contact angle measurements of 5 µL water droplets placed on glass slides coated with different wax types

Block	Wax	Initial contact angle (°)	Time < 90 (min)
1	Beeswax	106.00	12.50
1	Beeswax + Ethylene maleic anhydride (3:1)	108.85	16.75
1	Beeswax + Sasolwax C (1:1)	102.14	13.00
1	Beeswax + Synthetic beeswax (1:1)	104.61	13.00
1	Beeswax + Vaseline (1:1)	103.13	7.25
1	Carnauba	97.78	6.00
1	Lanolin	100.81	0.25
1	Merkur 300	106.53	1.50
1	Microcrystalline wax	110.64	38.50
1	Stearic acid	124.48	29.75
1	Sasolwax C	102.63	0.50
1	Sasolwax M3M	106.40	11.00
1	Sasolwax M3M + Ethylene maleic anhydride (3:1)	109.04	17.25
1	Soy wax	104.06	9.50
1	Synthetic beeswax	102.36	9.00
1	Tekniwax 600	107.09	39.50
1	Tekniwax 801	106.86	22.50
1	Vaseline	100.79	6.50
2	Beeswax	104.92	11.75
2	Beeswax + Ethylene maleic anhydride (3:1)	102.59	11.25
2	Beeswax + Sasolwax C (1:1)	104.85	14.25
2	Beeswax + Synthetic beeswax (1:1)	105.52	13.25
2	Beeswax + Vaseline (1:1)	104.42	12.00
2	Carnauba	99.02	7.00
2	Lanolin	95.07	0.07
2	Merkur 300	104.74	1.00
2	Microcrystalline wax	108.45	34.75
2	Stearic acid	137.23	37.00
2	Sasolwax C	91.36	0.50
2	Sasolwax M3M	102.36	13.00
2	Sasolwax M3M + Ethylene maleic anhydride (3:1)	107.70	15.50
2	Soy wax	111.92	13.00
2	Synthetic beeswax	102.93	23.50
2	Tekniwax 600	106.77	37.50
2	Tekniwax 801	106.90	37.00

Block	Wax	Initial contact angle (°)	Time < 90 (min)
2	Vaseline	101.48	9.00
3	Beeswax	106.47	12.75
3	Beeswax + Ethylene maleic anhydride (3:1)	111.27	19.00
3	Beeswax + Sasolwax C (1:1)	103.13	14.00
3	Beeswax + Synthetic beeswax (1:1)	107.13	11.25
3	Beeswax + Vaseline (1:1)	105.23	10.00
3	Carnauba	101.60	11.00
3	Lanolin	106.45	0.88
3	Merkur 300	103.19	1.50
3	Microcrystalline wax	107.87	35.50
3	Stearic acid	127.17	34.25
3	Sasolwax C	101.87	2.50
3	Sasolwax M3M	103.11	14.00
3	Sasolwax M3M + Ethylene maleic anhydride (3:1)	104.76	17.25
3	Soy wax	107.68	18.75
3	Synthetic beeswax	101.30	13.00
3	Tekniwax 600	108.93	40.00
3	Tekniwax 801	108.09	12.00
3	Vaseline	104.26	10.50
4	Beeswax	103.67	10.50
4	Beeswax + Ethylene maleic anhydride (3:1)	103.52	12.25
4	Beeswax + Sasolwax C (1:1)	107.45	18.00
4	Beeswax + Synthetic beeswax (1:1)	109.17	12.00
4	Beeswax + Vaseline (1:1)	103.53	9.00
4	Carnauba	100.84	9.50
4	Lanolin	98.10	0.03
4	Merkur 300	98.90	1.00
4	Microcrystalline wax	108.01	39.50
4	Stearic acid	112.48	19.75
4	Sasolwax C	104.65	1.50
4	Sasolwax M3M	108.51	22.00
4	Sasolwax M3M + Ethylene maleic anhydride (3:1)	108.93	19.50
4	Soy wax	107.82	8.25
4	Synthetic beeswax	101.38	11.00
4	Tekniwax 600	108.87	32.50
4	Tekniwax 801	106.94	21.50
4	Vaseline	101.18	6.50
5	Beeswax	105.73	15.25
5	Beeswax + Ethylene maleic anhydride (3:1)	112.29	24.25
5	Beeswax + Sasolwax C (1:1)	108.34	22.75
5	Beeswax + Synthetic beeswax (1:1)	104.73	18.00
5	Beeswax + Vaseline (1:1)	108.92	7.50
5	Carnauba	106.48	11.00

Block	Wax	Initial contact angle (°)	Time < 90 (min)
5	Lanolin	94.32	0.02
5	Merkur 300	102.49	1.00
5	Microcrystalline wax	110.13	59.50
5	Stearic acid	108.34	22.75
5	Sasolwax C	107.66	2.00
5	Sasolwax M3M	108.55	18.00
5	Sasolwax M3M + Ethylene maleic anhydride (3:1)	113.46	20.75
5	Soy wax	105.80	20.75
5	Synthetic beeswax	101.82	11.50
5	Tekniwax 600	107.90	23.50
5	Tekniwax 801	106.85	32.00
5	Vaseline	102.83	9.00
6	Beeswax	107.13	17.00
6	Beeswax + Ethylene maleic anhydride (3:1)	112.07	19.00
6	Beeswax + Sasolwax C (1:1)	107.94	23.25
6	Beeswax + Synthetic beeswax (1:1)	110.93	19.75
6	Beeswax + Vaseline (1:1)	107.93	11.75
6	Carnauba	92.76	5.50
6	Lanolin	98.78	1.02
6	Merkur 300	104.74	1.00
6	Microcrystalline wax	109.73	52.00
6	Stearic acid	118.60	26.25
6	Sasolwax C	105.29	6.50
6	Sasolwax M3M	106.53	15.00
6	Sasolwax M3M + Ethylene maleic anhydride (3:1)	114.40	22.25
6	Soy wax	99.53	8.75
6	Synthetic beeswax	102.36	12.50
6	Tekniwax 600	108.52	21.00
6	Tekniwax 801	105.86	16.50
6	Vaseline	100.70	7.50
7	Beeswax	105.90	16.50
7	Beeswax + Ethylene maleic anhydride (3:1)	113.79	21.25
7	Beeswax + Sasolwax C (1:1)	106.06	24.25
7	Beeswax + Synthetic beeswax (1:1)	109.56	17.75
7	Beeswax + Vaseline (1:1)	107.36	26.75
7	Carnauba	96.55	5.50
7	Lanolin	101.31	0.05
7	Merkur 300	99.55	1.50
7	Microcrystalline wax	106.88	50.25
7	Stearic acid	122.36	32.00
7	Sasolwax C	93.62	0.50
7	Sasolwax M3M	103.47	14.00
7	Sasolwax M3M + Ethylene maleic anhydride (3:1)	112.47	22.25

Block	Wax	Initial contact angle (°)	Time < 90 (min)
7	Soy wax	108.98	29.25
7	Synthetic beeswax	106.35	16.50
7	Tekniwax 600	100.50	25.00
7	Tekniwax 801	107.87	32.00
7	Vaseline	98.89	6.50
8	Beeswax	107.37	16.75
8	Beeswax + Ethylene maleic anhydride (3:1)	109.24	18.00
8	Beeswax + Sasolwax C (1:1)	105.08	16.25
8	Beeswax + Synthetic beeswax (1:1)	107.86	17.50
8	Beeswax + Vaseline (1:1)	109.72	9.25
8	Carnauba	100.97	13.00
8	Lanolin	100.72	0.12
8	Merkur 300	103.02	1.50
8	Microcrystalline wax	109.00	46.25
8	Stearic acid	132.05	42.50
8	Sasolwax C	97.08	0.50
8	Sasolwax M3M	108.55	18.00
8	Sasolwax M3M + Ethylene maleic anhydride (3:1)	113.76	20.50
8	Soy wax	103.84	15.25
8	Synthetic beeswax	101.65	8.00
8	Tekniwax 600	112.45	46.25
8	Tekniwax 801	106.11	19.50
8	Vaseline	99.73	7.00
9	Beeswax	105.56	14.50
9	Beeswax + Ethylene maleic anhydride (3:1)	116.44	23.25
9	Beeswax + Sasolwax C (1:1)	102.99	23.00
9	Beeswax + Synthetic beeswax (1:1)	110.58	17.50
9	Beeswax + Vaseline (1:1)	104.21	14.50
9	Carnauba	102.54	11.50
9	Lanolin	103.66	0.33
9	Merkur 300	106.88	2.00
9	Microcrystalline wax	112.49	41.00
9	Stearic acid	133.25	38.25
9	Sasolwax C	106.19	3.50
9	Sasolwax M3M	105.09	11.00
9	Sasolwax M3M + Ethylene maleic anhydride (3:1)	107.60	15.75
9	Soy wax	110.81	19.50
9	Synthetic beeswax	102.37	9.00
9	Tekniwax 600	109.82	58.25
9	Tekniwax 801	106.49	10.50
9	Vaseline	96.77	7.50
10	Beeswax	105.02	13.00
10	Beeswax + Ethylene maleic anhydride (3:1)	107.39	15.75

Block	Wax	Initial contact angle (°)	Time < 90 (min)
10	Beeswax + Sasolwax C (1:1)	100.82	12.75
10	Beeswax + Synthetic beeswax (1:1)	110.54	18.00
10	Beeswax + Vaseline (1:1)	104.55	10.00
10	Carnauba	107.38	12.00
10	Lanolin	106.47	1.03
10	Merkur 300	103.18	2.00
10	Microcrystalline wax	110.31	34.75
10	Stearic acid	139.76	31.75
10	Sasolwax C	102.47	2.00
10	Sasolwax M3M	107.03	31.50
10	Sasolwax M3M + Ethylene maleic anhydride (3:1)	108.09	17.00
10	Soy wax	106.74	14.00
10	Synthetic beeswax	105.27	15.00
10	Tekniwax 600	106.84	29.00
10	Tekniwax 801	106.31	10.50
10	Vaseline	103.04	13.00
11	Beeswax	103.37	13.50
11	Beeswax + Ethylene maleic anhydride (3:1)	106.84	16.00
11	Beeswax + Sasolwax C (1:1)	106.43	24.75
11	Beeswax + Synthetic beeswax (1:1)	106.99	16.00
11	Beeswax + Vaseline (1:1)	104.99	12.75
11	Carnauba	102.31	11.00
11	Lanolin	101.08	0.17
11	Merkur 300	108.00	0.90
11	Microcrystalline wax	111.41	37.75
11	Stearic acid	133.02	35.75
11	Sasolwax C	105.15	5.37
11	Sasolwax M3M	109.66	29.50
11	Sasolwax M3M + Ethylene maleic anhydride (3:1)	106.99	16.00
11	Soy wax	109.29	12.50
11	Synthetic beeswax	111.38	26.75
11	Tekniwax 600	109.82	57.50
11	Tekniwax 801	110.45	28.25
11	Vaseline	113.91	17.00

Appendix Table 1.2. ANOVA table for initial contact angles of 5 µL water droplets placed on glass slides coated with different wax types (α = 0.05)

Source of variation	d.f.	Missing values	SS	MS	F	p-value
Block	10		266.8	26.68	2.07	0.029
Wax	17		6929.51	407.62	31.63	< 0.001
Residual	169	-1	2177.71	12.89		
Total	196	-1	8879.22			

Missing value: Stearic acid (Block 5)

Appendix Table 1.3. Table of means for initial contact angles of 5 µL water droplets placed on glass slides coated with different wax types (α = 0.05)

Wax	Mean initial contact angle (°)
Lanolin	100.62
Carnauba wax	100.75
Sasolwax C	101.63
Vaseline	102.14
Synthetic beeswax	103.56
Merkur 300	103.75
Beeswax + Sasolwax C (1:1)	105.02
Beeswax	105.56
Beeswax + Vaseline (1:1)	105.82
Sasolwax M3M	106.30
Soy wax	106.95
Tekniwax 801	107.16
Tekniwax 600	107.95
Beeswax + Synthetic beeswax (1:1)	107.96
Beeswax + Ethylene maleic anhydride (3:1)	109.48
Microcrystalline wax	109.54
Sasolwax M3M + Ethylene maleic anhydride (3:1)	109.74
Stearic acid	128.13
Mean	106.78
Least significant difference	3.02

Missing value: Stearic acid (Block 5)

Appendix Table 1.4. ANOVA table for the time it took 5 µL water droplets placed on glass slides coated with different wax types to form contact angles of less than 90° (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	10	655.3	65.53	2.07	0.288
Wax	17	24504	1441.41	45.61	< 0.001
Residual	170	5372.1	31.6		
Total	197	30531.4			

Appendix Table 1.5. Table of means for the time it took 5 µL water droplets placed on glass slides coated with different wax types to form contact angles of less than 90° (α = 0.05)

Wax	Time < 90° (min)
Lanolin	0.36
Merkur 300	1.35
Sasolwax C	2.31
Vaseline	9.09
Carnauba wax	9.37
Beeswax + Vaseline (1:1)	11.89
Beeswax	14.00
Synthetic beeswax	14.16
Soy wax	15.41
Beeswax + Synthetic beeswax (1:1)	15.82
Beeswax + Ethylene maleic anhydride (3:1)	17.89
Sasolwax M3M	17.91
Sasolwax M3M + Ethylene maleic anhydride (3:1)	18.55
Beeswax + Sasolwax C (1:1)	18.75
Tekniwax 801	22.02
Stearic acid	31.82
Tekniwax 600	37.28
Microcrystalline wax	42.70
Mean	16.70
Least significant difference	4.73

Appendix Table 1.6. Raw data for contact angle measurements of 5 µL water droplets placed on OSB surfaces treated with different wax types (α = 0.05)

Block	Wax	Initial contact angle (°)	Time < 90° (min)
1	Beeswax	129.00	29.78
1	Beeswax + Ethylene maleic anhydride (3:1)	118.05	22.35
1	Beeswax + Sasolwax C (1:1)	132.20	41.68
1	Beeswax + Synthetic beeswax (1:1)	115.22	22.02
1	Beeswax + Vaseline (1:1)	131.68	31.68
1	Carnauba wax	108.09	12.52
1	Lanolin	97.20	0.01
1	Merkur 300	135.37	28.85
1	Microcrystalline wax	111.24	19.53
1	Stearic acid	105.17	7.35
1	Sasolwax C	130.02	18.18
1	Sasolwax M3M	121.20	18.70
1	Sasolwax M3M + Ethylene maleic anhydride (3:1)	130.29	30.85

Block	Wax	Initial contact angle (°)	Time < 90° (min)
1	Soy wax	94.90	4.78
1	Synthetic beeswax	106.48	15.02
1	Tekniwax 600	113.88	14.85
1	Tekniwax 801	115.65	1.85
1	Untreated OSB	132.98	22.20
1	Vaseline	111.63	12.53
2	Beeswax	121.72	28.00
2	Beeswax + Ethylene maleic anhydride (3:1)	125.30	38.68
2	Beeswax + Sasolwax C (1:1)	115.94	25.85
2	Beeswax + Synthetic beeswax (1:1)	123.38	33.35
2	Beeswax + Vaseline (1:1)	118.64	23.68
2	Carnauba wax	117.00	26.18
2	Lanolin	114.67	0.35
2	Merkur 300	130.48	43.02
2	Microcrystalline wax	108.77	22.85
2	Stearic acid	126.45	21.85
2	Sasolwax C	119.15	5.18
2	Sasolwax M3M	114.75	24.52
2	Sasolwax M3M + Ethylene maleic anhydride (3:1)	115.14	25.18
2	Soy wax	112.64	20.52
2	Synthetic beeswax	120.36	30.02
2	Tekniwax 600	119.92	27.85
2	Tekniwax 801	118.63	19.18
2	Untreated OSB	102.69	0.52
2	Vaseline	116.72	21.52
3	Beeswax	132.10	10.68
3	Beeswax + Ethylene maleic anhydride (3:1)	120.09	27.35
3	Beeswax + Sasolwax C (1:1)	114.52	28.35
3	Beeswax + Synthetic beeswax (1:1)	119.33	26.18
3	Beeswax + Vaseline (1:1)	117.17	19.68
3	Carnauba wax	115.70	25.85
3	Lanolin	107.62	0.52
3	Merkur 300	117.94	12.02
3	Microcrystalline wax	117.62	25.18
3	Stearic acid	131.15	34.68
3	Sasolwax C	111.58	1.02
3	Sasolwax M3M	121.97	15.18
3	Sasolwax M3M + Ethylene maleic anhydride (3:1)	115.41	20.68
3	Soy wax	111.60	14.68
3	Synthetic beeswax	108.75	7.18
3	Tekniwax 600	129.22	28.18
3	Tekniwax 801	124.55	20.85
3	Untreated OSB	115.88	1.52

Block	Wax	Initial contact angle (°)	Time < 90° (min)
3	Vaseline	127.47	8.52
4	Beeswax	126.07	32.52
4	Beeswax + Ethylene maleic anhydride (3:1)	109.49	19.35
4	Beeswax + Sasolwax C (1:1)	118.53	17.52
4	Beeswax + Synthetic beeswax (1:1)	126.79	37.35
4	Beeswax + Vaseline (1:1)	123.04	22.18
4	Carnauba wax	127.87	37.35
4	Lanolin	126.96	0.68
4	Merkur 300	138.74	25.52
4	Microcrystalline wax	117.62	25.18
4	Stearic acid	117.28	18.35
4	Sasolwax C	120.67	2.52
4	Sasolwax M3M	119.79	30.85
4	Sasolwax M3M + Ethylene maleic anhydride (3:1)	126.92	34.68
4	Soy wax	101.12	9.85
4	Synthetic beeswax	109.01	13.18
4	Tekniwax 600	125.75	22.85
4	Tekniwax 801	125.60	16.18
4	Untreated OSB	122.59	1.35
4	Vaseline	125.79	4.68
5	Beeswax	120.67	30.35
5	Beeswax + Ethylene maleic anhydride (3:1)	110.66	22.85
5	Beeswax + Sasolwax C (1:1)	125.69	38.25
5	Beeswax + Synthetic beeswax (1:1)	123.73	39.02
5	Beeswax + Vaseline (1:1)	130.22	35.52
5	Carnauba wax	110.59	19.52
5	Lanolin	122.70	0.52
5	Merkur 300	113.60	11.52
5	Microcrystalline wax	126.51	31.18
5	Stearic acid	101.37	10.18
5	Sasolwax C	133.11	3.18
5	Sasolwax M3M	127.63	31.02
5	Sasolwax M3M + Ethylene maleic anhydride (3:1)	115.53	24.18
5	Soy wax	97.75	7.68
5	Synthetic beeswax	119.08	27.02
5	Tekniwax 600	109.35	4.68
5	Tekniwax 801	127.38	8.85
5	Untreated OSB	136.77	23.52
5	Vaseline	117.22	25.02
6	Beeswax	113.03	23.18
6	Beeswax + Ethylene maleic anhydride (3:1)	116.20	27.35
6	Beeswax + Sasolwax C (1:1)	128.34	37.52
6	Beeswax + Synthetic beeswax (1:1)	122.52	28.18

Block	Wax	Initial contact angle (°)	Time < 90° (min)
6	Beeswax + Vaseline (1:1)	113.71	17.02
6	Carnauba wax	106.79	16.85
6	Lanolin	112.31	0.85
6	Merkur 300	112.77	17.35
6	Microcrystalline wax	103.62	14.52
6	Stearic acid	108.37	16.52
6	Sasolwax C	116.92	1.52
6	Sasolwax M3M	114.91	26.85
6	Sasolwax M3M + Ethylene maleic anhydride (3:1)	115.47	21.19
6	Soy wax	111.46	21.18
6	Synthetic beeswax	118.31	27.02
6	Tekniwax 600	128.70	30.68
6	Tekniwax 801	122.27	21.68
6	Untreated OSB	100.81	0.52
6	Vaseline	112.15	16.85

Appendix Table 1.7. ANOVA table for initial contact angles of 5 μL water droplets placed on OSB surfaces treated with different wax types (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	5	488.24	97.65	1.44	0.216
Wax	18	2588.74	143.82	2.13	0.011
Residual	90	6086.52	67.63		
Total	113	9163.5			

Appendix Table 1.8. Table of means for initial contact angles of 5 µL water droplets placed on OSB surfaces treated with different wax types (α = 0.05)

Wax	Mean initial contact angle (°)
Soy wax	104.91
Lanolin	113.58
Synthetic beeswax	113.66
Microcrystalline wax	114.23
Carnauba wax	114.34
Stearic acid	114.97
Beeswax + Ethylene maleic anhydride (3:1)	116.63
Vaseline	118.50
Untreated OSB	118.62
Sasolwax M3M + Ethylene maleic anhydride (3:1)	119.79
Sasolwax M3M	120.04
Tekniwax 600	121.14
Beeswax + Synthetic beeswax (1:1)	121.83
Sasolwax C	121.91
Tekniwax 801	122.35
Beeswax + Vaseline (1:1)	122.41
Beeswax + Sasolwax C (1:1)	122.54
Beeswax	123.77
Merkur 300	124.82
Mean	118.42
Least significant difference	9.43

Appendix Table 1.9. ANOVA table for the time it took 5 µL water droplets placed on OSB surfaces treated with different wax types to form contact angles of less than 90° (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	5	370	74	1.15	0.339
Wax	18	7675.36	426.41	6.6	< 0.001
Residual	90	5812.37	64.58		
Total	113	13857.73			

Appendix Table 1.10. Table of means for the time it took 5 µL water droplets placed on OSB surfaces treated with different wax types to form contact angles of less than 90° (α = 0.05)

Wax	Mean time < 90° (min)
Lanolin	0.49
Sasolwax C	5.27
Untreated OSB	8.27
Soy wax	13.12
Tekniwax 801	14.77
Vaseline	14.85
Stearic acid	18.16
Synthetic beeswax	19.91
Tekniwax 600	21.52
Carnauba wax	23.04
Merkur 300	23.05
Microcrystalline wax	23.08
Sasolwax M3M	24.52
Beeswax + Vaseline (1:1)	24.96
Beeswax	25.75
Sasolwax M3M + Ethylene maleic anhydride (3:1)	26.13
Beeswax + Ethylene maleic anhydride (3:1)	26.32
Beeswax + Synthetic beeswax (1:1)	31.02
Beeswax + Sasolwax C (1:1)	31.53
Mean	19.78
Least significant difference	9.218

Appendix Table 1.11. Average surface roughness (R_a = arithmetic mean deviation) of 10 x 10 mm^2 areas on glass slides coated with different wax types.

Block	Wax	Ra (µm)
1	Beeswax	5.16294
1	Beeswax + Ethylene maleic anhydride (3:1)	3.94652
1	Beeswax + Sasolwax C (1:1)	4.44696
1	Beeswax + Synthetic beeswax (1:1)	6.4234
1	Beeswax + Vaseline (1:1)	3.31673
1	Carnauba	2.82196
1	Lanolin	1.81064
1	Merkur 300	5.0747
1	Microcrystalline wax	2.71587
1	Sasolwax C	17.4593
1	Sasolwax M3M	5.98865
1	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.21281
1	Soy wax	5.50108
1	Stearic acid	47.6893

Block	Wax	Ra (µm)
1	Synthetic beeswax	3.80497
1	Tekniwax 600	7.02603
1	Tekniwax 801	3.2914
1	Vaseline	6.33682
2	Beeswax	5.68171
2	Beeswax + Ethylene maleic anhydride (3:1)	4.2811
2	Beeswax + Sasolwax C (1:1)	5.11672
2	Beeswax + Synthetic beeswax (1:1)	3.29567
2	Beeswax + Vaseline (1:1)	4.20563
2	Carnauba	3.16309
2	Lanolin	1.41078
2	Merkur 300	5.01177
2	Microcrystalline wax	2.77735
2	Sasolwax C	12.616
2	Sasolwax M3M	6.093
2	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.21808
2	Soy wax	6.07501
2	Stearic acid	55.1341
2	Synthetic beeswax	4.05762
2	Tekniwax 600	39.8572
2	Tekniwax 801	4.82457
2	Vaseline	5.67487
3	Beeswax	6.61471
3	Beeswax + Ethylene maleic anhydride (3:1)	8.20241
3	Beeswax + Sasolwax C (1:1)	20.4388
3	Beeswax + Synthetic beeswax (1:1)	5.02035
3	Beeswax + Vaseline (1:1)	4.78488
3	Carnauba	2.70228
3	Lanolin	1.66666
3	Merkur 300	4.81865
3	Microcrystalline wax	3.48744
3	Sasolwax C	12.9994
3	Sasolwax M3M	5.92905
3	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.07191
3	Soy wax	9.39039
3	Stearic acid	103.733
3	Synthetic beeswax	5.06654
3	Tekniwax 600	21.5233
3	Tekniwax 801	4.22715
3	Vaseline	5.30703

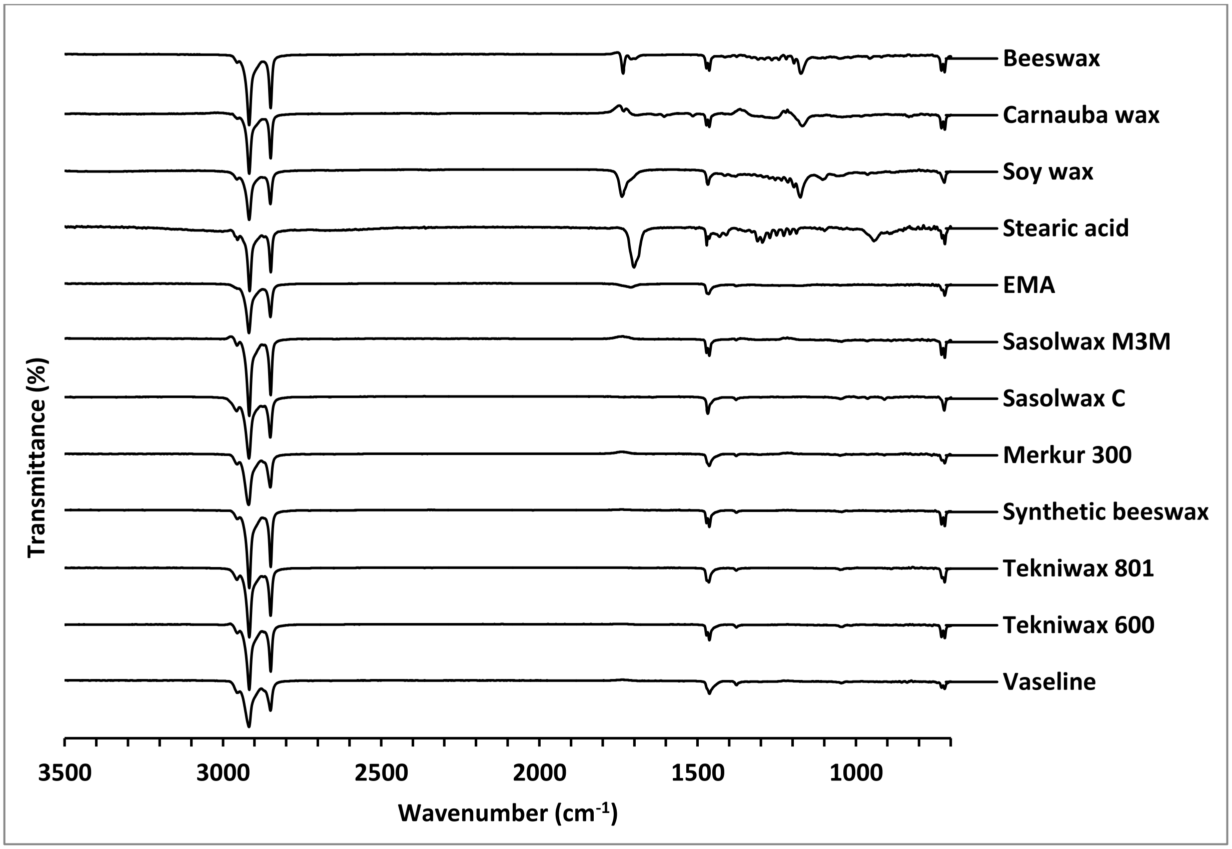
Appendix Table 1.12. ANOVA table for the natural logarithm of the average surface roughness (R_a = arithmetic mean deviation) of 10 x 10 mm^2 areas on glass slides coated with different wax types (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	2	0.75	0.38	3.48	0.0385
Wax	17	35.99	2.12	19.66	<.001
Residual	34	3.66	0.11		
Total	53	40.40			

Appendix Table 1.13. Table of means for the natural logarithm of the average surface roughness (Ra = arithmetic mean deviation) of 10 x 10 mm areas on glass slides coated with different wax types (α = 0.05)

Wax	ln(R_a)
Beeswax	1.756
Beeswax + Ethylene maleic anhydride (3:1)	1.644
Beeswax + Sasolwax C (1:1)	2.047
Beeswax + Synthetic beeswax (1:1)	1.555
Beeswax + Vaseline (1:1)	1.400
Carnauba	1.061
Lanolin	0.483
Merkur 300	1.603
Microcrystalline wax	1.090
Sasolwax C	2.653
Sasolwax M3M	1.792
Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.773
Soy wax	1.916
Stearic acid	4.172
Synthetic beeswax	1.453
Tekniwax 600	2.901
Tekniwax 801	1.402
Vaseline	1.750
Mean	1.747
Least significant difference	0.536

Appendix Figure 1.1. FTIR spectra for twelve wax types



EMA = Ethylene maleic anhydride

Appendix 2 - Chapter 4

Appendix Table 2.1. Raw data for Total thickness swelling, Half swell, and Quarter swell

Block	Control vs Treated	Wax	Quart swell (h)	Half swell (h)	Total thickness swelling (mm)
1	treated	Beeswax	144.9	247.9	2.4
1	treated	Carnauba	57.6	126.5	3.4
1	control	Control	44.0	91.3	2.9
1	treated	Lanolin	79.7	152.5	3.4
1	treated	Sasolwax M3M	69.1	129.2	3.7
1	treated	Sasolwax C	94.9	182.0	2.7
1	treated	Tekniwax 600	169.8	276.0	2.2
1	treated	Vaseline	130.2	213.0	3.0
2	treated	Beeswax	207.8	320.7	1.7
2	treated	Carnauba	66.1	161.3	2.7
2	control	Control	52.8	92.6	2.9
2	treated	Lanolin	50.0	162.4	2.7
2	treated	Sasolwax M3M	138.4	236.0	3.1
2	treated	Sasolwax C	47.7	114.3	2.5
2	treated	Tekniwax 600	48.0	142.3	2.4
2	treated	Vaseline	71.5	219.1	2.6
3	treated	Beeswax	247.0	353.8	2.0
3	treated	Carnauba	88.7	150.3	3.1
3	control	Control	68.8	128.1	3.4
3	treated	Lanolin	25.6	111.0	3.1
3	treated	Sasolwax M3M	65.3	148.4	2.8
3	treated	Sasolwax C	179.7	376.4	2.0
3	treated	Tekniwax 600	245.2	374.3	1.5
3	treated	Vaseline	206.4	296.1	2.7
4	treated	Beeswax	116.2	242.1	1.3
4	treated	Carnauba	79.5	167.9	2.1
4	control	Control	28.1	143.8	2.1
4	treated	Lanolin	21.5	41.2	1.6
4	treated	Sasolwax M3M	114.0	246.7	2.5
4	treated	Sasolwax C	105.9	207.8	2.9
4	treated	Tekniwax 600	58.1	131.2	3.1
4	treated	Vaseline	262.6	340.2	3.0
5	treated	Beeswax	101.8	206.0	1.8
5	treated	Carnauba	61.8	132.5	2.9
5	control	Control	51.3	112.9	3.0
5	treated	Lanolin	62.3	146.7	2.7
5	treated	Sasolwax M3M	66.3	151.7	3.0
5	treated	Sasolwax C	59.6	135.2	2.5

Block	Control vs Treated	Wax	Quart swell (h)	Half swell (h)	Total thickness swelling (mm)
5	treated	Tekniwax 600	84.6	214.7	2.8
5	treated	Vaseline	133.3	222.9	2.4
6	treated	Beeswax	71.5	150.6	3.3
6	treated	Carnauba	61.2	113.5	3.5
6	control	Control	21.2	61.4	2.7
6	treated	Lanolin	54.3	99.6	3.2
6	treated	Sasolwax M3M	39.6	87.8	3.6
6	treated	Sasolwax C	57.4	138.0	2.9
6	treated	Tekniwax 600	54.6	117.2	3.1
6	treated	Vaseline	48.0	92.1	2.8
7	treated	Beeswax	88.7	202.2	3.2
7	treated	Carnauba	34.5	82.0	2.2
7	control	Control	41.7	91.4	2.2
7	treated	Lanolin	71.5	206.7	1.8
7	treated	Sasolwax M3M	50.5	145.4	2.5
7	treated	Sasolwax C	53.3	124.3	2.7
7	treated	Tekniwax 600	41.7	100.0	2.7
7	treated	Vaseline	92.8	162.7	2.4

Appendix Table 2.2. ANOVA table for Total thickness swelling (α = 0.05)

Source of variation	d.f.	Missing values	SS	MS	F	p-value
Block	6		4.7818	0.797	4.66	0.0009
Control vs Treated	1		0.0509	0.0509	0.3	0.589
Wax type vs wax type	6		4.1442	0.6907	4.04	0.003
Residual	40	-2	6.843	0.1711		
Total	53	-2	14.7057			

Missing value: Beeswax (block 6); Tekniwax 600 (block 1)

Appendix Table 2.3. ANOVA table for Time to half swell (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	85197	14199	4.18	0.0019
Control vs Treated	1	37839	37839	11.15	0.002
Wax type vs wax type	6	77119	12853	3.79	0.004
Residual	42	142588	3395		
Total	55	342743			

Appendix Table 2.4. ANOVA table for Time to quarter swell (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	42536	7089	3.68	0.0044
Control vs Treated	1	15007	15007	7.8	0.008
Wax type vs wax type	6	47514	7919	4.12	0.002
Residual	42	80817	1924		
Total	55	185874			

Appendix Table 2.5. Table of means for Total thickness swelling, Half swell, and Quarter swell (α = 0.05)

Wax	Half swell (h)	Quarter swell (h)	Total thickness swell (mm)
Beeswax	246.2	139.7	2.03
Carnauba	133.4	64.2	2.84
Control	103.1	44	2.74
Lanolin	131.4	52.1	2.66
Sasolwax M3M	163.6	77.6	3.04
Sasolwax C	182.6	85.5	2.59
Tekniwax 600	193.6	100.3	2.73
Vaseline	220.9	135	2.68
Mean	171.85	87.3	2.743
Least significant difference	62.85	47.32	0.4468

Appendix Table 2.6. Raw data for thickness swelling

Block	Control vs Treated	Wax	2 h	24 h	72 h	240 h	480 h
1	treated	Beeswax	0.001	0.002	0.186	1.156	2.324
1	treated	Carnauba	0.007	0.328	1.049	2.737	3.407
1	control	Control	0.091	0.378	1.153	2.506	2.889
1	treated	Lanolin	0.007	0.199	0.765	2.498	3.344
1	treated	Sasolwax M3M	0.002	0.400	0.968	2.928	3.674
1	treated	Sasolwax C	0.020	0.173	0.465	1.764	2.641
1	treated	Tekniwax 600	-0.012	-0.020	0.040	0.905	2.113
1	treated	Vaseline	-0.002	0.033	0.284	1.712	2.893
2	treated	Beeswax	0.004	-0.001	0.028	0.565	1.586
2	treated	Carnauba	0.003	0.262	0.724	1.900	2.650
2	control	Control	0.056	0.364	1.042	2.625	2.917
2	treated	Lanolin	0.040	0.416	0.836	1.726	2.639
2	treated	Sasolwax M3M	0.002	-0.083	0.339	1.589	3.026
2	treated	Sasolwax C	0.028	0.381	0.841	2.133	2.527

Block	Control vs Treated	Wax	2 h	24 h	72 h	240 h	480 h
2	treated	Tekniwax 600	0.014	0.381	0.762	1.844	2.349
2	treated	Vaseline	0.072	0.401	0.655	1.390	2.522
3	treated	Beeswax	-0.003	-0.005	0.014	0.483	1.592
3	treated	Carnauba	0.020	0.155	0.557	2.257	2.979
3	control	Control	0.071	0.363	0.895	2.696	3.248
3	treated	Lanolin	0.102	0.772	1.281	2.468	3.033
3	treated	Sasolwax M3M	-0.002	0.189	0.762	2.218	2.730
3	treated	Sasolwax C	0.003	-0.012	0.154	0.662	1.568
3	treated	Tekniwax 600	-0.003	-0.012	0.019	0.365	1.083
3	treated	Vaseline	-0.003	-0.006	-0.020	0.964	2.204
4	treated	Beeswax	0.000	-0.027	0.174	0.627	1.145
4	treated	Carnauba	-0.001	0.128	0.480	1.413	2.022
4	control	Control	0.024	0.503	0.781	1.565	2.127
4	treated	Lanolin	-0.006	0.450	1.103	1.254	1.572
4	treated	Sasolwax M3M	-0.001	0.048	0.411	1.224	2.381
4	treated	Sasolwax C	0.007	0.290	0.580	1.891	2.850
4	treated	Tekniwax 600	0.001	0.208	1.003	2.227	3.028
4	treated	Vaseline	0.005	-0.017	-0.034	0.607	2.868
5	treated	Beeswax	-0.008	0.010	0.314	1.056	1.775
5	treated	Carnauba	0.003	0.142	0.825	2.418	2.912
5	control	Control	0.033	0.247	1.043	2.321	2.915
5	treated	Lanolin	-0.008	0.113	0.790	1.914	2.686
5	treated	Sasolwax M3M	0.002	0.189	0.818	2.233	3.025
5	treated	Sasolwax C	0.013	0.251	0.764	1.798	2.444
5	treated	Tekniwax 600	-0.004	0.139	0.620	1.601	2.731
5	treated	Vaseline	0.001	0.001	0.239	1.327	2.318
6	treated	Beeswax	0.039	0.336	0.834	2.446	3.259
6	treated	Carnauba	0.028	0.324	1.134	2.862	3.442
6	control	Control	0.089	0.723	1.480	2.431	2.648
6	treated	Lanolin	-0.003	0.374	1.131	2.792	3.199
6	treated	Sasolwax M3M	0.009	0.556	1.555	2.990	3.606
6	treated	Sasolwax C	0.000	0.273	0.864	2.103	2.818
6	treated	Tekniwax 600	0.034	0.396	0.973	2.644	3.096
6	treated	Vaseline	0.010	0.354	1.089	2.248	2.742
7	treated	Beeswax	0.031	0.290	0.685	1.928	3.154
7	treated	Carnauba	0.018	0.405	0.967	1.840	2.143
7	control	Control	0.031	0.318	0.875	1.862	2.200
7	treated	Lanolin	0.054	0.267	0.458	0.946	1.779
7	treated	Sasolwax M3M	0.049	0.390	0.777	1.697	2.441
7	treated	Sasolwax C	0.008	0.215	0.877	2.079	2.656
7	treated	Tekniwax 600	0.013	0.413	1.037	2.209	2.676
7	treated	Vaseline	-0.003	0.099	0.442	1.756	2.394

Appendix Table 2.7. ANOVA for 2 h thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	0.005153	0.000859	1.74	0.1321
Control vs Treated	1	0.012	0.012	24.26	< 0.001
Wax type vs wax type	6	0.001903	0.000317	0.64	0.697
Residual	42	0.020777	0.000495		
Total	55	0.039834			

Appendix Table 2.8. ANOVA for 24 h thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	0.43565	0.07261	3.07	0.0127
Control vs Treated	1	0.2397	0.2397	10.14	0.003
Wax type vs wax type	6	0.35646	0.05941	2.51	0.036
Residual	42	0.99256	0.02363		
Total	55	2.02438			

Appendix Table 2.9. ANOVA for 72 h thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	2.23085	0.37181	5.13	0.0004
Control vs Treated	1	0.94584	0.94584	13.06	<.001
Wax type vs wax type	6	2.11718	0.35286	4.87	<.001
Residual	42	3.04179	0.07242		
Total	55	8.33567			

Appendix Table 2.10. ANOVA for 240 h thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	7.3652	1.2275	4.53	0.001
Control vs Treated	1	1.6795	1.6795	6.2	0.017
Wax type vs wax type	6	5.7088	0.9515	3.51	0.007
Residual	42	11.3851	0.2711		
Total	55	26.1386			

Appendix Table 2.11. ANOVA for 480 h thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	4.7316	0.7886	2.98	0.0149
Control vs Treated	1	0.1098	0.1098	0.42	0.523
Wax type vs wax type	6	3.1287	0.5215	1.97	0.091
Residual	42	11.1003	0.2643		
Total	55	19.0705			

Appendix Table 2.12. Table of means for thickness swelling (α = 0.05)

Wax	2 h	24 h	72 h	240 h	480 h
Beeswax	0.01	0.09	0.32	1.18	2.12
Carnauba	0.01	0.25	0.82	2.20	2.79
Control	0.06	0.41	1.04	2.29	2.71
Lanolin	0.03	0.37	0.91	1.94	2.61
Sasolwax M3M	0.01	0.24	0.80	2.13	2.98
Sasolwax C	0.01	0.22	0.65	1.78	2.50
Tekniwax 600	0.01	0.22	0.64	1.69	2.44
Vaseline	0.01	0.12	0.38	1.43	2.56
Mean	0.02	0.24	0.69	1.83	2.59
Least significant difference	0.024	0.166	0.290	0.278	0.554

Appendix 3 - Chapter 5

Appendix Table 3.1. Raw data for oven dry mass, oven dry thickness, and initial moisture content of untreated and wax-treated OSB samples.

Block	Wax	Oven dry mass (g)	Oven dry thickness (mm)	Spread rate (g / m^2)	Initial moisture content (%)
1	Beeswax	240.00	18.48	118.7	8.80
1	Beeswax + Ethylene maleic anhydride (3:1)	242.38	18.54	96.4	8.10
1	Beeswax + Sasolwax C (1:1)	254.87	18.58	84.4	7.59
1	Beeswax + Synthetic beeswax (1:1)	255.07	18.59	131.1	7.36
1	Beeswax + Vaseline (1:1)	237.30	18.53	138.2	8.20
1	Carnauba	232.01	18.53	104.4	8.97
1	Control	245.56	18.72	0.0	7.73
1	Sasolwax M3M	239.39	18.62	133.3	8.36
1	Sasolwax M3M + Ethylene maleic anhydride (3:1)	247.20	18.76	96.4	8.45
1	Merkur 300	251.03	18.66	99.6	8.50
1	Microcrystalline	242.18	18.45	93.3	7.43
1	Stearic acid	235.03	18.65	129.3	8.86
1	Sasolwax C	233.43	18.57	124.4	9.24
1	Soy wax	236.59	18.76	90.2	8.76
1	Synthetic beeswax	240.73	18.59	128.9	8.59
1	Tekniwax 801	246.40	18.48	100.9	8.50
1	Vaseline	239.85	18.53	129.8	8.60
2	Beeswax	239.78	18.59	89.8	6.78
2	Beeswax + Ethylene maleic anhydride (3:1)	237.10	18.73	105.3	6.43
2	Beeswax + Sasolwax C (1:1)	236.77	18.72	96.0	6.81
2	Beeswax + Synthetic beeswax (1:1)	237.16	18.68	89.8	6.92
2	Beeswax + Vaseline (1:1)	237.46	18.48	66.2	7.05
2	Carnauba	237.46	18.62	67.6	7.09
2	Control	238.62	18.42	0.0	7.40
2	Sasolwax M3M	239.10	18.73	67.1	7.15
2	Sasolwax M3M + Ethylene maleic anhydride (3:1)	246.52	18.40	65.3	6.82
2	Merkur 300	241.43	18.40	69.8	6.58
2	Microcrystalline	242.40	18.86	80.9	6.82
2	Stearic acid	243.50	18.49	75.6	7.27
2	Sasolwax C	239.91	18.82	83.6	7.04
2	Soy wax	239.48	18.47	83.6	7.29
2	Synthetic beeswax	237.09	18.55	73.3	6.77
2	Tekniwax 801	240.94	18.86	72.4	6.99
2	Vaseline	242.42	18.52	74.7	6.81
3	Beeswax	254.14	19.23	85.8	6.55
3	Beeswax + Ethylene maleic anhydride (3:1)	251.87	19.27	81.3	7.41

Block	Wax	Oven dry mass (g)	Oven dry thickness (mm)	Spread rate (g / m^2)	Initial moisture content (%)
3	Beeswax + Sasolwax C (1:1)	253.77	19.19	68.9	7.00
3	Beeswax + Synthetic beeswax (1:1)	258.66	19.17	69.3	6.47
3	Beeswax + Vaseline (1:1)	258.48	19.34	72.0	6.79
3	Carnauba	257.28	19.25	79.6	6.84
3	Control	256.70	19.21	0.0	6.93
3	Sasolwax M3M	255.04	19.10	67.6	6.85
3	Sasolwax M3M + Ethylene maleic anhydride (3:1)	261.85	19.25	74.2	6.71
3	Merkur 300	253.96	19.30	71.6	6.97
3	Microcrystalline	260.93	19.20	70.2	6.45
3	Stearic acid	258.70	19.23	89.3	7.09
3	Sasolwax C	258.55	19.15	80.0	6.60
3	Soy wax	267.38	19.29	84.9	6.84
3	Synthetic beeswax	253.65	19.25	70.7	7.03
3	Tekniwax 801	261.30	19.43	66.7	6.56
3	Vaseline	256.48	19.45	79.1	7.85
4	Beeswax	251.47	19.46	70.7	7.08
4	Beeswax + Ethylene maleic anhydride (3:1)	259.10	19.54	95.1	6.61
4	Beeswax + Sasolwax C (1:1)	265.55	19.22	94.7	6.42
4	Beeswax + Synthetic beeswax (1:1)	259.29	19.59	89.3	6.67
4	Beeswax + Vaseline (1:1)	261.27	19.47	84.0	6.67
4	Carnauba	259.71	19.12	60.0	7.18
4	Control	253.40	19.40	0.0	7.35
4	Sasolwax M3M	249.02	19.43	70.2	7.30
4	Sasolwax M3M + Ethylene maleic anhydride (3:1)	259.47	19.21	95.6	6.59
4	Merkur 300	254.10	19.02	82.7	6.78
4	Microcrystalline	270.09	19.11	77.3	6.27
4	Stearic acid	259.89	19.12	79.6	7.17
4	Sasolwax C	253.08	19.09	64.0	7.02
4	Soy wax	256.66	19.11	95.6	6.74
4	Synthetic beeswax	254.48	18.99	68.0	5.80
4	Tekniwax 801	260.19	18.86	76.0	6.64
4	Vaseline	264.41	19.04	76.9	6.88
5	Beeswax	252.21	18.40	79.1	5.24
5	Beeswax + Ethylene maleic anhydride (3:1)	247.72	18.37	83.6	5.07
5	Beeswax + Sasolwax C (1:1)	254.05	18.25	77.3	4.86
5	Beeswax + Synthetic beeswax (1:1)	247.81	18.37	66.7	5.09
5	Beeswax + Vaseline (1:1)	252.90	18.24	72.4	5.00
5	Carnauba	246.44	18.00	74.2	5.19
5	Control	245.20	18.59	0.0	6.15
5	Sasolwax M3M	249.15	17.88	64.4	4.66
5	Sasolwax M3M + Ethylene maleic anhydride (3:1)	246.44	17.75	66.7	5.37

Block	Wax	Oven dry mass (g)	Oven dry thickness (mm)	Spread rate (g / m^2)	Initial moisture content (%)
5	Merkur 300	246.64	18.03	66.2	5.01
5	Microcrystalline	253.10	18.17	81.8	4.75
5	Stearic acid	245.28	17.87	100.4	5.29
5	Sasolwax C	251.61	18.34	66.7	5.66
5	Soy wax	248.89	18.37	63.6	5.36
5	Synthetic beeswax	250.55	18.51	71.1	5.34
5	Tekniwax 801	253.39	17.83	65.8	4.95
5	Vaseline	245.19	18.03	99.6	4.79
6	Beeswax	266.99	18.63	55.6	4.50
6	Beeswax + Ethylene maleic anhydride (3:1)	264.25	18.59	46.7	4.82
6	Beeswax + Sasolwax C (1:1)	257.43	18.76	64.4	5.13
6	Beeswax + Synthetic beeswax (1:1)	261.88	18.53	61.3	4.77
6	Beeswax + Vaseline (1:1)	265.10	18.97	66.2	4.80
6	Carnauba	260.25	18.71	45.3	5.22
6	Control	261.91	18.70	0.0	5.19
6	Sasolwax M3M	257.47	18.62	50.2	5.15
6	Sasolwax M3M + Ethylene maleic anhydride (3:1)	259.30	18.67	72.0	4.64
6	Merkur 300	262.34	18.79	53.3	5.02
6	Microcrystalline	259.91	18.49	46.7	4.83
6	Stearic acid	261.11	18.66	69.8	4.99
6	Sasolwax C	257.88	18.70	60.0	5.00
6	Soy wax	259.73	18.67	57.3	5.14
6	Synthetic beeswax	259.84	18.55	63.1	4.89
6	Tekniwax 801	259.44	18.48	56.4	4.81
6	Vaseline	264.74	18.61	57.8	4.95
7	Beeswax	253.27	18.71	58.2	4.48
7	Beeswax + Ethylene maleic anhydride (3:1)	257.45	18.85	62.2	4.01
7	Beeswax + Sasolwax C (1:1)	253.43	18.74	45.8	4.50
7	Beeswax + Synthetic beeswax (1:1)	250.29	18.69	55.6	4.43
7	Beeswax + Vaseline (1:1)	256.13	18.65	51.1	4.32
7	Carnauba	255.12	18.71	49.3	4.55
7	Control	252.52	18.64	0.0	4.41
7	Sasolwax M3M	254.66	18.71	53.8	4.42
7	Sasolwax M3M + Ethylene maleic anhydride (3:1)	252.10	18.65	59.1	4.19
7	Merkur 300	251.55	18.67	49.8	4.45
7	Microcrystalline	250.59	18.57	56.9	4.37
7	Stearic acid	257.23	18.80	47.1	4.49
7	Sasolwax C	257.19	18.74	54.2	4.28
7	Soy wax	251.67	18.85	54.7	4.42
7	Synthetic beeswax	253.27	18.70	50.7	4.12
7	Tekniwax 801	254.14	18.71	66.7	4.15

Block	Wax	Oven dry mass (g)	Oven dry thickness (mm)	Spread rate (g / m^2)	Initial moisture content (%)
7	Vaseline	252.28	18.57	54.2	4.54

Appendix Table 3.2. ANOVA table for the oven dried mass of OSB samples (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	6918	1153	64.83	< 0.0001
Wax	16	255.88	15.99	0.9	0.572
Residual	96	1707.25	17.78		
Total	118	8881.13			

Appendix Table 3.3. ANOVA table for the oven dried thickness of OSB samples (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	14.662	2.444	97.22	< 0.0001
Wax	16	0.379	0.024	0.94	0.524
Residual	96	2.413	0.025		
Total	118	17.454			

Appendix Table 3.4. ANOVA table for mass of wax applied on the 15 x 15 cm^2 surface of OSB samples (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	17.42979	2.90496	45.79	< 0.0001
Wax	15	1.06429	0.07095	1.12	0.352
Residual	90	5.70953	0.06344		
Total	111	24.20361			

Appendix Table 3.5. ANOVA table for the initial moisture content of OSB samples (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	204.9809	34.1635	335.96	< 0.0001
Wax	16	3.8227	0.2389	2.35	0.006
Residual	96	9.7623	0.1017		
Total	118	218.5659			

Appendix Table 3.6. Table of means for the oven dry mass, oven dry thickness, spread rate, and initial moisture content of untreated and wax-treated OSB samples (α = 0.05)

Wax	Oven dry mass (g)	Oven dry thickness (mm)	Spread rate (g / m^2)	Initial moisture condition (%)
Beeswax	251.12	18.78	275.7	6.20
Beeswax + Ethylene maleic anhydride (3:1)	251.41	18.84	269.6	6.07
Beeswax + Sasolwax C (1:1)	253.70	18.78	268.6	6.04
Beeswax + Synthetic beeswax (1:1)	252.88	18.80	264.8	5.96
Beeswax + Vaseline (1:1)	252.66	18.81	272.0	6.12
Carnauba	249.75	18.71	286.0	6.43
Control	250.56	18.81	286.8	6.45
Sasolwax M3M	249.12	18.73	278.6	6.27
Sasolwax M3M + Ethylene maleic anhydride (3:1)	253.27	18.67	271.6	6.11
Merkur 300	251.58	18.70	275.0	6.19
Microcrystalline	254.17	18.69	259.8	5.85
Stearic acid	251.53	18.69	286.8	6.45
Sasolwax C	250.24	18.77	284.8	6.41
Soy wax	251.49	18.79	282.8	6.36
Synthetic beeswax	249.94	18.73	270.1	6.08
Tekniwax 801	253.69	18.66	270.5	6.09
Vaseline	252.20	18.68	282.0	6.35
Mean	251.72	18.74	275.6	6.20
Least significant difference	4.51	0.17	15.2	0.34

Appendix Table 3.7. Raw data for water absorption of untreated and wax-treated OSB samples

Block	Control vs. Treated	Wax	Water absorption (mL)			
			2 h	24 h	48 h	72 h
1	treated	Beeswax	0.680	13.440	32.420	54.610
1	treated	Beeswax + Ethylene maleic anhydride (3:1)	4.150	24.430	46.470	73.660
1	treated	Beeswax + Sasolwax C (1:1)	4.270	17.280	30.480	44.900
1	treated	Beeswax + Synthetic beeswax (1:1)	0.720	7.010	15.390	25.820
1	treated	Beeswax + Vaseline (1:1)	1.450	14.500	34.260	60.230
1	treated	Carnauba	2.560	16.660	28.730	40.570
1	control	Control	7.000	28.440	49.430	71.270
1	treated	Sasolwax M3M	1.540	14.370	28.540	42.710
1	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.740	18.410	31.760	43.850
1	treated	Merkur 300	2.310	14.520	26.170	38.160
1	treated	Microcrystalline	3.360	23.820	43.720	66.580
1	treated	Stearic acid	2.380	10.620	16.740	24.150
1	treated	Sasolwax C	7.600	34.460	60.160	80.400
1	treated	Soy wax	4.690	19.710	34.330	48.790
1	treated	Synthetic beeswax	1.700	14.640	30.290	50.310
1	treated	Tekniwax 801	2.620	14.370	25.570	40.910
1	treated	Vaseline	2.070	19.990	44.180	70.380
1	control	“moisture resistant”	5.040	12.750	18.650	25.230
2	treated	Beeswax	1.940	10.740	21.190	31.880
2	treated	Beeswax + Ethylene maleic anhydride (3:1)	1.800	15.880	31.730	47.860
2	treated	Beeswax + Sasolwax C (1:1)	2.790	19.940	35.610	49.970
2	treated	Beeswax + Synthetic beeswax (1:1)	1.920	11.210	22.890	34.730
2	treated	Beeswax + Vaseline (1:1)	1.440	11.380	25.770	42.480
2	treated	Carnauba	2.060	12.500	23.700	34.600
2	control	Control	5.610	20.060	33.490	46.300
2	treated	Sasolwax M3M	3.240	17.250	30.190	43.380
2	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.590	17.310	31.640	45.590
2	treated	Merkur 300	3.970	19.570	34.560	47.660
2	treated	Microcrystalline	1.670	12.610	25.300	41.330
2	treated	Stearic acid	2.480	12.290	23.880	35.310
2	treated	Sasolwax C	5.790	20.980	33.620	44.310
2	treated	Soy wax	4.770	20.580	34.890	50.450
2	treated	Synthetic beeswax	1.910	9.990	20.700	32.380
2	treated	Tekniwax 801	3.820	19.390	32.600	44.400
2	treated	Vaseline	2.540	13.870	26.420	39.300
2	control	“moisture resistant”	4.530	14.730	23.040	30.630
3	treated	Beeswax	2.950	11.700	21.350	33.010
3	treated	Beeswax + Ethylene maleic anhydride (3:1)	2.760	13.950	27.230	39.960
3	treated	Beeswax + Sasolwax C (1:1)	4.600	15.500	25.220	34.510
3	treated	Beeswax + Synthetic beeswax (1:1)	1.550	7.980	16.150	24.420

Block	Control vs. Treated	Wax	Water absorption (mL)			
			2 h	24 h	48 h	72 h
3	treated	Beeswax + Vaseline (1:1)	2.240	9.400	18.910	28.340
3	treated	Carnauba	3.710	14.850	28.170	44.290
3	control	Control	6.710	18.270	28.540	37.110
3	treated	Sasolwax M3M	6.240	19.070	30.750	42.320
3	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	4.920	18.340	30.140	41.940
3	treated	Merkur 300	7.190	20.690	32.460	45.570
3	treated	Microcrystalline	3.030	12.630	24.480	36.600
3	treated	Stearic acid	5.500	16.930	26.020	34.710
3	treated	Sasolwax C	6.870	17.910	28.150	38.530
3	treated	Soy wax	8.940	23.220	34.840	44.960
3	treated	Synthetic beeswax	3.360	14.400	26.390	38.540
3	treated	Tekniwax 801	4.960	16.430	28.290	39.610
3	treated	Vaseline	4.770	15.830	26.310	35.890
3	control	“moisture resistant”	3.860	10.900	16.230	20.680
4	treated	Beeswax	2.860	13.820	31.130	53.200
4	treated	Beeswax + Ethylene maleic anhydride (3:1)	2.050	10.740	22.700	37.560
4	treated	Beeswax + Sasolwax C (1:1)	4.620	19.050	34.050	51.350
4	treated	Beeswax + Synthetic beeswax (1:1)	3.070	12.700	25.520	42.260
4	treated	Beeswax + Vaseline (1:1)	1.860	10.210	22.260	39.410
4	treated	Carnauba	3.380	14.900	28.750	45.760
4	control	Control	6.410	17.850	31.800	51.180
4	treated	Sasolwax M3M	4.520	17.310	30.810	45.650
4	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.870	16.860	34.350	54.510
4	treated	Merkur 300	5.380	18.540	30.330	45.670
4	treated	Microcrystalline	2.700	11.910	21.460	33.340
4	treated	Stearic acid	5.460	20.790	38.230	57.340
4	treated	Sasolwax C	6.060	17.430	27.720	38.140
4	treated	Soy wax	6.070	21.980	39.580	64.190
4	treated	Synthetic beeswax	2.000	11.590	23.390	41.520
4	treated	Tekniwax 801	4.510	16.340	31.160	47.600
4	treated	Vaseline	3.600	12.850	22.920	34.860
4	control	“moisture resistant”	7.040	17.600	26.510	33.910
5	treated	Beeswax	1.970	11.050	22.380	40.660
5	treated	Beeswax + Ethylene maleic anhydride (3:1)	1.460	12.400	28.350	53.740
5	treated	Beeswax + Sasolwax C (1:1)	5.520	23.240	42.600	71.540
5	treated	Beeswax + Synthetic beeswax (1:1)	2.850	17.070	36.120	62.480
5	treated	Beeswax + Vaseline (1:1)	1.850	12.330	29.200	58.240
5	treated	Carnauba	1.950	18.540	36.120	59.340
5	control	Control	6.520	28.420	49.310	80.610
5	treated	Sasolwax M3M	3.440	18.520	33.510	56.130
5	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	4.510	24.030	44.170	73.360

Block	Control vs. Treated	Wax	Water absorption (mL)			
			2 h	24 h	48 h	72 h
5	treated	Merkur 300	5.700	23.690	41.450	64.060
5	treated	Microcrystalline	2.190	11.660	22.470	36.820
5	treated	Stearic acid	3.880	18.020	31.810	52.390
5	treated	Sasolwax C	5.600	24.400	44.360	71.590
5	treated	Soy wax	5.840	25.060	45.740	70.500
5	treated	Synthetic beeswax	2.130	20.580	42.640	77.350
5	treated	Tekniwax 801	4.330	18.480	31.590	46.760
5	treated	Vaseline	3.200	16.420	37.230	72.580
5	control	“moisture resistant”	4.900	16.580	24.470	32.470
6	treated	Beeswax	3.710	16.820	30.220	45.510
6	treated	Beeswax + Ethylene maleic anhydride (3:1)	3.290	14.490	24.310	35.200
6	treated	Beeswax + Sasolwax C (1:1)	3.820	15.080	25.460	35.450
6	treated	Beeswax + Synthetic beeswax (1:1)	3.340	13.870	24.000	36.540
6	treated	Beeswax + Vaseline (1:1)	2.670	11.440	19.930	29.480
6	treated	Carnauba	2.950	13.680	23.670	36.080
6	control	Control	7.850	22.310	34.100	46.390
6	treated	Sasolwax M3M	4.440	18.590	31.430	45.880
6	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.790	14.200	24.910	37.460
6	treated	Merkur 300	5.100	17.010	25.700	33.610
6	treated	Microcrystalline	3.090	14.130	24.530	34.970
6	treated	Stearic acid	4.050	13.400	20.840	29.080
6	treated	Sasolwax C	8.460	24.230	37.650	52.040
6	treated	Soy wax	5.710	18.200	28.240	39.120
6	treated	Synthetic beeswax	3.840	15.450	24.970	35.470
6	treated	Tekniwax 801	4.530	16.930	27.630	38.920
6	treated	Vaseline	5.110	18.070	28.950	40.230
6	control	“moisture resistant”	4.680	15.880	29.460	43.500
7	treated	Beeswax	3.070	21.350	49.630	79.320
7	treated	Beeswax + Ethylene maleic anhydride (3:1)	2.500	11.550	22.220	36.120
7	treated	Beeswax + Sasolwax C (1:1)	2.460	15.560	31.810	50.120
7	treated	Beeswax + Synthetic beeswax (1:1)	2.400	12.260	23.020	33.520
7	treated	Beeswax + Vaseline (1:1)	2.380	11.740	22.710	36.390
7	treated	Carnauba	2.740	15.550	28.940	44.050
7	control	Control	4.710	17.770	28.730	41.700
7	treated	Sasolwax M3M	4.100	22.160	39.890	60.880
7	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	2.640	17.350	33.260	53.080
7	treated	Merkur 300	6.017	25.637	43.987	63.837
7	treated	Microcrystalline	2.750	15.050	27.600	42.450
7	treated	Stearic acid	3.210	13.190	22.560	32.930
7	treated	Sasolwax C	5.020	20.030	34.120	48.340
7	treated	Soy wax	5.680	22.690	37.780	55.010

Block	Control vs. Treated	Wax	Water absorption (mL) 2 h	24 h	48 h	72 h
7	treated	Synthetic beeswax	2.580	15.920	30.680	49.480
7	treated	Tekniwax 801	3.440	16.480	32.020	49.610
7	treated	Vaseline	3.440	17.250	31.370	45.300
7	control	“moisture resistant”	3.460	11.810	19.360	25.600

Appendix Table 3.8. ANOVA table for water absorption of untreated and wax-treated samples after 2 h (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	44.2324	7.3721	10.16	< 0.001
Control vs Treated	1	52.1282	52.1282	71.84	< 0.001
Wax type vs wax type	15	183.7183	12.2479	16.88	< 0.001
Residual	96	69.6575	0.7256		
Total	118	8881.13			

Appendix Table 3.9. ANOVA table for water absorption of “moisture resistant” and wax-treated samples after 2 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		41.3926	6.8988	8.86	< 0.0001
Huber vs Treated	1		9.6175	9.6175	12.35	< 0.001
Wax type vs wax type	15		186.3194	12.4213	15.95	< 0.001
Residual	95	-1	73.9632	0.7786		
Total	117	-1	308.5205			

Missing value: Beeswax (Block 7)

Appendix Table 3.10. ANOVA table for water absorption of untreated and wax-treated samples after 24 h (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	187.04	31.17	2.87	0.0123
Control vs Treated	1	192.56	192.56	17.71	< 0.001
Wax type vs wax type	15	1063.08	70.87	6.52	< 0.001
Residual	96	1044	10.88		
Total	118	2486.68			

*”moisture resistant” excluded

Appendix Table 3.11. ANOVA table for water absorption of "moisture resistant" and wax-treated samples after 24 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		128.706	21.451	2.16	0.052
Huber vs Treated	1		28.278	28.278	2.84	0.095
Wax type vs wax type	15		1111.656	74.11	7.45	< 0.001
Residual	95	-1	945.01	9.947		
Total	117	-1	2202.647			

Missing value: Beeswax (Block 7)

Appendix Table 3.12. ANOVA table for water absorption of untreated and wax-treated samples after 48 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		1362.67	227.11	6.44	< 0.001
Control vs Treated	1		281.86	281.86	7.99	0.006
Wax type vs wax type	15		1786.63	119.11	3.38	< 0.001
Residual	95	-1	3350.15	35.26		
Total	117	-1	6767			

Missing value: Beeswax (Block 7)
*"moisture resistant" excluded

Appendix Table 3.13. ANOVA table for water absorption of "moisture resistant" and wax-treated samples after 48 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		1033.93	172.32	4.93	0.0002
Control vs Treated	1		362.38	362.38	10.37	0.002
Wax type vs wax type	15		1784.32	118.95	3.4	< 0.001
Residual	95	-1	3319.81	34.95		
Total	117	-1	6493.54			

Missing value: Beeswax (Block 7)

Appendix Table 3.14. ANOVA table for water absorption of untreated and wax-treated samples after 72 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		7169.63	1194.94	13.55	< 0.0001
Control vs Treated	1		396.5	396.5	4.5	0.037
Wax type vs wax type	15		2366.34	157.76	1.79	0.047
Residual	95	-1	8378.74	88.2		
Total	117	-1	18301.96			

Missing value: Beeswax (Block 7)
*"moisture resistant" excluded

Appendix Table 3.15. ANOVA table for water absorption of "moisture resistant" and wax-treated samples after 72 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		5753.28	958.88	10.64	< 0.0001
Control vs Treated	1		1576.07	1576.07	17.49	< 0.001
Wax type vs wax type	15		2363.68	157.58	1.75	0.054
Residual	95	-1	8561.41	90.12		
Total	117	-1	18253.11			

Missing value: Beeswax (Block 7)

Appendix Table 3.16. Raw data for thickness swelling of untreated and wax-treated OSB samples

			Thickness swelling (mm)			
Block	Control vs. Treated	Wax	2 h	24 h	48 h	72 h
1	treated	Beeswax	0.033	0.336	0.712	1.269
1	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.133	0.631	1.142	1.564
1	treated	Beeswax + Sasolwax C (1:1)	0.155	0.721	1.111	1.512
1	treated	Beeswax + Synthetic beeswax (1:1)	0.040	0.124	0.328	0.636
1	treated	Beeswax + Vaseline (1:1)	0.032	0.539	0.967	1.514
1	treated	Carnauba	0.167	0.633	0.944	1.182
1	control	Control	0.195	0.743	1.216	1.703
1	treated	Sasolwax M3M	0.092	0.726	1.119	1.483
1	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.100	0.519	0.672	0.992
1	treated	Merkur 300	0.160	0.668	0.894	1.141
1	treated	Microcrystalline	0.160	0.788	1.334	1.816
1	treated	Stearic acid	0.100	0.493	0.719	0.916
1	treated	Sasolwax C	0.320	1.265	1.715	2.067
1	treated	Soy wax	0.227	0.794	1.104	1.434
1	treated	Synthetic beeswax	-0.048	0.333	0.731	1.144

Block	Control vs. Treated	Wax	Thickness swelling (mm)			
			2 h	24 h	48 h	72 h
1	treated	Tekniwax 801	0.195	0.523	0.867	1.132
1	treated	Vaseline	0.050	0.361	1.081	1.451
1	control	“moisture resistant”	0.077	0.187	0.267	0.347
2	treated	Beeswax	-0.015	0.370	0.703	1.017
2	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.169	0.655	1.321	1.711
2	treated	Beeswax + Sasolwax C (1:1)	0.048	0.688	1.236	1.683
2	treated	Beeswax + Synthetic beeswax (1:1)	0.094	0.475	0.781	1.105
2	treated	Beeswax + Vaseline (1:1)	0.428	0.581	0.999	1.457
2	treated	Carnauba	0.159	0.595	1.123	1.260
2	control	Control	0.214	0.851	1.268	1.651
2	treated	Sasolwax M3M	0.130	0.650	1.064	1.614
2	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.077	0.675	1.143	1.543
2	treated	Merkur 300	0.133	0.865	1.388	1.805
2	treated	Microcrystalline	-0.040	0.180	0.790	1.339
2	treated	Stearic acid	0.110	0.547	1.034	1.545
2	treated	Sasolwax C	0.158	0.647	0.982	1.281
2	treated	Soy wax	0.181	0.846	1.326	1.762
2	treated	Synthetic beeswax	0.086	0.458	0.740	1.077
2	treated	Tekniwax 801	0.093	0.688	1.137	1.492
2	treated	Vaseline	0.082	0.593	1.028	1.431
2	control	“moisture resistant”	0.074	0.304	0.490	0.631
3	treated	Beeswax	0.186	0.507	0.792	1.073
3	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.080	0.418	0.702	0.974
3	treated	Beeswax + Sasolwax C (1:1)	0.273	0.753	1.056	1.384
3	treated	Beeswax + Synthetic beeswax (1:1)	0.049	0.253	0.427	0.588
3	treated	Beeswax + Vaseline (1:1)	0.134	0.398	0.658	0.897
3	treated	Carnauba	0.232	0.689	1.094	1.448
3	control	Control	0.205	0.558	0.852	1.095
3	treated	Sasolwax M3M	0.249	0.700	1.074	1.336
3	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.061	0.394	0.702	0.970
3	treated	Merkur 300	0.289	0.807	1.141	1.386
3	treated	Microcrystalline	-0.136	0.264	0.556	0.788
3	treated	Stearic acid	0.252	0.624	0.929	1.189
3	treated	Sasolwax C	0.267	0.683	1.012	1.303
3	treated	Soy wax	0.432	0.879	1.185	1.630
3	treated	Synthetic beeswax	0.163	0.529	0.757	0.943
3	treated	Tekniwax 801	0.192	0.545	0.852	1.138
3	treated	Vaseline	0.235	0.603	0.947	1.219
3	control	“moisture resistant”	0.077	0.260	0.369	0.459
4	treated	Beeswax	0.170	0.706	1.096	1.729
4	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.059	0.354	0.607	0.993

Block	Control vs. Treated	Wax	Thickness swelling (mm)			
			2 h	24 h	48 h	72 h
4	treated	Beeswax + Sasolwax C (1:1)	0.219	1.003	1.564	1.959
4	treated	Beeswax + Synthetic beeswax (1:1)	0.177	0.640	1.019	1.414
4	treated	Beeswax + Vaseline (1:1)	0.083	0.341	0.594	1.053
4	treated	Carnauba	0.145	0.564	0.976	1.392
4	control	Control	0.284	0.781	1.203	1.694
4	treated	Sasolwax M3M	0.207	0.704	1.214	1.639
4	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.182	0.880	1.473	1.904
4	treated	Merkur 300	0.192	0.678	1.051	1.403
4	treated	Microcrystalline	0.174	0.689	1.016	1.330
4	treated	Stearic acid	0.279	0.892	1.274	1.721
4	treated	Sasolwax C	0.262	0.724	1.036	1.317
4	treated	Soy wax	0.235	0.791	1.287	1.888
4	treated	Synthetic beeswax	0.127	0.491	0.745	1.091
4	treated	Tekniwax 801	0.248	0.701	1.130	1.595
4	treated	Vaseline	0.174	0.677	1.058	1.420
4	control	“moisture resistant”	0.088	0.519	0.634	0.745
5	treated	Beeswax	0.090	0.446	0.789	1.255
5	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.046	0.282	0.676	1.333
5	treated	Beeswax + Sasolwax C (1:1)	0.211	0.764	1.324	2.036
5	treated	Beeswax + Synthetic beeswax (1:1)	0.159	0.726	1.190	1.787
5	treated	Beeswax + Vaseline (1:1)	0.097	0.431	0.937	1.505
5	treated	Carnauba	0.149	0.946	1.514	2.097
5	control	Control	0.336	0.995	1.527	2.244
5	treated	Sasolwax M3M	0.197	0.673	1.074	1.642
5	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.160	0.736	1.407	2.144
5	treated	Merkur 300	0.374	0.990	1.454	2.151
5	treated	Microcrystalline	0.161	0.566	0.926	1.309
5	treated	Stearic acid	0.183	0.736	1.075	1.570
5	treated	Sasolwax C	0.229	1.003	1.539	2.126
5	treated	Soy wax	0.267	0.985	1.508	2.079
5	treated	Synthetic beeswax	0.108	0.879	1.490	2.421
5	treated	Tekniwax 801	0.206	0.668	1.030	1.404
5	treated	Vaseline	0.175	0.538	0.958	1.918
5	control	“moisture resistant”	0.144	0.433	0.625	0.781
6	treated	Beeswax	0.188	0.569	0.926	1.297
6	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.202	0.573	0.821	1.097
6	treated	Beeswax + Sasolwax C (1:1)	0.148	0.603	0.936	1.208
6	treated	Beeswax + Synthetic beeswax (1:1)	0.201	0.566	0.944	1.292
6	treated	Beeswax + Vaseline (1:1)	0.151	0.421	0.699	0.971
6	treated	Carnauba	0.172	0.573	0.852	1.178
6	control	Control	0.346	0.847	1.230	1.564

Block	Control vs. Treated	Wax	Thickness swelling (mm) 2 h	24 h	48 h	72 h
6	treated	Sasolwax M3M	0.197	0.520	0.825	1.145
6	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.155	0.445	0.685	1.056
6	treated	Merkur 300	0.129	0.560	0.814	1.014
6	treated	Microcrystalline	0.142	0.575	0.928	1.241
6	treated	Stearic acid	0.183	0.540	0.882	1.019
6	treated	Sasolwax C	0.541	1.061	1.448	1.803
6	treated	Soy wax	0.193	0.599	0.917	1.197
6	treated	Synthetic beeswax	0.177	0.636	0.956	1.227
6	treated	Tekniwax 801	0.424	0.677	1.043	1.347
6	treated	Vaseline	0.300	0.848	1.156	1.479
6	control	"moisture resistant"	0.107	0.321	1.023	0.790
7	treated	Beeswax	0.100	0.678	1.477	2.226
7	treated	Beeswax + Ethylene maleic anhydride (3:1)	0.120	0.517	0.820	1.182
7	treated	Beeswax + Sasolwax C (1:1)	0.112	0.543	0.992	1.580
7	treated	Beeswax + Synthetic beeswax (1:1)	0.099	0.441	0.741	1.044
7	treated	Beeswax + Vaseline (1:1)	0.104	0.441	0.695	0.943
7	treated	Carnauba	0.126	0.556	0.986	1.554
7	control	Control	0.191	0.605	0.886	1.218
7	treated	Sasolwax M3M	0.156	0.787	1.219	1.746
7	treated	Sasolwax M3M + Ethylene maleic anhydride (3:1)	0.092	0.528	0.947	1.421
7	treated	Merkur 300	0.183	0.770	1.195	1.631
7	treated	Microcrystalline	0.136	0.590	0.960	1.403
7	treated	Stearic acid	0.159	0.507	0.580	1.000
7	treated	Sasolwax C	0.219	0.822	1.260	1.644
7	treated	Soy wax	0.190	0.711	1.097	1.501
7	treated	Synthetic beeswax	0.122	0.551	0.982	1.491
7	treated	Tekniwax 801	0.128	0.504	0.951	1.389
7	treated	Vaseline	0.145	0.744	1.182	1.570
7	control	"moisture resistant"	0.084	0.115	0.368	0.470

Appendix Table 3.17. ANOVA table for the natural logarithm of thickness swelling of untreated and wax-treated samples after 2 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		0.156024	0.026004	9.64	< 0.0001
Control vs Treated	1		0.039406	0.039406	14.61	< 0.001
Wax type vs wax type	15		0.228871	0.015258	5.66	< 0.001
Residual	94	-2	0.253596	0.002698		
Total	116	-2	0.662365			

Appendix Table 3.18. ANOVA table for the natural logarithm of thickness swelling of “moisture resistant” and wax-treated samples after 2 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block stratum	6		0.145201	0.0242	8.98	< 0.0001
Control vs Treated	1		0.022363	0.022363	8.29	0.005
Wax type vs wax type	15		0.230313	0.015354	5.69	< 0.001
Residual	93	-3	0.250737	0.002696		
Total	115	-3	0.630775			

Appendix Table 3.19. ANOVA table for the thickness swelling of untreated and wax-treated samples after 24 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		0.3586	0.05977	2.91	0.0113
Control vs Treated	1		0.15011	0.15011	7.32	0.008
Wax type vs wax type	15		1.41791	0.09453	4.61	<.001
Residual	95	-1	1.9491	0.02052		
Total	117	-1	3.85845			

Appendix Table 3.20. ANOVA table for the thickness swelling of “moisture resistant” and wax-treated samples after 24 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		0.32709	0.05451	2.47	0.028
Control vs Treated	1		0.65193	0.65193	29.57	< 0.001
Wax type vs wax type	15		1.70896	0.11393	5.17	< 0.001
Residual	95	-1	2.09423	0.02204		
Total	117	-1	4.7572			

Appendix Table 3.21. ANOVA table for the thickness swelling of untreated and wax-treated samples after 48 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		1.23288	0.20548	4.82	0.0002
Control vs Treated	1		0.18089	0.18089	4.24	0.042
Wax type vs wax type	15		2.40553	0.16037	3.76	< 0.001
Residual	95	-1	4.05254	0.04266		
Total	117	-1	7.81258			

Appendix Table 3.22. ANOVA table for the thickness swelling of “moisture resistant” and wax-treated samples after 48 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		1.0553	0.17588	3.9	0.0014
Control vs Treated	1		1.41787	1.41787	31.41	< 0.001
Wax type vs wax type	15		2.40267	0.16018	3.55	< 0.001
Residual	95	-1	4.28875	0.04514		
Total	117	-1	9.12533			

Appendix Table 3.32. ANOVA table for the thickness swelling of untreated and wax-treated samples after 72 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		4.25298	0.70883	11.37	< 0.0001
Control vs Treated	1		0.26283	0.26283	4.22	0.043
Wax type vs wax type	15		2.91041	0.19403	3.11	< 0.001
Residual	94	-2	5.86016	0.06234		
Total	116	-2	13.227			

Appendix Table 3.33. ANOVA table for the thickness swelling of “moisture resistant” and wax-treated samples after 72 h (α = 0.05)

Source of variation	d.f.	Missing value	SS	MS	F	p-value
Block	6		4.31308	0.71885	10.75	< 0.0001
Control vs Treated	1		4.21984	4.21984	63.12	<.001
Wax type vs wax type	15		2.71429	0.18095	2.71	0.002
Residual	95	-1	6.3514	0.06686		
Total	117	-1	17.5887			

Appendix Table 3.34. Raw data for Final moisture content, Total thickness swelling, and Time-delayed thickness swelling

Block	Wax	Final moisture content (%)	Time-delayed thickness swelling (mm)	Total thickness swelling (mm)
1	Beeswax + Synthetic beeswax (1:1)	9.93	0.14	0.77
1	Beeswax + Vaseline (1:1)	12.01	0.12	1.63
1	Beeswax	11.92	0.00	1.27
1	Beeswax + Ethylene maleic anhydride (3:1)	11.25	-0.16	1.41
1	Beeswax + Sasolwax C (1:1)	10.77	0.05	1.57
1	Carnauba	11.14	-0.20	0.98
1	Control	10.74	-0.22	1.49
1	“moisture resistant”	7.08	2.39	2.73
1	Sasolwax M3M	11.37	-0.16	1.32
1	Sasolwax M3M + Ethylene maleic anhydride (3:1)	10.96	-0.13	0.86
1	Merkur 300	11.13	-0.08	1.06
1	Microcrystalline	10.85	-0.02	1.79
1	Stearic acid	10.58	-0.20	0.71
1	Sasolwax C	12.64	-0.33	1.74
1	Soy wax	11.35	-0.22	1.21
1	Synthetic beeswax	11.67	0.03	1.18
1	Tekniwax 801	11.24	0.05	1.18
1	Vaseline	12.08	0.19	1.64
2	Beeswax + Synthetic beeswax (1:1)	11.32	0.02	1.12
2	Beeswax + Vaseline (1:1)	11.99	-0.04	1.41
2	Beeswax	11.33	0.02	1.04
2	Beeswax + Ethylene maleic anhydride (3:1)	11.96	-0.05	1.66
2	Beeswax + Sasolwax C (1:1)	12.29	-0.18	1.50
2	Carnauba	11.37	-0.07	1.19
2	Control	11.66	-0.19	1.46
2	“moisture resistant”	9.73	0.04	0.67
2	Sasolwax M3M	11.90	-0.14	1.47
2	Sasolwax M3M + Ethylene maleic anhydride (3:1)	11.66	0.00	1.54
2	Merkur 301	12.34	0.02	1.82
2	Microcrystalline	11.85	0.09	1.43
2	Stearic acid	11.35	-0.11	1.43
2	Sasolwax C	12.19	0.10	1.38
2	Soy wax	12.05	-0.14	1.62
2	Synthetic beeswax	11.21	0.02	1.10
2	Tekniwax 801	11.75	0.04	1.54
2	Vaseline	11.39	0.07	1.50
3	Beeswax + Synthetic beeswax (1:1)	10.70	0.17	0.75
3	Beeswax + Vaseline (1:1)	10.81	0.13	1.03

Block	Wax	Final moisture content (%)	Time-delayed thickness swelling (mm)	Total thickness swelling (mm)
3	Beeswax	11.03	0.05	1.12
3	Beeswax + Ethylene maleic anhydride (3:1)	11.52	0.07	1.04
3	Beeswax + Sasolwax C (1:1)	11.41	-0.06	1.33
3	Carnauba	11.53	-0.03	1.42
3	Control	10.79	-0.08	1.02
3	“moisture resistant”	9.84	0.37	0.83
3	Sasolwax M3M	11.50	0.04	1.38
3	Sasolwax M3M + Ethylene maleic anhydride (3:1)	11.40	0.12	1.09
3	Merkur 302	12.09	0.11	1.49
3	Microcrystalline	11.39	0.27	1.06
3	Stearic acid	11.12	-0.04	1.15
3	Sasolwax C	11.79	0.11	1.41
3	Soy wax	11.54	-0.18	1.45
3	Synthetic beeswax	11.49	0.07	1.02
3	Tekniwax 801	11.38	0.13	1.27
3	Vaseline	12.44	0.03	1.25
4	Beeswax + Synthetic beeswax (1:1)	11.27	-0.06	1.36
4	Beeswax + Vaseline (1:1)	11.62	0.18	1.23
4	Beeswax	12.04	0.01	1.74
4	Beeswax + Ethylene maleic anhydride (3:1)	11.70	0.16	1.15
4	Beeswax + Sasolwax C (1:1)	12.05	0.10	2.06
4	Carnauba	11.76	0.06	1.45
4	Control	12.17	-0.05	1.64
4	“moisture resistant”	26.36	-1.32	-0.57
4	Sasolwax M3M	11.90	-0.09	1.55
4	Sasolwax M3M + Ethylene maleic anhydride (3:1)	12.10	-0.01	1.89
4	Merkur 303	12.32	0.27	1.67
4	Microcrystalline	10.89	0.07	1.40
4	Stearic acid	12.25	-0.04	1.68
4	Sasolwax C	11.68	0.05	1.37
4	Soy wax	12.24	0.05	1.94
4	Synthetic beeswax	10.40	0.03	1.12
4	Tekniwax 801	11.77	0.07	1.67
4	Vaseline	11.16	0.03	1.45
5	Beeswax + Synthetic beeswax (1:1)	12.98	0.37	2.15
5	Beeswax + Vaseline (1:1)	12.83	0.59	2.09
5	Beeswax	11.38	0.23	1.49
5	Beeswax + Ethylene maleic anhydride (3:1)	12.91	0.47	1.80
5	Beeswax + Sasolwax C (1:1)	13.88	0.54	2.58
5	Carnauba	12.28	0.18	2.28
5	Control	13.74	0.31	2.55

Block	Wax	Final moisture content (%)	Time-delayed thickness swelling (mm)	Total thickness swelling (mm)
5	“moisture resistant”	10.04	0.02	0.80
5	Sasolwax M3M	13.32	0.71	2.35
5	Sasolwax M3M + Ethylene maleic anhydride (3:1)	12.96	0.27	2.41
5	Merkur 304	13.67	0.82	2.97
5	Microcrystalline	12.71	0.89	2.20
5	Stearic acid	12.68	0.40	1.97
5	Sasolwax C	14.16	0.55	2.68
5	Soy wax	12.92	0.14	2.22
5	Synthetic beeswax	13.61	0.32	2.75
5	Tekniwax 801	12.58	0.55	1.95
5	Vaseline	13.32	0.54	2.45
6	Beeswax + Synthetic beeswax (1:1)	10.90	0.29	1.59
6	Beeswax + Vaseline (1:1)	10.53	0.24	1.21
6	Beeswax	11.13	0.31	1.61
6	Beeswax + Ethylene maleic anhydride (3:1)	10.83	0.35	1.45
6	Beeswax + Sasolwax C (1:1)	11.15	0.31	1.52
6	Carnauba	11.04	0.21	1.39
6	Control	11.11	0.10	1.67
6	“moisture resistant”	11.19	0.13	0.92
6	Sasolwax M3M	11.56	0.31	1.46
6	Sasolwax M3M + Ethylene maleic anhydride (3:1)	11.18	0.42	1.48
6	Merkur 305	10.80	0.24	1.26
6	Microcrystalline	10.81	0.20	1.44
6	Stearic acid	10.29	0.20	1.22
6	Sasolwax C	12.25	0.34	2.14
6	Soy wax	10.81	0.20	1.39
6	Synthetic beeswax	10.62	0.23	1.46
6	Tekniwax 801	10.87	0.20	1.54
6	Vaseline	11.11	0.30	1.77
7	Beeswax + Synthetic beeswax (1:1)	13.34	1.12	2.16
7	Beeswax + Vaseline (1:1)	12.20	0.93	1.88
7	Beeswax	14.09	0.70	2.92
7	Beeswax + Ethylene maleic anhydride (3:1)	11.98	0.91	2.09
7	Beeswax + Sasolwax C (1:1)	13.67	1.00	2.58
7	Carnauba	12.39	0.87	2.42
7	Control	13.09	1.00	2.22
7	“moisture resistant”	9.95	0.25	0.72
7	Sasolwax M3M	13.65	0.97	2.71
7	Sasolwax M3M + Ethylene maleic anhydride (3:1)	13.27	1.14	2.56
7	Merkur 306	13.67	0.73	2.36
7	Microcrystalline	13.92	1.28	2.69

Block	Wax	Final moisture content (%)	Time-delayed thickness swelling (mm)	Total thickness swelling (mm)
7	Stearic acid	12.38	0.97	1.97
7	Sasolwax C	13.35	0.81	2.45
7	Soy wax	14.12	1.27	2.77
7	Synthetic beeswax	13.15	1.09	2.58
7	Tekniwax 801	13.19	1.01	2.40
7	Vaseline	14.07	1.16	2.73

Appendix Table 3.35. ANOVA table for Final moisture content (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	79.8992	13.3165	52.67	0
Control vs Treated	1	0.0044	0.0044	0.02	0.895
Wax type vs wax type	15	9.8363	0.6558	2.59	0.003
Residual	96	24.2736	0.2529		
Total	118	114.0135			

Appendix Table 3.36. ANOVA table for Total thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	24.69145	4.11524	62.72	0
Control vs Treated	1	0.02001	0.02001	0.3	0.582
Wax type vs wax type	15	2.38831	0.15922	2.43	0.005
Residual	96	6.29901	0.06561		
Total	118	33.39877			

Appendix Table 3.37. ANOVA table for Time-delayed thickness swelling (α = 0.05)

Source of variation	d.f.	SS	MS	F	p-value
Block	6	14.64518	2.44086	153.55	0
Control vs Treated	1	0.10878	0.10878	6.84	0.01
Wax type vs wax type	15	0.47672	0.03178	2	0.023
Residual	96	1.52608	0.0159		
Total	118	16.75676			

Appendix Table 3.38. Table of means for Final moisture content, Total thickness swelling, and Time-delayed thickness swelling

Wax	Final moisture (%)	Total thickness swelling (mm)	Time-delayed thickness swelling (mm)
Beeswax	11.847	1.597	0.188
Beeswax + Ethylene maleic anhydride (3:1)	11.735	1.515	0.25
Beeswax + Sasolwax C (1:1)	12.173	1.876	0.253
Beeswax + Synthetic beeswax (1:1)	11.493	1.415	0.291
Beeswax + Vaseline (1:1)	11.713	1.498	0.307
Carnauba	11.646	1.59	0.146
Control	11.9	1.721	0.125
Sasolwax M3M	12.172	1.749	0.234
Sasolwax M3M + Ethylene maleic anhydride (3:1)	11.935	1.691	0.258
Merkur 300	12.287	1.804	0.30
Microcrystalline	11.773	1.716	0.398
Stearic acid	11.523	1.447	0.167
Sasolwax C	12.58	1.881	0.233
Soy wax	12.149	1.799	0.158
Synthetic beeswax	11.737	1.599	0.257
Tekniwax 801	11.826	1.65	0.293
Vaseline	12.224	1.828	0.33
Mean	11.924	1.669	0.246
Least significant difference	0.5376	0.2738	0.1348