PARTICLE MOISTURE CONTENT EFFECTS ON THE PHYSICAL AND MECHANICAL PROPERTIES OF MAGNESITE CEMENT-BONDED PARTICLEBOARD

by

INDIA E.O. MUSOKOTWANE

B.Sc. (Hons.) Forestry, Makerere University, 1975

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Department of FORESTRY

The University of British Columbia
1956 Main Mall
Vancouver, Canada
V6T 1Y3

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ABSTRACT

The effects of initial particle moisture content, wood-cement ratio and density on physical (thickness swelling and water absorption) and mechanical properties (MOE, MOR, IB and edgewise compression) were investigated. Five initial particle moisture content levels - 0-6%, 8-15%, 25-30%, 40-50% and 60-80%; three wood-cement ratios - 1:1, 1:1.5 and 1:2; and three density levels at each wood-cement ratio - 1:1 - 0.472 g/cm^3, 0.528 g/cm^3 and 0.622 g/cm^3, 1:1.5 - 0.636 g/cm^3, 0.707 g/cm^3 and 0.809 g/cm^3; and 1:2 - 0.763 g/cm^3, 0.847 g/cm^3 and 0.939 g/cm^3 were used.

Combinations of the above variables gave 45 treatments. Three replicate boards were made for each treatment thus giving a total of 135 panels for the study. A total of 135 test specimens were used for each property tested. Results from the tests were compared to the German and ISO Standards for similar boards and to the Canadian Waferboard Standard.

Initial particle moisture content was highly significant in the development of physical and mechanical properties of magnesite cement-bonded particleboard. Increasing initial particle moisture content from 0-6% to 60-80% resulted in the reduction of the physical and mechanical properties of the boards. The highest initial particle moisture content of (60-80%) yielded the lowest physical and mechanical properties. For manufacture of boards of favourable mechanical properties, an initial particle moisture content of not more than 15% is recommended. On the other hand, a higher initial particle moisture content (>40%) is considered desirable if board thickness and water absorption are to be minimized.

All the mechanical properties tested consistently increased by increasing wood-cement ratio and density and were highest at 1:2 wood-cement ratio and density level 3 of each wood-cement ratio. Thickness swelling and water absorption were consistently reduced by increasing wood-cement ratio and density. In both physical properties tests, the 1:2 wood-cement ratio and density level 3 yielded the lowest values.

Thirty-two of the forty-five treatment combinations of initial particle moisture content, density and wood-cement ratio pass the MOE requirement of the German Standard DIN 52 362 for Portland cement-bonded particleboard; forty-one treatments met the minimum MOE Canadian Waferboard Standard requirements, while no treatment meet the MOR requirements for this Standard. Eleven of the forty-five treatments met the minimum IB Canadian Waferboard Standard requirements. All the 45 treatments pass the ISO building board requirements in thickness swelling, while 18 treatments pass the water absorption requirements for this Standard. Most of the treatment combinations compare favourably with results obtained in tests conducted in Europe for cement-bonded particleboard.

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GLOSSARY

Dolomite - limestone containing from 35 to 46 percent magnesium carbonate ($MgCO_3$).

Gypsum - the mineral consisting primarily of fully hydrated calcium sulphate, $CaSo_4.2H_2O$ or calcium sulphate dehydrate.

Magnesite cement - dolomitic limestone that has been heated with or without additives to a temperature sufficiently high and for a long enough time to decompose the carbonate structure so as to form magnesium oxide. Magnesite cement contains not less than 85 percent magnesium oxide. Magnesite, sometimes referred to as dead-burnt cement is resistant to subsequent hydration and recombination with carbon dioxide.

Portland cement - a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, and usually containing one or more forms, of calcium sulphate as an interground addition.

Pozzolanas - substances which are not in themselves cementitious but which react with $Ca(OH)_2$ in the presence of water at ordinary temperature and thereby act as cements. Examples include certain naturally occurring materials of volcanic origin.

Sorel (Magnesium) cement - a magnesium oxychloride based cement. It is obtained by treating a mixture of MgO and aggregate with a concentrated solution of $MgCl_2$.

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1.0 INTRODUCTION

1.1 Background Information

It is estimated that before the end of the century an additional two billion people will need to be housed (4). This apparent high demand for housing will result in increased demand for building materials and wood fibre products. Rational and efficient utilization of the available growing forest reserves will be required in order to satisfy all demands. In addition, optimum and complete forest utilization programmes will have to be developed. An important aspect of such programmes will be to find uses for tree species still considered as waste wood and to develop processes leading to the manufacture of useful products from forest, mill and agricultural residues. Kollman (27) has estimated that more than 50% of the wood harvested ends up as waste as a result of processing.

The urgent need for providing housing, especially in developing countries, will call for erection of quick-built, low-cost housing units. The main feature of such housing systems are mass production and on-site erection from prefabricated engineered building materials (14).

Plywood, fibreboards and particleboards have been extensively used for many years and have given excellent performance as structural materials. However, the excellent potential of these wood-based panels can, under adverse conditions be negated by the attack and deterioration by fungi and insects and degradation due to fire and weather. Therefore, if these panels are to be effectively used in housing construction, practices that minimize these hazards must be employed; treatments

with preservatives and fire-retardants, building techniques that prevent undue wetting of panel elements or the application of wood finishes are usually implemented. The high cost of these protective measures, coupled with the relatively high production cost of these panels, have tended to preclude their use in housing especially in developing countries.

Wood-cement products are unique as building elements since they have the potential to overcome the disadvantages that plywood and other wood-based panels have as structural elements in housing. Dinwoodie (15) has reported that wood-cement products rate very highly in resistance against fire, insect and fungi. Wood-wool slabs are reported by Chittenden et al. (9) to have a Class 1 spread of flame rating and a fire propagation index (I) not exceeding 12.0 and a sub-index (i) not exceeding 6.0 when tested according to British Standard (B.S. 476). Deppe (14) reported that the thickness swelling of cement-bonded particleboard is considerably lower than that of the synthetic resin-bonded boards.

The presently manufactured wood-cement products include: the wood-wool slabs, first made in Austria in 1914 using a mixture of magnesium chloride and magnesium oxide as a binder; and the cement-bonded particleboard originally developed and patented in USA in 1965 and 1966 by Elmendorf. The success and extensive use of wood-wool slabs for partitioning, cladding, roofing floor base and as permanent shutter in Europe and Japan are largely due to their insulating properties and high degree of fire resistance (9).

The presently employed wood-cement systems, whose properties and classification are shown in Table 1, suffer from numerous disadvantages which limit the world-wide growth of the industry.

The basic raw material for the presently made wood cement systems comprise lignocellulosic fragments as filler materials and employ as binding agents some form of mineral cement. Typical cements have included Portland and other hydraulic cements, pozzolans and magnesium cement such as Sorel cement.

The problem of forming products of adequate strength and with a wide density range arises because of the inferior junction bond strengths, that is, inadequate adherence of the mineral mass to the wood fragments (36). Substances which were shown to be the major cause for poor bonding include sugars, starches, proteins, polyphenolics, waxes, fatty substances, gums and various sequestered minerals (5, 12, 24). Because of inferior bonding due to the above substances, the number of wood species for wood-cement system manufacture is limited. At present cement-bonded compositions are largely restricted to a few species such as spruces (Picea spp.), true firs (Abies spp.), poplars (Populus spp.) and some pines (Pinus spp.). Other suitably tested species require pretreatments in the form of "mineralization" with mineral additives, (such as waterglass, calcium or magnesium chloride, borax), to either remove inhibiting substances, to seal fragment surfaces or to convert near-surface contaminants to innocuous residues (34, 45).

Stillinger et al. (48) has described typical treatments to eliminate retardation or inhibition in gelling and hydration of Portland cements to include:

(a) impregnating the fragment surfaces with soluble metal salts such as chlorides or soluble sulphates of calcium or magnesium, which hasten the setting of hydraulic cement slurry adjacent to the fragment,

(b) digesting the extractable substances at and near fragment surfaces by treatment with baths of lime or caustic soda with or without further stabilization by a pozzolan or a polyvalent metal salt, and

(c) loading the surfaces of fragments with a mineral gel e.g. sodium silicate.

Stillinger (48) further noted that such costly pretreatments necessitate at least an additional drying step for wood - Portland cement systems and thus further complicate the manufacturing process.

A further processing difficulty with Portland cement-bonded systems such as the DURIPANEL, is the long pressing time, 8 to 24 h, required to obtain a solid product. Elmendorf (16) reported a press cycle of 7 to 9 h for cement-bonded particleboard, while Chittenden et al. (9) noted that due to the long press dwell time coupled with a high degree of automation (e.g. in DURIPANEL), the wood-cement systems are unlikely to prove economically viable anywhere other than a highly industrialized country.

Efforts to shorten the press dwell time and expand the list of suitable wood species for wood-cement system production, led to the use of magnesite cements as binding agents. The bonding mechanism of the magnesite setting, as described by Simatupang et al. (44) is essentially a high-temperature hydration of magnesium oxide, with wood fragments

treated with magnesium chloride or magnesium sulphate. A pressing time of 15 minutes was achieved with this process and the inhibiting effects of wood extractives was minimized (44). A comparison of properties of Portland cement-bonded and magnesite-bonded particleboard is shown in Table 2.

However, the extremely large amount of energy required to heat the panels during the initial 10 minutes pressing time and subsequent conditioning stages, seems to be a big disadvantage with the magnesite-cement process. According to Simatupang et al. (46), the required hydration temperature is in the range of 120°C to 200°C. It is estimated that 500,000 kcal (≅ 600 kWh) of heating energy and between 140-290 kWh are required to produce 1 m^3 of magnesite cement-bonded particleboard. The equivalent dollar requirement for energy alone at the current price of Cdn$0.04/kWh, is Cdn$35.60/m^3. It is reported (36) that the production of magnesite-bonded particleboards by HERAKLITH in Radentenheim, Austria was halted due to the high energy cost.

1.1.1 The Paszner Process

Paszner (36) invented and patented (37) an improved process for the rapid bonding or combining lignocellulosic fragments with mineral inorganic binder materials and forming the admixture into a structural product.

The invention is based on the discovery that when a major volume proportion of lignocellulosic fragment mass is admixed with either aqueous solutions of phosphoric acids, or solutions of neutral phosphate salts, particularly aqueous solutions of ammonium salts of polyphosphoric acids in amounts so as to partially impregnate the fragment,

and the mixture is then dusted with a minor volume proportion of magnesium or calcium oxides, hydroxides, or carbonates, a bond is developed at the fragment surfaces which sets rapidly from a gel phase to a strongly adhered, rigid concrete integral with the fragments. The presence of sugars, phenolics or extractables in the lignocellulosic fragments has no inhibitory effect on the bond formation (36, 37).

The products molded by the process according to the invention, may comprise any of the common structural shapes such as boards, panels, slabs, beams, and blocks and may comprise frames, poles, trusses and virtually any castable or sprayable configuration. Such products, after curing, are reported (36) to be fire, decay, insect, fungi and weather resistant.

The Paszner process can utilize a major volume proportion of ligneous plant fragments such as softwoods and hardwoods, sugarcane rind shreds, cereal and fibre plant stalks.

The process basically involves the following steps: lignocellulosic fragments, having thicknesses ranging from 0.3 mm to 8 mm including chips, shavings, strips, strands, slivers, fibre bundles, fibres and peeled or sawn sheets, are mixed with solution of ammonium polyphosphate supplying from 0.15 to 0.4 parts P_2O_5 as phosphate ion per part of fragment by weight. To these wetted fragments, particulate cement solids comprising of dead burnt MgO, or CaO, or $Mg(OH)_2$, or $Ca(OH)_2$, or $MgCO_3$, or $CaCO_3$ ranging from 0.55 to 2.5 part per part of fragment and from 0.01 to 0.80 parts of inert filler particles (such as silica sand) are added with rapid mixing. The mixture is molded and held under predetermined compaction pressure until the product has

solidified in about 3-10 minutes. Best results occur when the phosphate solution is mainly absorbed into the fragment surfaces before the cement solids are dusted onto the wet surfaces (36). Satisfactory products may also be fabricated if the phosphoric solution is applied to the cement - dusted dry particles (37).

Depending on the magnesium oxide source and purity, the curing time of the mixture can be regulated within relatively wide limits, i.e. almost instantaneous to sufficiently delayed gelling (36).

The cement setting in the Paszner process, is largely exothermic and does not require initiation by heat as indicated by Figure 1. However, Paszner (36) reported that variations in ambient temperature have a pronounced effect on the onset of the exothermic setting reaction, as indicated in Table 3.

Products made by the process attain at least 50% of their ultimate strength within the first 15 minutes from the time of mixing, up to 75% within 30 minutes and full strength in 7 days.

1.1.2 The Study

The present study employs the Paszner process in the manufacture of cement-bonded particleboards.

1.2 Objective and Scope of Study

The main objective of this study is to investigate the effects of initial wood particle moisture content on the physical and the mechanical properties of the magnesite cement-bonded particleboard.

This investigation was prompted by the publication (FID-II/21) of the Food and Agricultural Organization of the United Nations (FAO, 1978)

in which Paszner (36) indicated that regardless of type or length of cure and particle size, wood particle moisture content could have an adverse effect on the ultimate crushing strength of dead-burnt magnesite cement bonded products. These preliminary findings by Paszner were considered to be of paramount importance in the manufacture of magnesite cement bonded products.

Since the above-mentioned study by Paszner was exploratory in nature, it was decided to conduct an extensive investigation on the effect of a wide range of particle moisture content on physical and mechanical properties. The physical and mechanical properties chosen for the study are those considered by the USA F.P.L. technical report No. 10, to be important with respect to the practical application of the products as structural elements.

To study the particle moisture content effects, magnesite cement-bonded particleboards were made using mixed softwoods as wood raw material. Physical and mechanical strength tests were conducted according to established standard procedures.

The following board production variables were used:

1. Five levels of initial wood particle moisture content,
2. Three levels of wood-cement ratio,
3. Three levels of density for each wood-cement ratio.

Results from this study could serve to indicate, in addition to particle moisture effects, the treatment combinations of particle moisture, density and wood-cement ratio which give the most favourable physical and mechanical properties. If boards of high strength and

favourable physical properties can be manufactured from relatively wet wood particles, the study will have an impact on energy saving, in that the wood particle drying stage during manufacture, as required in resin-bonded particleboard, could be omitted.

In addition, a scanning electron microscopy (SEM) study was conducted in order to obtain preliminary indications on the particle moisture content effect on bonding between the magnesite-cement and wood.

2.0 LITERATURE REVIEW

This literature review focuses on the physical and chemical characteristics of the main raw materials (wood and binders) in the presently manufactured wood - Portland cement systems. A further section of the review covers the pretreatments of wood raw material employed in order to improve the wood-cement bond quality.

2.1 Raw Materials

Basically three groups of raw materials can be identified in the manufacture of wood-cement boards, these are:

1. Wood (including other lignocellulosic materials).
2. Binders (either of cement, gypsum, magnesite or resin glue).
3. Pretreatment chemicals (minerals).

2.1.1 Wood

Wood is the most important of the raw materials. Owing to its intrinsic physical and chemical characteristics it may determine success or failure of the final product.

In the presently employed wood-cement systems, the form in which the wood raw material is procured, depends to a large extent, on the board material desired, i.e., the technology available for wood particle preparation and the available raw material. Wood may be obtained as round logs from thinnings (24), logging and wood processing residues (24, 49) and secondary wood species. Manufacturing wastes such as slabs, edgings, and trimmings (24, 35) from mills and furniture

factories, have been extensively used in the past. Table 4 summarizes the form of wood raw material before and after preparation, and the final product obtained.

2.1.1.1 Physical Characteristics of Wood

The physical characteristics of wood are considered here in relation to the manufacture of wood-wool cement boards. Variations noted (18) in hammermilling or crushing different wood species would probably be related to higher energy consumption. Crushing of wood is a relatively simple process compared with wood wool manufacture in which individual wood sizes are determined and maintained by controlled production.

For wood wool production, relatively straight logs are split and squared for efficient gripping by chucks (18, 20, 23, 51). Machines are designed to handle 10-12 cm diameter logs in 50 cm lengths. Similarly, machines are also available for reduction of edgings, slabs and trimmings into wood wool. Wacker (51) reported that crooked logs jam machines, reduce maximum length of individual wood ribbons (fibres), and tend to make ribbons brittle. Hubbard (23) noted that knots constitute potential hazards for knife damage, while sound defects like wane, spiral grain and reaction wood reduce volume output per unit of log input. Weatherwax (53) reported that decayed wood lowers the strength of cement boards and that it releases chemicals inhibitory to cement setting. Bark, which is high in phenolic compounds, is reported (52) to be also inhibitory to the setting of cement and is usually removed immediately from the fresh wood.

2.1.1.2 Effect of Chemical Characteristics of Wood on Cement Setting

The gross structure and complementary properties of mature wood arises from the nature and organization of its chemical constituents (33). The chemical components of the cell wall substance in normal wood are given in Table 5.

Weatherwax (52) observed that both major and minor chemical components of wood had marked effects on the curing (setting) of cement. Owing to the great variability in chemical constitution between individual trees, a great variation is to be expected in the suitability of woods for wood-cement boards. Such variation is most pronounced between hardwoods and softwoods (2, 13, 52, 53). Christensen et al. (10) found that hardwood hemicellulose had a pronounced inhibitory effect on the setting of cement, and Sanderman (39) reported that starches tannins, sugars and certain phenols were most inhibitory.

Wood is an organic material, and when used as an aggregate in cement-water mixtures may undergo certain unfavorable reactions which affects the setting of cement mixture (7, 11, 17, 52, 53). Sanderman et al. (38) pointed out that while small concentrations of certain sugars may have a positive retarding effect, others may be without effect. Hemicelluloses hydrolyse readily in dilute acids and alkali to form free reducing sugars and sugar acids. Where hemicelluloses form a substantial fraction of the wood substance, as in many hardwoods, they were found to be troublesome in cement setting (13, 32, 52, 53). Sanderman et al. (38) reported three different groups of carbohydrates that can be identified in wood-cement mixtures:

(i) water-soluble sugars

(ii) water-soluble higher carbohydrates and

(iii) water soluble constituents formed from water insoluble carbohydrates due to the action of the alkaline cement.

Not all of these carbohydrates hinder cement setting. It was reported (38) that sugar additions of about 0.125%, increased the strength of cement appreciably while an addition of 0.25% of most sugars to cement sludge causes complete setting inhibition. The effect of two particular sugars, fructose and raffinose was reported. An addition of 0.5% of fructose to the slurry gave a favourable result, whereas the same concentration of raffinose inhibited the crystallization process and caused crumbling of concrete. Sanderman et al. (38) attributed the non-inhibitory effect of fructose to the fact that it forms a sparingly soluble compound [$C_6H_{12}O_6$ + CaO + $6H_2O$] with lime water. Since $Ca(OH)_2$ is available during preparation of the cement sludge, this compound might be formed.

In another study, Sanderman (39) stated that starches, tannins, sugars and certain polyphenols had inhibitory properties. Of all the organic constituents of wood, carbohydrates appear to have the greatest effect on the setting of cement (5). Of the major carbohydrates, the order of inhibition was: glucose, followed by carboxymethyl cellulose and lastly cellulose. It has been reported that in softwoods, the cellobiose of decayed wood is more inhibitory than glucose (53).

2.1.1.2.1 Wood Cellulose

Wood cellulose and most other cellulosic materials are not obtainable in pure form. Cellulose always contains small amounts of simple sugar compounds closely linked with it. These sugars, according to Wise et al. (54) and Won-Yung et al. (56), are mainly mannose, galactose, glucose, fructose, xylose and arabinose. On drying of wood raw material in particle form, migration of these simple sugars to the surface of the particle takes place (19). Many such sugars act as inhibitors of cement hydration, resulting in poor wood-cement bonds. Generally, it is believed that inhibition is the result of interference by such sugars of crystal formation in cement, thereby affecting possible mechanical interlocking between wood and cement and within the cement itself (56).

Apart from inhibitory effects of the simple sugars, it has been postulated by Weatherwax (53) that the relatively high inhibitory effects of cellulose might also be due to the hydrolysis products of cellulose, mainly cellobiose and cellotriose.

2.1.1.2.2 Lignin

Lignin has been reported to have no effect on cement setting (2, 16). Its low hygroscopicity and insolubility in acids might explain this feature of lignin.

2.1.1.2.3 Wood Extractives

Among the important wood extractives are polyphenols and resins. The later are the source of the steam distilled turpentine, tall oil and rosin, while the former include a large number of important chemicals

such as tannins, anthocyanins, flavones, catechins, kinos and lignans (38). These occur both in angiosperms and gymnosperms. Irrespective of quantity, the presence of extractives generally have profound effects on the physico-chemical properties of wood. When the extractives are coloured, they enhance the usefulness of wood for wood wool, for packaging glass wares for display and they reduce the cost of dyeing the stuff artificially (39). Putrid smell of certain extractives disqualify the wood for use in wood wool building slabs (18, 39, 49). Toxic extractives are desirable for long service life of wood since they resist fungal decay and insect damage (27). Tannins, especially the hydrolyzable ones, were found to have a significant inhibitory effect on cement setting (5). Terpenes were found to have no effect on cement setting (11), whereas several organic acids of higher molecular weight, such as aliphatic acids, were found to be inhibitory. Lignosulphonic acid and hydroxylated carboxylic acids were reported as being used commercially as retarders of cement setting (22).

The type and percentage of inhibitory organic substances in wood vary between sapwood and heartwood as well as between earlywood and latewood. Wood zone and season of cut, therefore affect setting of wood-cement mixtures (13, 53). Ground heartwood mixtures require longer setting time than those of sapwood, because heartwood contains more phenolics than sapwood. According to Kamil (24), the maximum allowable sugars and tannins content is 1 and 2 percent respectively.

Tropical hardwoods in general contain more extractives and therefore are less suitable for wood-cement board manufacture.

2.1.1.3 Effect of Decay and Stain Fungi

Wood decayed by brown-rot fungi (Peniophora spp.) may be severely inhibitory (53). It has been shown that decayed wood can have inhibitory indices ranging from 2,000 to 11,000, while bark averages 200 and heartwood 70. The inhibitory index is calculated from the formula:

$$I = \frac{100\ \theta - \theta s}{\theta s}$$

where: I is the inhibitory index, θ is the setting time of inhibited cement and θs is the setting time of uninhibited cement (52, 53). Very few wood species satisfy this equation due to the very high sensitivity of cement setting to extractives which are almost invariably present in wood. For this reason, if hardwoods (which are reputed for being highly inhibitory because of the high hemicellulose and phenolic contents), were to be used for manufacture of wood-Portland cement boards, pretreatment would be inevitable.

Davis (13) studied the effects of blue stain on the setting of $CaCl_2$ mineralized, excelsior-cement mixtures. The results of his study indicated that blue-stained wood promoted the setting of wood-concrete mixtures containing $CaCl_2$. Mixtures containing blue-stained wood showed an earlier rise in temperature and an earlier setting than did mixtures containing non-blue-stained wood. This finding by Davis (13) is converse to that observed in partially decayed wood which strongly inhibits cement setting (53). However, it should be noted that Weatherwax et al. (53) did not include $CaCl_2$ in their decayed wood-concrete mixtures.

Davis (13) attributed the different effects of blue-stained and partially decayed wood on concrete setting as a reflection of the difference in the physiology of these two groups of organisms. Decay fungi attack the structural components of the wood and consequently lower the degree of polymerization of the wood constituents, thereby increasing the amounts of carbohydrates soluble in dilute alkali. At the same time the metabolic products of the fungi are accumulating in the wood. Stain organisms, on the other hand, utilize soluble constituents with little or no effect on the structural components (13).

Elimination of decayed wood material in wood-cement board manufacture is therefore an important step towards trouble free cement setting. It has been suggested (51) that short storage periods of not more than one year should be instituted in order to prevent decay and subsequent production of soluble inhibitors. Kiln drying, for both preventing decay and achieving low inhibition index, I, was found very effective (52, 53).

Weatherwax et al. (52) constructed curves from which tolerance levels of wood-concrete slabs for various mixes of highly decayed wood can be read. Reasonable amounts of decayed wood in wood-concrete slab mixes did not seriously reduce the strength of the final product. It was suggested (52) that wood mixes with an inhibition index, I, of 40, will just survive handling when the moulds are removed. Based on this finding, it was recommended that only 12% of severely decayed wood, and either 33% of bark or 60% of heartwood could be tolerated in wood-cement board products (52).

2.1.2 Binders

From the above brief discussion it can be seen that the curing of cement is very critically affected by the nature of the wood raw material. The type of wood being used is also of great significance. However, work done so far also indicates that the type of binder and the wood pretreatment chemical used, are also important.

Originally, in Germany, only magnesite was used as a bonding agent in mineral bonded slabs. Since its first application in 1928 in the production of wood wool boards, Portland cement has increased in use (14). By 1936, 39% of total Germany's output of wood wool slabs was manufactured with Portland cement, 35% with magnesite and 26% with plaster as binding agent (50). Today more than 80% of wood-wool boards are manufactured using cement (mainly Portland cement) as the binding agent (14). Plasters, resin etc. are used to a lesser degree (3). For this reason only Portland cement will be reviewed here in some detail, while others will only be mentioned.

2.1.2.1 Cements

The cements that have been used in wood-cement boards manufacture over the years included magnesium oxysulphate, magnesium oxychloride and Portland cement. Because of abundance, Portland cement is the most important (1, 21, 24, 50).

Portland cement is made from a mixture of lime and clay-bearing materials which are calcined to form a clinker consisting essentially several forms of hydrated calcium silicates. This clinker is then pulverized to a fineness which permits nearly all of it to pass through a sieve with 40,000 openings to the square inch. Gypsum can be added to

control the rate of set and other materials such as grinding aids and air entraining agents can also be added in small amounts (31). Portland cement is defined in the ASTM C 150-41 as .... the product obtained by pulverizing clinker which consists essentially of hydraulic calcium silicates. It is specified that no additions should be made to the silicates subsequent to calcination other than water and/or untreated calcium sulphate.

According to Larson (31) Portland cement is composed mainly of three oxides: silica (SiO_2), lime (CaO), and alumina (Al_2O_3). It also contains small quantities of magnesium oxide (MgO), sulphur trioxide (SO_3) and ferric oxide (Fe_2O_3). These oxides occur in various combinations, the mixture of which forms the cement. The principal compounds of Portland cement together with some of their characteristics are shown in Table 6. Appendix I contains the compound composition of Portland cement and gives the special use conditions for the five types covered by the ASTM specifications.

Cement sets by a process of hydration which is exothermic in nature. The process steps include gelation as well as crystallization. Both the gel and crystals are closely packed, fill the empty spaces between particles and hence result in high hardness products (24). Hydration depends more specifically on the surface exposed to the action of water than on the chemical constitution of the cement (55). This has been recognized since as early as 1918 when Duff Abrahams introduced the water-cement ratio law. The law states that "With given concrete materials and conditions of test, the quantity of mixing water used per bag of cement determines the strength of the concrete so long as the mix

is of workable plasticity." Photomicrographs have shown Portland cement types I and II to contain more unhydrated particles after 28 days of hydration than type III (31).

In the bonding of wood, cement is very vulnerable to toxic organic substances as stated earlier. Sugar and other compounds prevent the hydration process of cement. It should, however, be noted that since hydration depends on the amount of cement particle surface in contact with water, the wood particles might limit hydration by displacing water from the reaction sites, thereby reducing the amount of water needed for hydration to occur.

In massive construction such as large concrete dams, Portland cement liberates large quantities of heat (about 100 calories per gram of cement) (31). To avoid damage due to excessive heat, the composition of cement is usually altered so that the high heat-producing compounds, C_3S and C_3A, are present in lesser amounts. This results in 60 to 70 calories of heat per gram of cement. On the contrary, in the production of wood-wool slabs, rapid set or early attainment of maximum strength is desirable. For this reason high heat-producing cements are preferred (24, 29). The amount of hydration temperature and the time taken to reach maximum hydration temperature have been used as a measure of the suitability of woods for wood-cement board manufacture (24, 41, 52, 53). In essence, the rate at which wood is able to diminish the ability of high heat Portland cements to liberate heat, can be used as an index of its non-suitability for board manufacture. Type II Portland cement described in Table 7, which is rich in tricalcium silicate, and

alumino ferrite, has been highly favoured in wood-wool cement board manufacture.

2.1.2.2 Other Binders

Gypsum and magnesium cement are potential substitutes to Portland cement in the manufacture of wood-cement products.

Magnesium cement, often called Sorel cement, after its inventor, has mainly been used as a binder for the manufacture of the so-called HERAKLITH board, a wood-wool board bonded with magnesium oxysulphate (27). In some cases calcinated dolomite can successfully replace the more expensive magnesium oxide in magnesite cements (37). As dolomite is a mineral with wide occurrence (25), the possibility for using this binder in the manufacture of particleboards has good potential.

Gypsum has been used in the manufacture of gypsum wallboards. These boards are composed of gypsum core and a kraft paper wrapping and are widely used in indoor applications (46). Simatupang et al. (46), reported that FAMA International of Germany have since 1976, successfully introduced on the market a gypsum-bonded fibreboard using cellulose fibres of recycled newspaper as raw material. Gypsum, in the form of a hemihydrate ($CaSO_4 \cdot 1/2H_2O$) also called "Plaster of Paris" is used as a binder in the FAMA Process. In order to regulate crystallization, retarding additives are reportedly added (46).

Gypsum boards are generally weaker and more susceptible to variations in atmospheric humidity than cement boards (29). They are therefore not recommended for use under continuously humid and wet conditions. The increased use of gypsum as a binder in wood composites

will depend, among other things, on the development of an efficient method for increasing its moisture resistance.

2.1.3 Pretreatment of Wood

2.1.3.1 General

In order to increase the number of suitable wood species in wood-cement board manufacture, preventive, biological, and chemical treatments of wood aimed at improving cement setting and strength characteristics of the boards have been proposed and applied in many cases.

In addition to the treatments mentioned above, certain practices for reinforced bonding, which tend to counterbalance bond inhibitory effects have been reported. Such practices as the use of wire netting, addition of inert aggregates such as sand (2) were suggested (2, 30, 32, 47). Higher than normal cement ratios in the mix have been favoured in order to impart the required strength to panels.

2.1.3.2 Biological Treatments

Treatment of wood with blue-stain fungi (Ceratocystis pilifera) has been proposed by Davis (13). He claimed that this group of fungi when used to infect southern pine (Pinus spp.) wood during a period of more than 4 months, decreased setting time of the cement. Biblis et al. (5) also concluded from their investigations, that blue-stain fungi probably use the wood sugars that otherwise inhibit cement setting.

The feasibility of biological control is, however, still remote as it is difficult to avoid contamination of the blue-stain culture from

wood decay fungi. If the action of blue-stain fungi were faster, close control over a relatively short time might be feasible. Since the required treatment periods are generally long, prohibitively large storage facilities would be required for industrial wood procurement. Another disadvantage of stain fungi is that they can be used only to treat the living sapwood which is generally a relatively small portion of most trees.

2.1.3.3 Hot Water Extraction

Probably the simplest of pretreatments of wood in preparation for cement bonding is hot-water extraction. It has been reported (53) that hot-water treatment considerably reduces setting time of wood-cement slurry. The same workers (53) observed that the treatment shows a more pronounced setting-time reduction on cement mixed with heartwood than mixed with sapwood. Parker (35) used the hot-water pretreatment process in his studies on sawdust-cement boards in 1947. His treatment sequence was as follows:

1. Boil the sawdust in water.
2. Drain and wash with water.
3. Boil in a solution of ferrous sulphate in water.
4. Drain and rewash.

The use of ferrous sulphate was to precipitate the tannins as ferric tannate by oxidation. Sawdust of appreciable tannin content turned black when treated with ferrous sulphate. This stage can be omitted when sawdust of negligible tannin content is used. According to Parker (35), the hot-water treatment extracts soluble carbohydrates and

tannins, which otherwise dissolve readily in the slightly alkaline mixing water of the cement paste. It was observed that the treatment seemed to remove oily (fatty) material by the solution either in the steam or hot-water.

2.1.3.4 Chemical Pretreatments

Chemical treatments have been widely used to improve the bonding of wood to cement and hence improve the ultimate strength of the wood-cement panels. These treatments are applied with or without hot-water extraction.

Chemicals, commonly called "additives", which are industrially used at present include the following; chlorides of calcium and magnesium, silicates of sodium or potassium (waterglass) and a mixture of aluminum sulphate and lime water. Sanderman (42) also reported that calcium formate and calcium acetate are used as additives. When using chloride-containing additives, their metal corroding properties should be taken into account.

Calcium chloride has been used to reduce setting time of wood cement slurries. It was reported (5) that among various southern pine wood-cement mixtures, 1.0% $CaCl_2$ reduced setting time significantly. Christensen (10) found that diluted solutions of 1.0 to 3.0% $CaCl_2$ were required to neutralize the effects of 0.1% sugars on setting time. He also reported that up to 10% solutions of hydrated lime did not decrease the setting time in a wood-cement mixture to which 0.1% sugar was added. Kleinlogel (26), reported that incorporation of more than 4% $CaCl_2$ into the wood-cement mixture did, on the other hand, reduce the

strength of the final product. This could be attributed to the fact that the higher additive concentration results in an accelerated curing time, resulting in very high-hydration temperatures which are detrimental to the wood furnish. The corrosion effect (hydrolysis) could also be the cause of reduced strength when high $CaCl_2$ concentrations are used.

German wood-cement board producers disagree on preference of $CaCl_2$ to sodium silicate (Na_2SiO_3) as additives (50). Sodium silicate was preferred because of its efficiency, but $CaCl_2$ was preferred, in some cases, because of its availability.

Aluminum sulphate has also been used as an additive. Schmidt (43) suggested the use of 4 to 5% aqueous aluminum sulphate to minimize the inhibitory effect of sugars. According to Simatupang et al. (46), the effect of certain additives is influenced by the chemical composition of the cement. He suggested further investigations to establish the principal influence of various additives on cement of different chemical composition.

The chemical treatment of wood is commonly carried out in two ways. In the wood-wool industry, the wood-wool is soaked in the additive solution and excess water is removed. In the other application the solution of additives is sprayed onto the wood. According to Simatupang et al. (46) and Sanderman (42), dipping is not favoured due to the fact that the inhibiting compounds may leach out from the wood into the main solution.

3.0 MATERIALS AND METHODS

3.1 Experimental Design

The design of the experiment included three variables. There were five wood particle moisture content levels, three wood-cement ratios and three board density levels for each wood-cement ratio. The experimental design was as follows:

Five wood particle moisture content levels - 0-6%, 8-15%, 25-30%, 40-50% and 60-80%

Three wood-cement ratios - 1:1, 1:1.5 and 1:2

Three board density levels and resultant densities for each wood-cement ratio as follows:

Wood-cement ratio	Density level	Wood (gm)	Cement (gm)	Density (gm/cm^3)
1:1	1	300	300	0.472
	2	350	350	0.528
	3	400	400	0.622
1:1.5	1	300	450	0.636
	2	350	525	0.707
	3	400	600	0.809
1:2	1	300	600	0.763
	2	350	700	0.847
	3	400	800	0.939

All combinations of the above variables gave 45 treatments. Three replicate panels (boards) were made for each treatment, thus giving a total of 135 panels for the study.

Experimental Design - Layout

Test	Wood-cement ratio	Density level	Particle moisture content %				
			0-6	8-15	25-30	40-50	60-80
		1	3*	3*	3*	3*	3*
i) Static bending	1:1	2	3*	3*	3*	3*	3*
ii) Compress.//surface		3	3*	3*	3*	3*	3*
		1	3*	3*	3*	3*	3*
iii) Internal bond	1:1.5	2	3*	3*	3*	3*	3*
iv) Swelling in		3	3*	3*	3*	3*	3*
thickness +		1	3*	3*	3*	3*	3*
water absorp-	1:2	2	3*	3*	3*	3*	3*
tion		3	3*	3*	3*	3*	3*

N.B. 3* - Represents number of replications.

3.2 Preparation of Materials

3.2.1 Wood Particles Description

The wood particles used in the manufacture of the boards in this study were a mixture of White Spruce (Picea glauca) and Jack Pine (Pinus banksiana) obtained from a hammermill in Prince Albert, Saskatchewan. The average particle size was 2 to 15 mm long, 0.4 to 2.5 mm wide and 0.3 to 1.55 mm in thickness.

3.2.2 Magnesite Cement Description

The cement used in this study was 100 percent commercial dead burnt magnesium oxide (MgO) - based cement supplied by Kaiser Refractories, Oakland, California. There were no inert filler particles added to the

cement. The cement solids were of grain size passing 100 mesh and retained on 200 mesh screen, 70 percent passing 150 mesh.

3.2.3 Ammonium Polyphosphate (Reactant) Description

The reactant used for this study was an aqueous solution of commercial ammonium polyphosphate of analysis 10:34 (10% nitrogen as ammonia and 34% P_2O_5 as phosphate ion) having a specific gravity of 1.4 and a solid content of 40% by weight (37).

Based on 100 grams of solution, the relative weight proportions of the P_2O_5 contents of the orthophosphate and polyphosphate compounds of the commercial ammonium polyphosphate solution were:

Orthophosphate	7.20 parts
Pyrophosphate	10.10 parts
Tripolyphosphate	0.61 parts
Tetra and higher polyphosphate	0.20 parts

3.2.4 Mold

The mold used for the manufacture of the boards was made out of 19 mm lucite or plexiglass. The mold, shown in Figure 2, is comprised of three parts: the plunger, the frame and the base. The dimensions of the various parts of the mold are shown in Figure 3.

The mold was designed for manufacture of 405 mm x 176 mm (16" x 7") boards of any desired thickness.

3.2.5. Press

The press used in the manufacture of boards in this study was a laboratory size, single opening, hydraulic press with 900 square

centimetre platen area. It has a force capacity of 22,720 kg (50,000 lbs). The press model is 25-12-2TMB and manufactured by Wabash Metal Products Inc. of Indiana. The press is shown in Figure 4.

3.2.6 Manufacture of Magnesite Cement-Bonded Particleboard

3.2.6.1 Wood Particle Moisture Content Adjustment

A sample of wood particles was taken from each of the 5 bags received, for moisture content (oven-dry basis) determination. The procedure for determination of particle moisture content was in accordance with ASTM standard - D143-52 of 1980. Using the formula:

$$D = \frac{100W}{100+M}$$

where: D = wood particle green weight; W = weight of wood particles at known moisture content; M = wood particle moisture content to be attained, the amount of water needed to raise the moisture content of a certain weight of wood particles (W) at known moisture content, was calculated. The calculated amount of water was added to a known weight of wood particles (W) contained in a plastic bag. The contents were then thoroughly mixed. The bag and its contents was then sealed and stored in a cold room maintained at 35°F for a period of one month. The bags were shaken three times every week to ensure even distribution of the water added.

The average initial moisture content of the wood particles was found to be 15 percent. The lower particle moisture content of 0-6 percent required for the study was attained by conditioning the particles

in a controlled temperature and humidity (C.T.H.) chamber at 21% RH and 38°C.

After one month the final particle moisture content was determined before board manufacture, to ensure that the particles had attained the desired moisture content level.

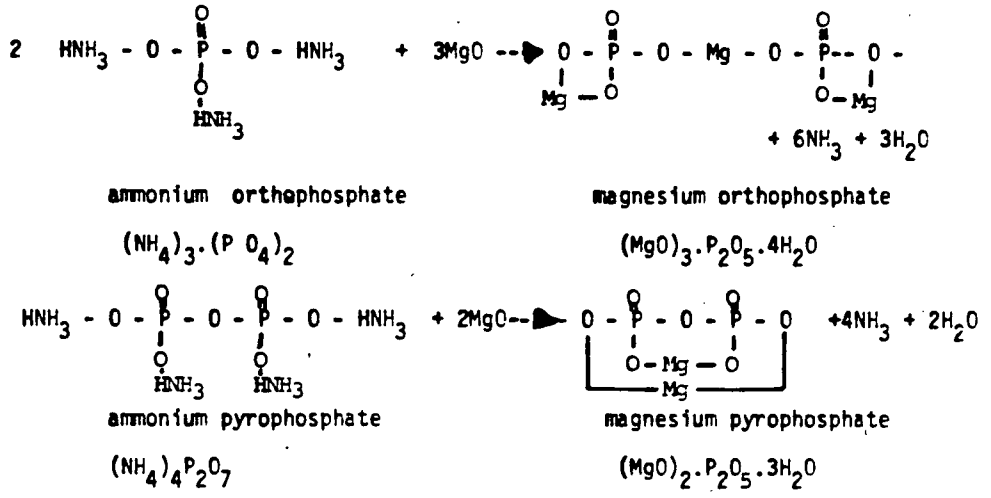
3.2.6.2 Mixing of Wood Particles with Reactant and Cement

According to the treatment combination desired (see Section 3.1) a known weight of wood particles was put in a 788 mm x 450 mm plastic bag. The reactant (an aqueous solution of ammonium polyphosphate) equivalent to 80 percent the weight of the cement, was added to the wood particles and the contents mixed thoroughly and allowed to stand for 3 minutes, so as to allow some of the catalyst to be absorbed into the wood particle surfaces while retaining a surface wetting film. The magnesite cement solids were then added as an adherent coating on the said wetting film and the contents again mixed thoroughly for 1 min and then quickly poured into the mold, levelled (using a leveller shown in Figure 5) and put under cold press.

3.2.6.2.1 The Reaction Characteristics

Upon applying the magnesite cement solids to the wetting film of ammonium polyphosphate on the wood particles, an exothermic reaction follows. Structural diagrams illustrative of the formation of oxyphosphate reaction products in aqueous solutions of ammonium orthophosphate and ammonium pyrophosphate (the two main components of the reactant), respectively, with magnesium oxide, as reported by

Paszner (37), are schematically indicated below:



3.2.6.3 Pressing Time and Control of Temperature

A press dwell time of 10 min was used in the manufacture of boards for this study. All boards were manufactured at room temperature of approximately 20 to 24°C. No heat was applied since the reaction is exothermic.

3.2.6.4 Pressure

The molded mass was held under compaction pressure developed by pressing the plunger and base against the molded mass. The molded mass was compacted so as to produce a board of 19 mm (3/4") thickness. The pressure was varied from 0.3 to 14 kg/cm^2.

3.2.6.5 Board Conditioning

After manufacture, the boards were stored for seven days in a fume cupboard to allow the ammonia gas that is generated during the reaction,

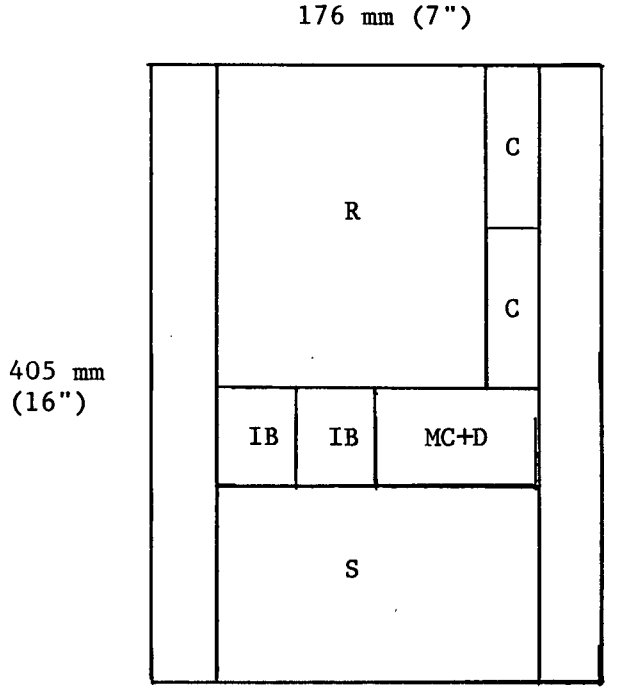
to escape. The boards were finally stored in the C.T.H. room, maintained at a temperature of 70°F ± 3.5°F, and a relative humidity of 50% ± 2%, for a period of 60 days before preparation of test specimens.

3.2.7 Test Specimen Preparation

3.2.7.1 Cutting of Specimens

The specimens were cut using a circular bench rip-saw and a cross-cut saw. The use of these saws did not imply a grain direction in the boards, but was for convenience. Both these saws were fitted with carbide sawteeth. No problems were encountered in sawing the boards using these saws. After cutting 120 running metres (360 ft) on the rip saw and 90 running metres (270 ft) on the cross-cut, no sharpening of the teeth was required.

3.2.7.2 Cutting Plan for Test Specimens



R	=	Static bending	200 mm x 100 mm (8" x 4")
C	=	Compression//surface	25 mm x 100 mm (1" x 4")
IB	=	Internal bond	50 mm x 50 mm (2" x 2")
S	=	Thickness swelling + water absorption	150 mm x 150 mm (6" x 6")
MC+D	=	Moisture content and density	

3.2.8 Board Testing Procedures

The following board properties were tested:

Modulus of elasticity - tested in accordance with BS 1811:1952 (see Appendix 2).

Modulus of rupture - tested in accordance with BS 1811:1952 (see Appendix 2).

Compression parallel to surface - tested in accordance with ASTM 1980:D1037-34.22 (see Appendix 3).

Tensile strength perpendicular to the surface (internal bond) - tested in accordance with ASTM 1980:D1037-28 (see Appendix 4).

Thickness swelling and water absorption - tested in accordance with ASTM 1980:D1037-100 (see Appendix 5).

3.2.9 Board Characterization

3.2.9.1 Moisture Content and Density

The moisture content and the density of the boards at test were determined in accordance with ASTM standards D1037-126 (see Appendix 6).

3.3 Statistical Analysis

Factorial analysis of variance[1] was performed in order to facilitate the interpretation of the main and interacting effects that could emerge, and to show the comparative performance of treatments. Treatments were analyzed with respect to compression, modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IB), thickness swelling and water absorption tests.

A step-wise regression was also performed with respect to edgewise compression, MOE, MOR and IB, in order to show main effects affecting these mechanical properties as well as their relative importance. The regression analysis was performed using the following power exponential fit equation:

$$f(R,M,D) = a(R^{b_1}\ c_1{}^{R}\ M^{b_2}\ c_2{}^{M}\ D^{b_3}\ c_3{}^{D})$$

where; f = Mechanical property (MOE, MOR, IB or compression)

R = Wood-cement ratio

D = Density

M = Initial particle moisture content

a = Constant

b's = Exponents of the power term

c's = Bases of exponential term.

Equations for prediction of edgewise compression, MOE, MOR, and IB were generated.

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[1]Analysis of variance for factorial experiment.

3.4 Scanning Electron Microscopy (SEM) Study

SEM studies were undertaken on tested internal bond specimens in order to obtain a preliminary indication on the effect of wood particle moisture content on the bonding between cement and wood in the magnesite cement particleboard. The nature of the failure in the internal bond test specimens was also observed.

SEM studies of main raw materials used in board manufacture (magnesite cement and ammonium polyphosphate) were also done in order to compare their crystal formations to those of the final reaction products. Electron micrographs of pure magnesium oxide (the main compound in the magnesite cement used) were also taken for comparison purposes.

The scanning electron microscope used for the study was an Autoscan model No. 26 manufactured by the Etec Corporation.

4.0 RESULTS AND DISCUSSION

4.1 Mechanical Properties

4.1.1 Modulus of Elasticity (MOE)

Table 8 summarizes the average MOE values for 45 treatment combinations of initial particle moisture content, density and wood-cement ratio. Boards made from 0-6% particle moisture content, wood-cement ratio 1:2 and density level 3 gave the highest MOE of 317.02 x 10^3 kg/cm^2. There is a general reduction in MOE values as the initial particle moisture content increases from 0-6% to 60-80%. The MOE values increase with increasing density and wood-cement ratio.

The factorial analysis[1] (Table 17) for MOE shows that initial particle moisture content A, density B and wood-cement ratio C and interactions A-B, B-C, A-C and A-B-C are all highly significant at 0.01 level. The significant interaction between the main effects A-B-C means that we cannot directly say which main effect has the greatest and least influence. However, this interaction may be more clearly understood by referring to Figures 8, 9, and 10. Figure 8 shows that MOE is lowest at initial particle moisture content of 60-80% and density 1. The highest MOE value of 81.19 x 10^3 kg/cm^2 is produced at density level 3 and 0-6% initial particle moisture content. Density level 3 consistently gives the highest MOE values followed by density level 2, indicating that density has a positive effect on MOE. At initial particle moisture contents of 0-6%, 8-15%, and 60-80%, the difference in MOE between density level 1 and 2 is small. Generally, there is an increase in MOE

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[1]Analysis of variance for factorial experiment.

with increasing density and a reduction in MOE values with an increase in the initial particle moisture content at all density levels.

As shown in Figure 9, at wood-cement ratio 1:1.5, density level 3 and an initial particle moisture content of 0-6% gave the highest MOE of 120.98 x 10^3 kg/cm^2. Although density level 3 consistently gave the highest MOE values at all levels of initial particle moisture content, the difference in MOE between density level 2 and 3 is consistently about 1.2 times, with no significant difference at 40-50% initial particle moisture content. As in Figure 8, an increase in the initial particle moisture content resulted in a reduction in MOE.

Figure 10 shows that at 1:2 wood-cement ratio, the highest MOE of 317.02 x 10^3 kg/cm^2 is produced at density level 3 and 0-6% initial particle moisture content. Apart from a sharp decrease in MOE as initial particle moisture content is increased from 0-6% to 8-15% at density level 3, the rate of decrease in MOE at the three density levels is not significantly different as confirmed by the nearly parallel lines.

The step-wise regression analysis of MOE as a function of density and initial particle moisture content, together with regression coefficients and standard errors of estimate are summarized in Table 22. Figure 29 shows MOE vs density curves predicted to best fit the data at different particle moisture content levels. Actual data points are shown.

From Table 22 it is shown that density with a regression coefficient of 2.6252, is the main factor affecting MOE. Figure 29 shows that at all levels of particle moisture content MOE increases with increasing

density. However, the rate of increase in MOE is slowest at particle moisture level 5 and highest at particle moisture level 1. The results shown in Figure 29 indicate that higher MOE is achieved as density is increased.

4.1.2 Modulus of Rupture (MOR)

The average MOR values for the 45 treatment combinations of initial particle moisture content, density and wood-cement ratio are summarized in Table 9.

In this test, again boards manufactured using 0-6% initial particle moisture content, density level 3 and wood-cement ratio of 1:2, gave the highest MOR of 52.10 kg/cm^2. From Table 9, it is noted that an increase in the initial particle moisture content had a general reduction effect on MOR and an increase in density resulted in an increase in MOR.

The results of the factorial analysis shown in Table 17, indicate that at 0.01 probability level, initial particle moisture content A, density B and wood-cement ratio C are all highly significant factors in the development of bending strength in magnesite bonded wood-cement boards. The interactions A-C and B-C are also highly significant at 0.01 level. These interactions are graphically shown in Figures 6 and 7.

From Figure 6, it is observed that the highest MOR of 36.60 kg/cm^2 is produced at a wood-cement ratio of 1:2 and density level 3. The 1:2 wood-cement ratio consistently gave the higher MOR values at all density levels followed by the 1:1.5 wood-cement ratio. However, the difference in MOR between the 1:2 and 1:1.5 wood-cement ratios, especially at density level 2, is not very pronounced.

Figure 7 shows that the highest MOR of 41.90 kg/cm^2 occurs at 0-6% initial particle moisture content, and 1:2 wood-cement ratio. The 1:2 wood-cement ratio consistently gives the highest MOR values at all particle moisture content levels. As in MOE, there is a decrease in MOR as initial particle moisture content is increased from 0-6% to 60-80%.

For this test, the most favourable MOR (52.0 kg/cm^2) is given by the treatment combinations of 1:2 wood-cement ratio, 0-6% particle moisture content and density level 3 (Table 9).

The results of the regression analysis for MOR are summarized in Table 22 and the predicted best fit curves are shown in Figure 30.

From Table 22, it is shown that wood-cement ratio followed by density are the two main factors affecting MOR. Wood-cement ratio has a regression coefficient of 3.3976 and density has a coefficient of 3.2399. Figure 30 shows that MOR increases with increasing density. This trend is true for all the initial particle moisture content levels. As with MOE, the increase in MOR as density increases is higher in particle moisture level 1 than level 5. However, the difference in MOR increase with density is small between 0-6% and 8-15% particle moisture contents, indicating that the change in MOR as initial particle moisture content is increased from 0-6% and 8-15% is not very pronounced.

4.1.3 Internal Bond Strength (IB)

Table 10 gives the average IB for the 45 treatment combinations of wood-cement ratio, initial particle moisture content and density.

Boards made with 1:2 wood-cement ratio at density level 3 and particle moisture content 0-6% produced the highest IB strength of 6.94

kg/cm^2. IB generally increased with an increase in density but was reduced as the initial particle moisture content increased.

Results of the factorial analysis of IB are summarized in Table 18. The results show that initial particle moisture content A, density B and wood-cement ratio C, significantly affect the IB strength in magnesite cement-bonded boards. Similarly, the interactions A-C and B-C are significant at 0.01 level. The interaction A-B is significant at 0.05 level.

From Figure 11, it is evident that wood-cement ratio 1:2 gives the highest IB strength of 4.82 kg/cm^2 at density level 3. Generally, at a wood-cement ratio of 1:2 highest IB strength at all density levels is obtained. There is an increase in internal bond strength with an increase in density.

Figure 12 shows that wood-cement ratio 1:2 consistently gives higher IB strength at all initial particle moisture content levels. As the particle moisture content increases, there is a tendency for IB strength to decrease. The difference in IB strength between the three wood-cement ratios gets smaller as the initial particle moisture content increases. This trend indicates that the influence of wood-cement ratio on IB strength diminishes as initial particle moisture content increases, yet it is the most significant factor in determining IB.

The regression analysis for IB strength is shown in Table 23. Curves that best fit the data for the five particle moisture content levels are shown in Figure 31. From Table 23, it is evident that density and initial particle moisture content are the two main factors affecting IB strength development in magnesite cement-bonded boards.

From Figure 31, it is noted that at particle moisture content level 1, IB strength rapidly increases as density increases. The rate of increase in IB strength diminishes as the initial particle moisture content is increased from level 1 to 5. Figure 31 also shows that the difference in the rate of increase between particle moisture content levels 3 and 4 and between 4 and 5 is small. This trend indicates that as the particle moisture content is increased from level 3 (25-30%) to level 5 (60-80%), the increase in IB strength as density increases becomes lower.

4.1.4 Compressive Strength Parallel to Surface (Edgewise Compression)

Table 11 summarizes the average edgewise compression results for the 45 treatment combinations of wood-cement ratio, density and initial particle moisture content.

In this test, the highest edgewise compression strength was obtained at 0-6% initial particle moisture content, 1:2 wood-cement ratio and density level 3. As in the other mechanical properties tested, boards made from high initial particle moisture content showed low edgewise compression strength. An increase in density, at any particle moisture content level, resulted in an increase in edgewise compression strength.

Factorial analysis of edgewise compression (Table 18) showed that the main effects, i.e. initial particle moisture content A, density B and wood-cement ratio C significantly affect edgewise compression at 0.01 level. Similarly, the interactions B-C and A-C are highly significant at 0.01 level.

Figure 13 shows that the wood-cement ratio of 1:2 gives the highest edgewise compression strength of 22.80 kg/cm^2 at 0-6% initial particle moisture content. The 1:1 wood-cement ratio gives the lowest edgewise compression strength of 2.80 kg/cm^2 at 60-80% initial particle moisture content. There is a general decrease in edgewise compression strength as the initial particle moisture content is increased. The 1:2 wood-cement ratio shows a sharp rate of change in edgewise compression as initial particle moisture content is increased while the rate of change in samples made with 1:1 and 1:1.5 wood ratio is smallest as the initial particle moisture content is increased from 0-6% to 8-15%. This trend indicates that at 1:1 and 1:1.5 wood-cement ratios, increasing the initial particle moisture content from 0-6% to 8-15% has no significant effect on edgewise compression strength.

Figure 14 shows that there is an increase in edgewise compression strength as the density level increases. The rate of increase in edgewise compression strength in the 1:1 wood-cement ratio exhibits a slow change from density level 1 to 2 and then a sharp change from density level 2 to 3. The 1:2 wood-cement ratio shows no big change between density levels 1 and 2, and 2 and 3. In the 1:1.5 wood-cement ratio the rate of increase in edgewise compression strength from density level 1 to 3 was found to be relatively constant. This behaviour indicates that at wood- cement ratio 1:1, the increase in density from level 1 to 2 has no major effect on edgewise compression strength while at 1:1.5 and 1:2 wood cement ratios, edgewise compression strength is more sensitive to an increase in density.

In this test, the highest edgewise compression strength of 23.70 kg/cm^2 is attained at 1:2 wood-cement ratio and density level 3. Density level 1 and 1:1 wood-cement ratio produced the lowest edgewise compression of 3.10 kg/cm^2.

Table 23 summarizes the results of the step-wise regression on edgewise compression strength. Figure 32 shows the best fit curves at different particle moisture content levels.

Table 23 shows that density and wood-cement ratio are the main factors affecting edgewise compression strength.

Figure 32 shows that samples made with 60-80% (level 5) initial particle moisture content have the least increase in edgewise compression strength as density is increased, while 0-6% (level 1) initial particle moisture content shows the sharpest rate of increase. The increase in initial particle moisture content from level 3 to 5 (25-30% to 60-80%) does not seem to have a significant effect on the rate of increase in edgewise compression strength with an increase in density.

4.2 Physical Properties

4.2.1 Moisture Content and Density of the Boards at Test

Table 12 gives the average moisture content of the boards at test (after 60 days in the CTH room) for 45 treatment combinations of density, wood-cement ratio and initial particle moisture content. Wood particles (mixture of White Spruce and Jack Pine) stored under identical conditions attained an equilibrium moisture content of 8.50 percent.

From Table 12, it is noted that boards made from higher initial particle moisture content furnish, tended to have a higher moisture

content. The variation in board moisture content between density levels within a wood-cement ratio is not statistically significant. This trend applies to all particle moisture levels.

Table 21 shows the average density of the boards at test (after 60 days in the CTH room) for 45 treatment combinations of particle moisture content, density and wood-cement ratio.

It will be noted from Table 21 that board density variation between wood-cement ratios and between particle moisture levels was significantly high.

4.2.2 Thickness Swelling

4.2.2.1 Thickness Swelling from 50% R.H. to 2 h Cold Soaking

Table 13 shows the average thickness swelling after 2 h cold soaking for 45 treatment combinations of particle moisture content, density and wood-cement ratio. In this test, the highest thickness swelling of 16.19% after 2 h cold soaking was obtained on the samples made with particles having their initial moisture content set at 0-6%, and formulated to a density level 3 and using a wood-cement ratio of 1:1. Generally an increase in the initial particle moisture content resulted in reduced thickness swelling, while an increase in density level had no significant effect on thickness swelling.

Factorial analysis results of thickness swelling after 2 h cold soaking (Table 19) indicate that initial particle moisture content A, wood-cement ratio C and the interaction A-C are highly significant at 0.01 level. From Figure 15 the highest thickness swelling of 15.170% after 2 h of cold soaking in water is produced by a treatment

combination of 1:1 wood-cement ratio and 0-6% initial particle moisture content. The lowest thickness swelling of 1.00% is given by 1:2 wood-cement ratio and 60-80% particle moisture content. The 1:1 wood-cement ratio shows a sharp decrease in thickness swelling as the initial particle moisture content increased. Similarly, the 1:1.5 and 1:2 ratios exhibit a decrease in thickness swelling with increasing initial particle moisture content but only up to 40-50% particle moisture content level. Thereafter the 1:1.5 ratio shows a significant increase in thickness swelling whereas the 1:2 ratio shows no significant increase in thickness swelling. It is thought that this trend is due to the variability in thickness swelling within and between the cement boards.

Wood-cement ratios 1:1.5 and 1:2 show (Figure 15) a small difference in thickness swelling at an initial particle moisture content of 25-30% and 40-50%. Generally, the difference in thickness swelling between the three wood cement ratios gets smaller with increasing initial particle moisture content.

4.2.2.2 Thickness Swelling from 50% R.H. to 24 h Cold Soaking

The average thickness swelling for 45 treatment combinations of initial particle moisture content, density and wood-cement ratio are shown in Table 14.

As in the 2 h test, boards made with 1:1 wood-cement ratio, 0-6% initial particle moisture content and density level 3 gave the highest thickness swelling of 18.80%. Generally an increase in the initial particle moisture content resulted in a decrease in thickness swelling whereas, an increase in density resulted in a slight increase in

thickness swelling. Surprisingly, extending the swelling time to 24 h resulted in little further swelling from that achieved in 2 h cold soaking. This observation indicates that 2 h cold soaking is adequate in the determination of thickness swelling in magnesite cement boards.

In Table 19, the factorial analysis results show that the main effects of initial particle moisture content A and wood-cement ratio C, are highly significant at 0.01 level. Similarly, the interaction between initial particle moisture content A, and wood-cement ratio C is highly significant. Figure 16 shows a similar trend to Figure 15. The treatment combination of 1:1 wood-cement ratio and initial particle moisture content set at 0-6% gives the highest thickness swelling value of 16.66%. The 1:2 wood-cement ratio and initial particle moisture content of 60-80% produced the lowest thickness swelling.

Figure 16 shows that all the wood-cement ratios exhibit a decrease in thickness swelling with increasing initial particle moisture content up to 40-50%. Thereafter the 1:1.5 wood-cement ratio shows a sharp increase in thickness swelling whereas wood-cement ratios 1:1 and 1:2 show a slow increasing trend in thickness swelling. As observed in the 2 h cold soaking test, the increase in thickness swelling from 40-50% to 60-80% initial particle moisture, is thought to be due to variability between and within the boards. With boards made of particles having initial moisture content 25-30%, the difference in thickness swelling between the 1:1.5 and 1:2 wood-cement ratios is very small (Figure 16).

4.2.3 Water Absorption

4.2.3.1 Water Absorption from 50% R.H. to 2 h Cold Soaking

Table 15 summarizes the average water absorption results for the 45 treatment combinations of particle moisture content, density and wood-cement ratio.

Boards made from the 1:1 wood-cement ratio, density level 1 and initial particle moisture content of 0-6% produced the highest water absorption value of 70.20%. Generally, an increase in the initial particle moisture content resulted in a decrease in water absorption.

It will be noted that the treatment combination producing the highest water absorption values in the 2 h cold soaking test did not correspondingly produce the highest thickness swelling. This trend is thought to be due to the loss of the excess polyphosphate solids which dissolve in water during the soaking.

The factorial analysis results of water absorption after 2 h cold soaking test are summarized in Table 20. The results indicate that the main effects namely, initial particle moisture content A, density B, and wood-cement ratio C and the interactions B-C and A-C are highly significant at 0.01 level. From the A-C interactions, which are shown graphically in Figure 18, the 1:1 wood-cement ratio gives the highest water absorption of 64.70% at 0-6% initial particle moisture content. The 1:2 wood-cement ratio gives the lowest water absorption value of 19.99% at 60-80% initial particle moisture content. The 1:1 wood-cement ratio consistently gives the highest water absorption percentage at all levels

of initial particle moisture content, followed by the 1:1.5 wood-cement ratio.

Generally, as the initial particle moisture content increases the water absorption rate decreases. This trend is true for all wood-cement ratios.

Figure 17 shows that the 1:1 wood-cement ratio gives the highest water absorption value of 60.74% at density level 1. The 1:2 wood-cement ratio gives the lowest water absorption value of 21.26% at density level 3. There is a general decrease in water absorption with an increase in density (Figure 17). The 1:1 wood-cement ratio consistently gives the highest water absorption percentage at all density levels.

4.2.3.2 Water Absorption from 50% R.H. to 24 h Cold Soaking

Table 16 shows the average water absorption values for 45 treatment combinations of wood-cement ratio, density and initial particle moisture content.

In this test, the highest water absorption of 95.20% was obtained on the boards made of furnish having an initial particle moisture content of 0-6%, a 1:1 wood-cement ratio and density level 1.

As in the 2 h cold soaking test, there is a decrease in water absorption with increasing initial particle moisture content. Similarly there is a decrease in water absorption with both increasing wood-cement ratio and density level.

Results of the factorial analysis of water absorption after 24 h immersion in water (Table 20) indicate that the main effects, particle

moisture content A, density B, wood-cement ratio C and the interactions A-C and B-C are highly significant at 0.01 level. The interaction A-B is significant at 0.05 level.

Figure 20 shows that the highest water absorption of 85.67% occurs at 1:1 wood-cement ratio and 0-6% initial particle moisture content. The lowest water absorption of 25.39% is given by boards made with the 1:2 wood-cement ratio at 60-80% initial particle moisture content. The 1:1 wood-cement ratio consistently results in higher water absorption at all levels of initial particle moisture followed by the 1:1.5 wood-cement ratio. All the wood-cement ratios exhibit a drop in water absorption as the initial particle moisture content is raised from 0-6% to 60-80%. Conversely, samples prepared with particles of high initial moisture content absorbed less water even on prolonged soaking.

Figure 19 shows that water absorption decreases with increasing density. The 1:2 wood-cement ratio shows a constant decrease in water absorption with increase in board density, while samples made from the 1:1 and 1:1.5 wood-cement ratios exhibit a slow initial decrease followed by a sharp decrease from density level 2 to 3. The highest water absorption of 79.40% for the B-C interaction is produced at 1:1 wood-cement ratio and density level 1.

4.3 Scanning Electron Microscopy (SEM) Observations

The results of the SEM study are shown on the electron micrographs in Figures 21 to 28.

Figures 21, 22 and 23 illustrate crystal formations in the pure magnesium oxide powder, dead burnt magnesite cement powder and dried

ammonium polyphosphate respectively. Pure magnesium oxide powder exhibits well-defined oval-shaped crystals (Figure 21), whereas crystals are scale-like in the dead burnt magnesite cement powder (Figure 22). Ammonium polyphosphate (Figure 23) is characterized by well defined rod-like crystals.

Figures 24 to 28 serve to illustrate the effect of initial particle moisture content on crystal formations in dead burnt magnesite cement-bonded particleboard manufactured using a 1:1 wood-cement ratio and at density level 1. Figure 24 shows electron micrographs of boards made from furnish with an initial particle moisture content of 0-6%. Well defined plate-like, near rectangular crystal formations are observed in Figure 24(i) and the great amount of wood failure is observed in Figure 24(ii). Boards manufactured from particles having 8-15% initial moisture content (Figure 25), show similar crystal formations to those observed in Figure 24. However, the crystal formations in Figure 25, though plate-like in appearance, are circular and closely packed together. Figure 26 shows a well-defined spade-like crystal formation in boards manufactured using 25-30% initial particle moisture content. Figure 27 and 28 represent electron micrographs for boards manufactured using 40-50% and 60-80% initial particle moisture content respectively. In Figures 27 and 28 there is no crystal formations observed.

From Figures 24 to 28, it has been shown that the oxyphosphate, which is the reaction product of dead burnt magnesite cement and ammonium polyphosphate has crystal formations which are dissimilar to the crystals of the reacting compounds shown in Figures 21 to 23. These micrographs indicate that successful high strength bond formation

between cement and wood is strongly moisture sensitive. Figures 24 to 26 indicate that the fully developed and well defined crystal formations appear to result in successful bond formation between cement and wood furnish having a relatively low initial moisture content. On the other hand, Figures 27 and 28 shows no crystal formation, indicating that the high initial particle moisture content of 40-50% and 60-80% respectively, interfered with the successful bonding between the wood and the cement. The poor bond formation observed in Figures 27 and 28, can be attributed to the premature precipitation of either the phosphate or oxyphosphate complex due to the excess water in the wood furnish.

From Table 10, it is observed that there is a decrease in internal bond strength as the initial particle moisture content increases from 0-6% to 60-80%. Treatment combinations represented by Figures 24, 25 and 26 show a higher internal bond strength than those represented by Figures 27 and 28. This observation indicates that fully developed and well defined crystal formation results in excellent bond strength. The high initial particle moisture content in Figures 27 and 28 interfered with the crystallization process which is evidently associated with high strength development.

4.4 Probable Factors Accounting for the Trends in Treatment

4.4.1 Mechanical Properties

Results obtained and presented in Tables 8 to 11 and those of the analysis of variance (Tables 17 and 18) and the step-wise regression (Tables 22 and 23), show beyond doubt that the main effects of initial

particle moisture content, density and wood-cement ratio and their interactions, have a significant effect on the development of mechanical strength in magnesite cement-bonded boards.

In all cases, increase in the initial particle moisture content resulted in a decrease in the mechanical properties of the boards (Figures 6, 7, 8, 9, 10, 12, 13). It is evident that moisture interferes either with the bonding between the wood particles and magnesite cement or seriously affect the strength and structure of the cement. The scanning electron microscopy study undertaken (Section 4.3) confirms the adverse effect of the high initial particle moisture content on the development of the mechanical properties of magnesite cement bonded boards.

Won-Yung et al. (56) have studied the bond formation in wood - Portland cement systems using scanning electron microscopy. They concluded that the bonding between the wood fragments and Portland cement was achieved by a mechanical interlocking mechanism. They attributed the mechanical interlocking phenomenon to the crystals that develop during the hydration of Portland cement, once water is added to the wood-cement mix.

Parameswaran et al. (34) also studied the interaction between Portland cement with wood particles in wood-Portland cement composites, using scanning electron microscopy and X-ray microanalysis. They observed that the inorganic substances of the Portland cement affect the woody tissue in that small particles penetrate into the cell wall. They noted that the impregnation with alkaline Portland cement solutions appeared to result in fine structural changes of the cell wall, which

also included the cellulose component. It is thought that this interaction between the wood fragment and mineral binder is responsible for enhanced durability of wood-cement composites against microorganisms, and noncombustibility of the wood.

In the board forming process employed in this study, the bonding between the wood fragments and the magnesite cement binder, as described by Paszner (37), differs slightly to that described by Won-Yung et al. (56) and Parameswaran et al. (34). Paszner (37) reported that the ammonium polyphosphate aqueous solutions penetrate the wood fragment, and subsequent drying results in the retention of a crystalline residue salt deposit within lumina and pores. These deposits were found to greatly enhance strength and flame retardant properties of the boards, the improvements generally increasing with loading up to the physical limit. Paszner (37) also observed that when an adhered mineral deposit of metal oxyphosphate is attached to the wood surface as a continuous anchored layer, the impairment of strength resulting from fissuring and cracking produced by cutting and crushing processes of forming wood fragments is not only offset, but the wood fragment gains intrinsic bending and compressive strengths, exceeding by about 100% (aspen) the air-dry values for clear whole-wood specimens. The gain in mechanical properties is thought to be due to the presence of a shell of mineral material at the fragment surface, through which the generated oxyphosphate compounds have migrated for distances 30 to 150 microns prior to the setting of the compound (37).

In the Paszner process, the formation of the shell of mineral-vegetable layer at the wood fragment surface is followed by the crystal-

lization of the colloidal metal oxyphosphates which have migrated into minute surface openings. Colloidal migration appears to be effected both by capillary transport of the suspending liquid or by mechanically-induced pressure gradients therein and by electrostatic forces within the catalyst solution i.e. by Brownian movement (37). The crystal formation was confirmed by the results of the SEM study (Section 4.3).

It is therefore evident from Paszner's (37) observation above, that wood fragments, whose cell lumina are saturated with water, will not be available for impregnation by the ammonium polyphosphate (reactant). If some catalyst does partially impregnate a nearly saturated cell lumen, the dilution effect of the cell lumen water will tend to wash away the salts of the reactant and make these unavailable for bonding. This will have an adverse effect on the amount of crystalline salt deposition. Similarly, it is suggested that when the reactant is applied to the surface of a wood fragment of high moisture content, followed by deposition of powdered magnesite cement, a high fluidity of the liquid/solid mixture will result prior to gelation. This high fluidity, it is suggested, will tend to make the cladding thickness uneven due to dripping, flowing and squeeze-out into interstical cavities, thereby also decreasing the cement layer thickness between the particles.

The reduction of cladding thickness and decreased cement penetration into the wood structure and the absence of properly crystallized, high-strength salt deposits on the fibre surface having had high initial moisture content, are thought to be the two most important factors responsible for the observed reduction in mechanical properties of boards made of wood particles having high initial moisture content.

It is thus obvious that for highest mechanical strength boards to be made, the initial particle moisture content must be as low as possible. The particle moisture content effect appears to be more pronounced with high wood-cement ratios (Figure 7). There also appears to be no break on the particle moisture content/MOR curves and hence no minimum initial particle moisture content above 15% can be recommended. The results appear to be highly consistent and the interactions highly significant.

4.4.2 Physical Properties

Results presented in Tables 13 and 14 show that there is an increase in thickness swelling from 2 to 24 h cold soaking of magnesite cement-bonded boards previously conditioned to 50% R.H. In Table 19 it is shown that initial particle moisture content A, wood-cement ratio C and the interactions of A and C all have a highly significant effect on the board thickness swelling following 2 to 24 h cold soaking test, respectively. On the other hand, density B and the interaction of A-B and B-C do not appear to affect significantly the thickness swelling of the boards following 2 to 24 h cold soaking tests.

Broker et al. (8) investigated the dimensional changes (thickness swelling and shrinkage) of Portland cement-bonded boards. The results of their investigation showed that the shrinkage and swelling of the Portland cement-bonded boards was independent of the wood component, but was strongly influenced by the shrinkage and swelling of the porous hydrated Portland cement.

However, results of the present study show that both the wood-cement ratio and the wood fragment have an effect on the thickness swelling of the magnesite cement-bonded boards. Figures 15 and 16, show that at all levels of wood-cement ratio, there is a decrease in thickness swelling as initial particle moisture content increased. Table 12 shows that after conditioning the boards at 50% R.H. for 60 days, the equilibrated moisture content of the boards showed an increasing trend as the particle moisture content increased from 0-6% to 60-80%. Further, an increase in the equilibrium moisture content of the boards was noted as the wood-cement was increased from 1:1 to 1:2.

It is therefore evident that since the wood fragments were partially filled with water, at the time of their encasement in the rigid oxyphosphate shell, their capacity to absorb more water and swell further is limited, resulting in little to no thickness swelling occurring. Regarding the effect of the wood-cement ratio, it is suggested that a high cement fraction results in the formation of a superior gel mass which is impermeable to water.

It is quite apparent that moisture absorption of the boards is controlled by the effects of both the initial particle moisture content and the wood-cement ratio. Since water absorption results in swelling, boards made of particles bonded in their maximum swollen condition will show a lesser tendency to pick up water. Unfortunately, this better dimensional stability property of the magnesite cement boards made of high moisture content fibres does not coincide with tendencies of maximum mechanical strength development. Thus, a compromise must be reached as to which parameter should be maximized in the product.

Obviously, the decision will depend on the most critical requirement i.e. strength versus dimensional stability.

4.5 Comparison of Study Results with some National Standards and Other Tests

4.5.1 German Standard for Cement-bonded Wood Particleboard

The product specifications of the German Standard DIN 52 361 and DIN 52 362 for cement-bonded particleboard are shown in the following table:

A. German Standard for cement-bonded wood particleboard.

Wood particle	Binder type	Density gm/cm^3 (DIN 52 361)	M.O.E $kg/cm^2 x10^3$ (DIN 52 362)
Flakes/shavings	Magnesium cement	0.9-1.50	70-130
Flakes/shavings	Portland cement	1.0-1.35	60-150
Wood Pulp	Gypsum	$\leq$ 1.0	40-70

Treatment combinations from this study that meet the above exterior grade cement-bonded particleboard requirements for MOE are summarized in the following table:

B. Test MOE results that meet German Standard DIN 52 362 for magnesite cement-bonded particleboard.

Wood/ cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		MOE, $kg/cm^2 \times 10^3$				
1:1.0	1	-	-	-	-	-
	2	-	-	-	-	-
	3	81.187	72.803	67.437	53.563	39.923
1:1.5	1	77.553	47.610	42.237	-	-
	2	110.393	99.800	73.950	61.960	42.917
	3	120.980	111.883	86.853	67.670	55.253
1:2.0	1	136.410	117.017	93.377	41.623	-
	2	156.777	140.917	126.523	88.647	55.633
	3	317.017	187.333	163.873	119.680	96.169

As noted from the comparison above, thirty-two of the forty-five treatments meet the specification requirements for the German Standard for modulus of elasticity.

It is evident from the above comparison that boards with a higher density and wood-cement ratio gave the highest MOE and hence met the standard requirement for cement bonded wood particleboard. It is interesting to note that denser boards made from very wet particles met the specification requirements. The implication of this observation is that it may not be necessary to dry wood particles prior to manufacture of magnesite cement-bonded particleboard in order to meet the German

specification for M.O.E. This can result in considerable heat energy savings.

4.5.2 Canadian Standard for Waferboard

No specified standard exists for cement-bonded particleboard in Canada and the USA. In this section an attempt will be made to compare the test results of the present study to waferboard standard specifications. Waferboard has been chosen for comparison because of its favourable growth in the exterior grade panel market. The cement-bonded particleboard is also intended for use as an exterior grade panel.

The properties specifications of the Canadian Standard Can 3 - 0188.0-M78 for waferboard are as follows:

C. Canadian Waferboard Standard.

Property	kg/cm^2
MOE	27,530.00
MOR	143.00
Tensile strength perpendicular to surface (IB)	2.85

Treatment combinations from this study, that meet the above requirements are as follows:

1. MOE

   Forty-one out of forty-five treatment combinations meet the minimum requirements specified by Canadian Waferboard Standard

for MOE. This implies that for use categories where MOE is of prime consideration the magnesite cement-bonded boards can favourably compete with waferboard. The treatment combinations that meet the MOE Canadian Waferboard Standard are indicated in Table 8.

2. MOR

From Table 9, there is no treatment combination that meets this Standard.

3. Internal Bond Strength

From the comparison in Table 10, eleven out of the 45 treatments combinations from the study, meet the Canadian Waferboard Standard requirements for IB strength.

4.5.3 International Organization for Standards (ISO)

Water absorption and thickness swelling of building boards (wood-based panel boards), when calculated according to I.S.O. Publication 769 shall not exceed the following values:

D. ISO requirement for water absorption and thickness swelling in building boards.

	Max water absorbed %[1]	Max swelling in thickness %[1]
Building board	40.00	20.00

[1] Based on immersion in 20°C water for 24 h ± 15 min.

Treatment combination from the study that meet the above requirement are as follows:

1. Thickness swelling after 24 h cold soaking (Table 14)

   All the 45 treatment combinations meet the I.S.O. building board requirements in thickness swelling.

2. Water absorption after 24 h cold soaking.

   Treatment combinations from the study that meet I.S.O. requirements are indicated in Table 16.

   Out of the 45 treatments, 18 treatment combinations meet the requirements. As noted in Figures 19 and 20 a decrease in water absorption results as the board density and particle moisture content increases. Thus, for manufacture of boards with acceptable water absorption and thickneses swelling the higher wood-cement ratios and higher density are favourable for this purpose. The initial particle moisture content should be as high as possible.

4.5.4 General

In tests carried out in Europe, Deppe (14) reported that single-layer cement-bonded wood chipboard (type DURIPANEL), in comparison with resin-bonded panel boards, are weaker in modulus of rupture, modulus of elasticity and internal bond strength. On the other hand, he reported that thickness swelling was much lower in the single-layered cement-bonded boards than in resin-bonded boards. For example, tests by

E.M.P.A. of Zurich-Dubendorf and the Universtat Karlsruhe and results reported by Deppe (14) showed the following properties for Portland cement-bonded and resin-bonded particleboard (resin-bonded boards in brackets):

(a) MOE 20,000 (32,000) kg/cm^2

(b) MOR 150 (220 $\pm$ 12) kg/cm^2

(c) I.B. strength 5.0 (4.0) kg/cm^2.

(d) Thickness swelling % after 24 h 2.7 (11.0)

(e) Shrinkage (air dry to normal) % 0.15 (0.25 to 0.50)

(f) Board density 1100 (750 $\pm$ 25) kg/cm^3

(g) Board thickness (mm) 11.5 $\pm$ 4 (13.0 $\pm$ 0.3).

From the above comparison, no MOR treatment combination from the study met the test results reported. Forty-one, five, and forty-one treatment combinations met the test results reported above for MOE, IB and thickness swelling, respectively.

5.0 SUMMARY AND SUGGESTIONS FOR FURTHER STUDY

5.1 Summary

The information listed below contributes to the knowledge of the effects of initial particle moisture content on the physical and mechanical properties of magnesite cement-bonded boards.

1. The analysis of variance and regression analysis performed have established that the initial particle moisture content has a pronounced effect on the physical and mechanical properties of magnesite cement bonded boards. An increase in initial particle moisture content resulted in a decrease in the physical and strength parameters tested. However, high initial particle moisture content is desirable if boards of low water absorption capacity are to be manufactured. The difference in most physical and mechanical properties tested has tended to be small between the 0-6% and 8-15% initial particle moisture content, thus no particle moisture content of more than 15% is recommended.

2. Similarly, the effect of wood-cement ratio (a major factor in manufacturing cost) is found to be highly significant in all the ANOVAs carried out. The effect of density is found highly significant in 6 of the 8 ANOVAs. However, the effect of density on thickness swelling from 50% relative humidity to 2 h and 24 h cold soaking was overshadowed by the significant effect of the initial moisture content of the fibre furnish.

This effect certainly would warrant closer anatomical and microscopic investigation.

3. The study has demonstrated that boards with high mechanical properties result as the wood-cement ratio and density increase. Wood cement ratio 1:2 at density level 3 gave the highest mechanical properties followed by 1:1.5 wood-cement ratio. However, magnesium oxyphosphate bonded boards did not reach the MOR values reported for DURISOL boards. This is possibly due to the lower density of the boards at equivalent wood-cement ratios.

4. Thirty-two out of the 45 treatments meet the requirements of the German Standard for the 3 categories of cement-bonded boards. However, only 21 of the treatment combinations pass the German requirements of the magnesite-bonded particleboards. It should be noted that at 1:2 wood cement ratio, boards made from wood particles with 40-50% and 60-80% moisture content pass the German Standard, while at the lower wood-cement ratio (1:1) only those boards made from lower particle moisture content (0-6% and 8-15%) pass the standard for cement-bonded boards.

5. The physical properties tested (thickness swelling and water absorption) are found to worsen with increasing wood-cement ratio, density and decrease in particle moisture content. It is found that 18 out of the 45 treatment combinations pass the

board water absorption of the I.S.O. standard while all the 45 treatments pass the thickness swelling I.S.O. standard requirement.

6. It is found that the boards manufactured in this study, exhibit, in comparison to resin-bonded boards:
   (a) substantially lower MOR and comparable MOE
   (b) but possess higher internal bond strength, lower thickness swelling and water absorption (a favourable occurrence).

5.2 Suggestions for Further Study

Conclusive evidence has been presented for the effect of the initial particle moisture content on the physical and mechanical properties of magnesium oxyphosphate cement-bonded particleboard. The study has also shown that depending on treatment combinations of particle moisture content, density and wood-cement ratio, boards that meet the I.S.O. and German standard specifications for similar boards can be manufactured. An immediately suggested area of study is as follows:

The cost of dead burnt magnesium oxide-based cement powder is in the region of US$0.17/lb. This cost is considerably high. However, it has been shown in initial tests by Paszner (37) that an inert material such as raw powdered dolomite can successfully replace a major part of the more expensive magnesium oxide. It is suggested that a study should be carried out to determine the level of magnesium oxide replacement with dolomite at which undersirable loss in mechanical and physical properties occurs. Such a study would have a far-reaching impact on the economics of the board manufactured by this technology.

6.0 CONCLUSION

The findings of this study are considered to be of interest to the would-be manufacturers of the cement-bonded particleboard using phosphate activated dead burnt magnesite cement as the binder. There is no doubt that the short curing time, coupled with the favourable physical and mechanical properties of the boards made by this process will be of great interest in both developed and developing countries.

The boards manufactured in this study show properties which meet the European products codes and compare favourably with products made by the conventional Portland cement technology. It is, however, noted that due to the inertness of the cement bonding process to wood sugars and phenolics, all wood species can be used for the process. The rapid room temperature curing characteristics of the phosphate activated magnesite process provides further advantages in product processing and reduced material handling within the plant.

In order to manufacture ammonium polyphosphate activated magnesite cement boards of favourable mechanical properties, an initial particle moisture content of not more than 15% is recommended, together with 1:2 wood-cement ratio at density level 3. Favourable dimensional stability properties (thickness swelling) are achieved when an initial particle moisture of more than 25% and 1:2 wood-cement ratio with density level 3 are used.

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TABLE 1. Some distinguishing features of mineral-bonded wood composites*

	Less compressed mineral-bonded wood composites		Higher compressed mineral-bonded wood composites		
Structure of material	coarse-porous	porous	compact surface		
Wood particle/fibre	wood-wool	flakes, shavings, sawdust	flakes, shavings	flakes, shavings	wood pulp
Particle dimensions length width in mm thickness	 500 3-6 0.2 - 0.5	 4-60 2-15 to nearly 6	 10-30 1-3 nearly 0.3 (partially fine particle surface)	such as resin bonded particle board	<0.001
Actual binders	Portland cement and magnesium cement	Portland cement	Portland cement	magnesium cement	gypsum
Density in g/cm^3 by DIN	0.36 - 0.57 1101	0.45 - 0.80 1101	1.0 - 1.35 52 361	0.9 - 1.15 52 361	<1.0 52 361
Bending strength in N/mm^2 by DIN	0.4 - 1.7 1101	0.4 - 2.0 1101	6.0 - 15 52 362	>7.0 - 13.0 52 362	4.0 - 7.0 52 362
Fire test by DIN 4102 A2 = non-combustible B1 = difficult inflammable	difficult inflammable B1	difficult inflammable non-combustible* B1	difficult inflammable non-combustible* A2-B1	difficult inflammable A2-B1	non-combustible A2
Names	wood-wood light-weight building boards acc. to DIN 1101 and 1104	DURISOL-ISO-Span-, ISO-Tex-, VELOX-building elements	BER-building elements* Duripanel Famapanel Isopanel	Homogen Pyroverth*	Fermacell
Products	Boards	Boards, mouldings, building elements	boards, mouldings	boards	boards
Information	Bundesverband Leichtbauplatten Beethovenstr. 8 D-8000 Munchen 15		Informationsverbund Massivbau-Dämmsteine Postfach 1348 D-8190 Wolfratshausen		

*Source: Simatupang (46).

TABLE 2. Comparison of raw materials, processing features and mechanical properties of cement- and magnesite-bonded wood particle boards*

	Cement-bonded	Magnesite-bonded	
		Pyroverth-olok[1]	Homogen - M[2]
Wood particles	free from cement inhibitors	wood and agricultural residues	
Binder	Portland cement	calcined magnesite	
Additives	$Al_2(SO_4)_3 + Ca(OH)_2$	$MgCl_2$ or $MgSO_4$	
Manufacturing process			
Setting time	8 - 24 hrs	approx. 10 min.	
Equipment	special equipment due to long setting time	conventional wood particles board machinery with slight modifications	
Ratio binder/wood	2.5:1	1 - 1.5:1	approx. 1.0:1
Board properties			
Specific gravity (air dry)	1.25	0.87	1.15
Bending strength (N/mm^2)	10.0 - 13.0	7.0	13.0
Compression strength (N/mm^2)	15.0	not available	110.0
Fungal resistance	good	not known	good
Termite resistance	good	not known	susceptible - good[3]
Fire resistance (DIN 4102)	B1	A2	B1
Thickness swelling after 2 h water soaking	0.8 - 1.2%	4	4

A2 = non combustible
B1 = difficult inflammable

1) Joachim Hille, D-2000 Hamburg 36, Jungfernstieg 36, West Germany.
2) Osterreichische Homogenholzges. mbH, A-8775 Kalwang, Austria.
3) Depends on termite species.

*Source: Sumatupang (46).

TABLE 3. Effect of variation of ambient temperature on onset of gelling and development of a temperature maximum for 75:25 mixture of silica sand and dead-burnt magnesite cement*

Curing parameter	Ambient temperature, T, °C				
	+32	+27	+22	+15	-1
Gelling Time, $T_{crit.}$, min	3	5	7	25	150
Cure Time, $T_{max.}$, min	18	20	23	56	280
Exotherm Max. Temp. °C	68	63	56	40	17

*Source: Paszner (36).

TABLE 4. Wood raw material for production of wood-cement boards

Cellulosic materials	Particle type	Final product wood/cement combination
Round wood (logs) slabs, edgings, trimmings	wood wool	wood-wool cement boards
Round wood (logs) slabs, edgings trimmings	crushed wood*	cement-wood boards
Sawdust, shavings and chips	fine or coarse particles	sawdust, wood chip or wood shaving concrete board
Fibres, flax, straw and bagasse	fibre or crushed particles	bagasse - or flax-fibro-cement board

*Source: Korneyev (30)

TABLE 5. Chemical components of the cell wall substance in normal wood*

I. PRIMARY COMPONENTS	
A. Total polysaccharide fractions expressed as holocellulose	60-70 percent
1. Cellulose ... ... (Long chain polymer with low solubility)	40-50 percent
2. Hemicellulose ... ... Noncellulosic polysaccharides; these are readily soluble in dilute alkali and hydrolyzable by dilute acids to component sugars and uronic acids.	15-20 percent
B. Lignin	15-35 percent
II. SECONDARY COMPONENTS	
A. Tannins	
B. Volatile oils and resins	
C. Gums, latex, alkaloids, and other complex organic compounds including dyes and coloring materials.	
D. Ash	less than 1 percent

*Source: Panshin et al. (33)

TABLE 6. Principal compounds in Portland cement*

Name of compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

*Source: Larson (31).

TABLE 7. The behaviour of principal components which occur in Portland cement*

Property	Relative behaviour of each compound**			
	C_3S	C_2S	C_3A	C_4AF
Rate of reaction	Medium	Slow	Fast	Slow
Heat liberated, per unit of compound	Medium	Small	Large	Small
Cementing value per unit of compound:				
Early	Good	Poor	Good	Poor
Ultimate	Good	Poor	Poor	Poor

* Source: Larson (31).

**C_3S is tricalcium silicate; C_2S, Dicalcium silicate; C_3A; Tricalcium aluminate; and C_4AF, Tetracalcium aluminoferrite.

TABLE 8. Interaction of particle moisture content, density and wood-cement ratio on modulus of elasticity

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Modulus of Elasticity, $kg/cm^2 x 10^3$				
1:1	1	32.947*	28.610*	13.487	13.370	11.727
	2	36.650*	36.537*	34.167*	28.583*	14.317
	3	81.187*	72.803*	67.437*	53.563*	39.923*
1:1.5	1	77.553*	47.610*	42.237*	39.700*	29.743*
	2	110.393*	99.800*	73.950*	61.960*	42.917*
	3	120.980*	111.883*	86.853*	67.670*	55.253*
1:2	1	136.410*	117.017*	93.377*	41.623*	29.313*
	2	156.777*	140.917*	126.523*	88.647*	55.633*
	3	317.017*	187.333*	163.873*	119.680*	96.164*

*Indicates treatment combination results that meet Canadian Waferboard Standard requirements for MOE.

TABLE 9. Interaction of particle moisture content, density and wood-cement ratio on modulus of rupture

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Modulus of Rupture, kg/cm^2				
1:1	1	8.390	7.573	3.070	2.253	1.800
	2	13.100	11.463	8.187	6.313	5.117
	3	25.173	16.547	13.097	9.467	7.523
1:1.5	1	20.673	13.917	12.400	9.620	3.477
	2	38.273	27.427	16.987	13.550	7.873
	3	41.957	37.723	30.227	23.123	16.167
1:2	1	35.407	25.170	18.010	9.007	5.113
	2	38.067	29.173	22.823	15.713	10.297
	3	52.103	44.310	36.313	27.387	22.873

TABLE 10. Interaction of particle moisture content, density and wood-cement ratio on internal bond strength

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Internal Bond, kg/cm^2				
1:1	1	0.916	0.833	0.639	0.499	0.339
	2	1.610	1.288	1.198	0.722	0.639
	3	2.499	1.846	1.666	0.916	0.876
1:1.5	1	1.860	1.541	1.332	0.985	0.639
	2	3.402*	2.374	2.138	1.693	1.166
	3	4.332*	2.707	2.499	1.943	1.527
1:2	1	3.776*	3.320*	2.332	1.249	0.694
	2	5.636*	4.235*	2.916*	1.926	1.470
	3	6.942*	5.803*	4.915*	3.776*	2.666

*Indicates treatment combination results that meet the Canadian Waferboard Standard requirements for IB.

TABLE 11. Interaction of particle moisture content, density and wood-cement ratio on compressive strength parallel to surface

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Compressive strength parallel to surface, kg/cm^2				
1:1.0	1	4.420	4.070	2.737	2.527	1.757
	2	7.370	5.403	3.510	2.490	2.107
	3	13.123	11.540	8.910	7.440	4.423
1:1.5	1	9.683	8.943	5.613	4.777	2.753
	2	14.243	12.807	10.703	8.527	6.320
	3	19.053	18.650	15.617	11.687	9.473
1:2.0	1	17.893	17.020	5.790	4.833	4.130
	2	22.107	19.647	16.837	9.477	7.190
	3	28.377	26.843	24.887	21.230	17.017

TABLE 12. Interaction of particle moisture content, density and wood-cement ratio on board moisture content at test

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Board moisture content %				
1:1	1	10.133	11.333	13.633	14.867	15.467
	2	10.833	11.600	14.333	15.767	16.267
	3	11.033	12.517	13.233	16.000	16.900
1:1.5	1	11.207	12.067	15.067	15.167	16.267
	2	11.800	12.833	15.067	16.733	16.867
	3	12.267	13.667	14.667	17.167	15.600
1:2	1	13.033	14.067	16.067	16.300	16.500
	2	13.400	15.133	16.500	15.767	16.533
	3	13.700	15.300	16.633	17.633	17.830

*EMC of wood furnish (White Spruce and Jack Pine mixture) under identical conditions was 8.50%.

TABLE 13. Interaction of particle moisture content, density and wood-cement ratio on thickness swelling after 2 h cold soaking

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Thickness swelling %				
1:1	1	15.407	8.897	2.737	2.633	2.187
	2	13.917	12.090	3.917	2.793	1.293
	3	16.187	9.930	3.760	1.683	1.443
1:1.5	1	6.797	4.513	2.057	1.290	1.253
	2	7.880	3.930	2.770	1.810	2.783
	3	8.187	3.820	2.203	0.647	1.717
1:2	1	3.610	2.623	2.007	1.507	1.090
	2	3.563	2.583	1.650	0.680	1.347
	3	4.157	2.863	2.190	0.487	0.553

TABLE 14. Interaction of particle moisture content, density and wood-cement ratio on thickness swelling after 24 h cold soaking

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Thickness swelling %				
1:1	1	16.313	10.627	3.663	3.100	3.850
	2	14.880	13.500	4.227	3.737	3.367
	3	18.800	11.307	4.500	2.220	3.947
1:1.5	1	7.520	5.313	2.273	2.047	1.697
	2	9.333	6.200	3.830	2.043	5.200
	3	9.107	4.847	2.637	1.930	4.487
1:2	1	4.610	3.303	2.730	1.957	1.790
	2	4.140	2.967	2.040	1.043	1.630
	3	5.193	3.577	2.627	1.190	2.270

TABLE 15. Interaction of particle moisture content, density and wood-cement ratio on water absorption after 2 h cold soaking

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Water absorption %				
1:1	1	70.223	63.563	61.210	61.930	46.760
	2	66.543	57.637	59.863	54.330	47.063
	3	57.263	51.770	48.970	50.020	37.807
1:1.5	1	45.113	39.217	39.803	37.060	31.643
	2	41.870	36.767	35.873	32.853	28.480
	3	35.333	30.247	27.637	32.043	26.033
1:2	1	25.857	24.187	26.137	24.557	21.180
	2	26.583	24.650	23.270	22.333	20.313
	3	25.067	21.703	21.523	19.673	18.340

TABLE 16. Interaction of particle moisture content, density and wood-cement ratio on water absorption after 24 h cold soaking

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Water absorption %				
1:1	1	95.190	82.347	77.223	75.440	66.697
	2	91.050	72.330	77.607	69.883	62.647
	3	70.773	62.667	61.287	61.093	52.547
1:1.5	1	60.917	56.617	53.307	48.200	42.913
	2	60.760	48.470	48.287	42.107	41.350
	3	45.683	36.393*	34.610*	40.883	33.653*
1:2	1	37.087*	34.960*	33.960*	30.373*	27.593*
	2	34.193*	31.690*	28.727*	26.920*	25.890*
	3	32.213*	28.233*	25.497*	24.123*	22.687*

*Indicates treatment combination results that meet the ISO Standard requirements for water absorption.

TABLE 17. Analysis of variance for testing the effects of particle moisture content, density and wood-cement ratio on MOR and MOE in cement-bonded particleboard

Src. No.	Source	D.F.	Sum of squares	Mean square	F value	F. Prob.
ANALYSIS OF VARIANCE FOR VARIABLE MODULUS OF RUPTURE						
1	Moisture (A)	4	7837.431074	1959.357666	164.0359	0.0000**
2	Density (B)	2	5290.605228	2645.302490	221.4627	0.0000**
3	AB	8	140.735446	17.591919	1.4728	0.1776
4	W/C ratio (C)	2	6692.250833	3346.125244	280.1350	0.0000**
5	AC	8	1046.745375	130.843170	10.9541	0.0000**
6	BC	4	442.820172	110.705032	9.2681	0.0000**
7	ABC	16	314.158665	19.634903	1.6438	0.0732
8	Error	90	1075.021933	11.944688		
9	Total	134	22839.768726			
ANALYSIS OF VARIANCE FOR VARIABLE MODULUS OF ELASTICITY						
1	Moisture (A)	4	98652.096388	24663.023438	61.7286	0.0000**
2	Density (B)	2	78992.633024	39496.316406	98.8546	0.0000**
3	AB	8	10096.653132	1262.081543	3.1588	0.0035**
4	W/C ratio (C)	2	172152.270135	86076.125000	215.4384	0.0000**
5	AC	8	39513.250532	4939.156250	12.3621	0.0000**
6	BC	4	16544.635163	4136.156250	10.3523	0.0000**
7	ABC	16	14935.878215	933.492188	2.3364	0.0062**
8	Error	90	35958.552000	399.539307		
9	Total	134	466845.968588			

**Significant at 0.01 level.

TABLE 18. Analysis of variance for testing the effects of particle moisture content, density and wood-cement ratio on internal bond strength and compressive strength parallel to surface

Src. No.	Source	D.F.	Sum of squares	Mean square	F value	F. Prob.
ANALYSIS OF VARIANCE FOR VARIABLE INTERNAL BOND STRENGTH						
1	Moisture (A)	4	89.095596	22.273895	77.2174	0.0000**
2	Density (B)	2	59.039160	29.519577	102.3362	0.0000**
3	AB	8	5.036775	6.295969E-01	2.1826	0.0359*
4	W/C ratio (C)	2	127.065196	63.532593	220.2498	0.0000**
5	AC	8	24.270048	3.033755	10.5172	0.0000**
6	BC	4	13.506140	3.376534	11.7055	0.0000**
7	ABC	16	1.763792	1.102369E-01	0.3822	0.9833
8	Error	90	25.961123	2.884569E-01		
9	Total	134	345.737830			
ANALYSIS OF VARIANCE FOR VARIABLE COMPRESSION//SURFACE						
1	Moisture (A)	4	1551.253144	387.813232	68.5518	0.0000**
2	Density (B)	2	2044.713761	1022.356689	180.7170	0.0000**
3	AB	8	55.658127	6.957266	1.2298	0.2906
4	W/C ratio (C)	2	2608.437228	1304.218506	230.5403	0.0000**
5	AC	8	242.171550	30.271439	5.3509	0.0000**
6	BC	4	254.139941	63.534973	11.2308	0.0000**
7	ABC	16	126.354793	7.897174	1.3959	0.1615
8	Error	90	509.150400	5.657227		
9	Total	134	7391.878944			

* Significant at 0.05 level.
**Significant at 0.01 level.

TABLE 19. Analysis of variance for testing the effects of particle moisture content, density and wood-cement ratio on thickness swelling after 2 h and 24 h cold soaking

Src. No.	Source	D.F.	Sum of squares	Mean square	F value	F. Prob.
ANALYSIS OF VARIANCE FOR VARIABLE THICKNESS SWELLING: 50% R.H. to 2 h cold soaking						
1	Moisture (A)	4	1102.298941	275.574707	206.3927	0.0000**
2	Density (B)	2	2.061453	1.030726	0.7720	0.4690
3	AB	8	14.600450	1.825056	1.3669	0.2212
4	W/C ratio (C)	2	485.138564	242.569275	181.6731	0.0000**
5	AC	8	441.349828	55.168716	41.3188	0.0000**
6	BC	4	3.207049	8.017622E-01	0.6005	0.6663
7	ABC	16	24.619381	1.538711	1.1524	0.3215
8	Error	90	120.167667	1.335196		
9	Total	134	2193.443333			
ANALYSIS OF VARIANCE FOR VARIABLE THICKNESS SWELLING: 50% R.H. to 24 h cold soaking						
1	Moisture (A)	4	1168.691551	292.172852	159.9616	0.0000**
2	Density (B)	2	7.717213	3.858606	2.1125	0.0000**
3	AB	8	23.359698	2.919962	1.5986	0.1246
4	W/C ratio (C)	2	608.858258	304.428955	166.6717	0.1356
5	AC	8	464.813720	58.101700	31.8101	0.0000**
6	BC	4	16.797502	4.199375	2.2991	0.0000**
7	ABC	16	32.812364	2.050773	1.1228	0.3468
8	Error	90	164.386733	1.826519		
9	Total	134	2487.437040			

**Significant at 0.01 level.

TABLE 20. Analysis of variance for testing the effects of particle moisture content, density and wood-cement ratio on water absorption after 2 h and 24 h cold soaking

Src. No.	Source	D.F.	Sum of squares	Mean square	F value	F. Prob.
ANALYSIS OF VARIANCE FOR VARIABLE WATER ABSORPTION: 50% R.H. to 2 h cold soaking						
1	Moisture (A)	4	2310.570341	577.642578	64.7348	0.0000**
2	Density (B)	2	1363.540013	681.769775	76.4041	0.0000**
3	AB	8	73.731201	9.216400	1.0329	0.4178
4	W/C ratio (C)	2	24625.742443	12312.871094	1379.8704	0.0000**
5	AC	8	548.409628	68.551193	7.6823	0.0000**
6	BC	4	286.547973	71.636978	8.0282	0.0000**
7	ABC	16	106.662856	6.666428	0.7471	0.7395
8	Error	90	803.088667	8.923207		
9	Total	134	30118.293133			
ANALYSIS OF VARIANCE FOR VARIABLE WATER ABSORPTION: 50% R.H. to 24 h cold soaking						
1	Moisture (A)	4	4073.753249	1018.438232	70.0652	0.0000**
2	Density (B)	2	3828.178601	1914.089111	131.6831	0.0000**
3	AB	8	301.358147	37.669754	2.5916	0.0136*
4	W/C ratio (C)	2	40998.176313	20499.085939	1410.2700	0.0000
5	AC	8	627.592480	78.449051	5.3970	0.0000**
6	BC	4	592.671256	148.167801	10.1935	0.0000**
7	ABC	16	243.455284	15.215955	1.0468	0.4174
8	Error	90	164.386733	1.826519		
9	Total	134	51973.387197			

* Significant at 0.05 level.
**Significant at 0.01 level.

TABLE 21. Interaction of particle moisture content, density level and wood-cement ratio on board density at test

Wood-cement ratio	Density level	Particle moisture content %				
		0-6	8-15	25-30	40-50	60-80
		Board density gm/cm^3				
1:1	1	0.515	0.545	0.423	0.447	0.429
	2	0.592	0.569	0.498	0.528	0.452
	3	0.655	0.687	0.606	0.602	0.558
1:1.5	1	0.711	0.694	0.636	0.605	0.534
	2	0.782	0.762	0.678	0.707	0.604
	3	0.840	0.882	0.821	0.773	0.731
1:2	1	0.812	0.839	0.761	0.715	0.688
	2	0.895	0.868	0.845	0.883	0.746
	3	0.933	1.028	0.905	0.924	0.904

TABLE 22. Details of curve fitting of MOE and MOR

Variable	Partial	Coefficient	Std. error[1]	T-stat	Signif.**
		MOE			
CONSTANT		$5.3183=b_0$	0.53413-1	99.570	0.0000
LNDNS	0.89477	$2.6252=b_1$	0.11403	23.022	0.0000
MOISFRAC	-0.49338	$-0.72820=b_2$	0.11174	-6.5170	0.0000
		MOR			
CONSTANT		$8.3061=b_0$	1.3582	6.1154	0.0000
LNDNS	0.60263	$3.2399=b_1$	0.21476	15.086	0.0000
MOISFRAC	-0.60263	$-1.0874=b_2$	0.12629	-8.6102	0.0000
WCRATIO	-0.24423	$-3.9492=b_3$	1.3753	-2.8715	0.0048
LNWC	-0.28398	$3.3976=b_4$	1.0061	3.3769	0.0010

N.B. LNDNS - Log density
MOISFRAC - Moisture fraction
LNWC - Log wood-cement ratio
WCRATIO - Wood-cement ratio

**Significant at 0.01 level.
[1]Standard error of regression parameters.

TABLE 23. Details of curve fitting of edgewise compression and IB strength

Variable	Partial	Coefficient	Std. error[1]	T-stat	Signif.**
		Edgewise compression strength			
CONSTANT		3.2971=b_0	0.17667	18.662	0.0000
LNDNS	0.77787	3.2619=b_1	0.23024	14.167	0.0000
LNMF	-0.38745	-0.1405=b_2	0.29217-1	-4.8103	0.0000
LNWC	0.23682	0.51232=b_3	0.118363	2.7899	0.0000
		IB strength			
CONSTANT		-2.4939=b_0	0.16064	-15.524	0.0000
LNDNS	0.81528	3.7323=b_1	0.23073	16.176	0.0000
LNMF	-0.49970	-0.21695b_2	0.32733-1	-6.6280	0.0000

N.B. LNDNS - Log density
LNWC - Log wood-cement ratio
LNMF - Log moisture fraction

**Significant at 0.01 level.
[1]Standard error of regression parameters.

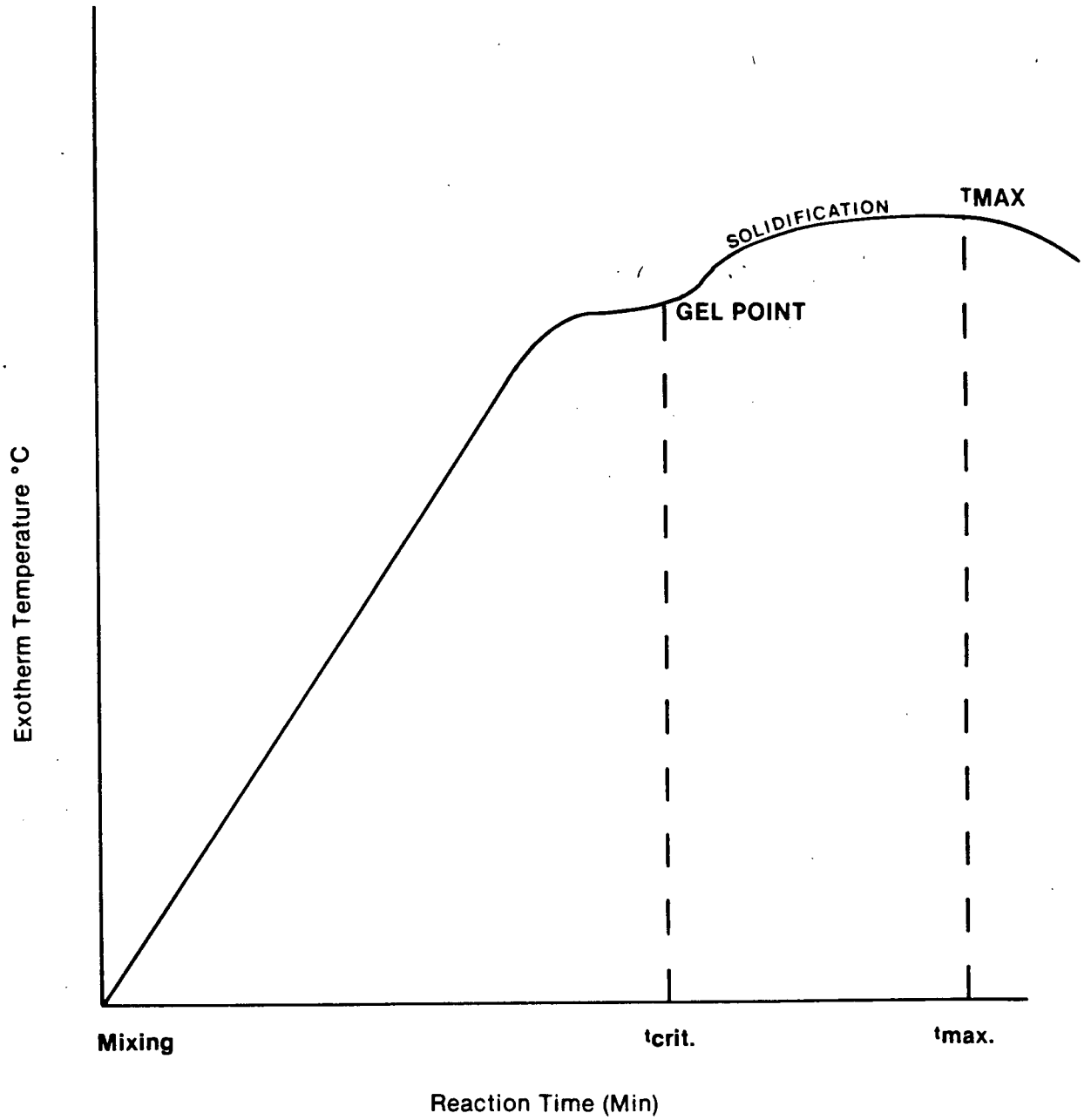

Fig. 1

Exotherm Characteristics of Ammonium Polyphosphate Activated Magnesium Oxide Cements.

Source: Paszner (**36**)

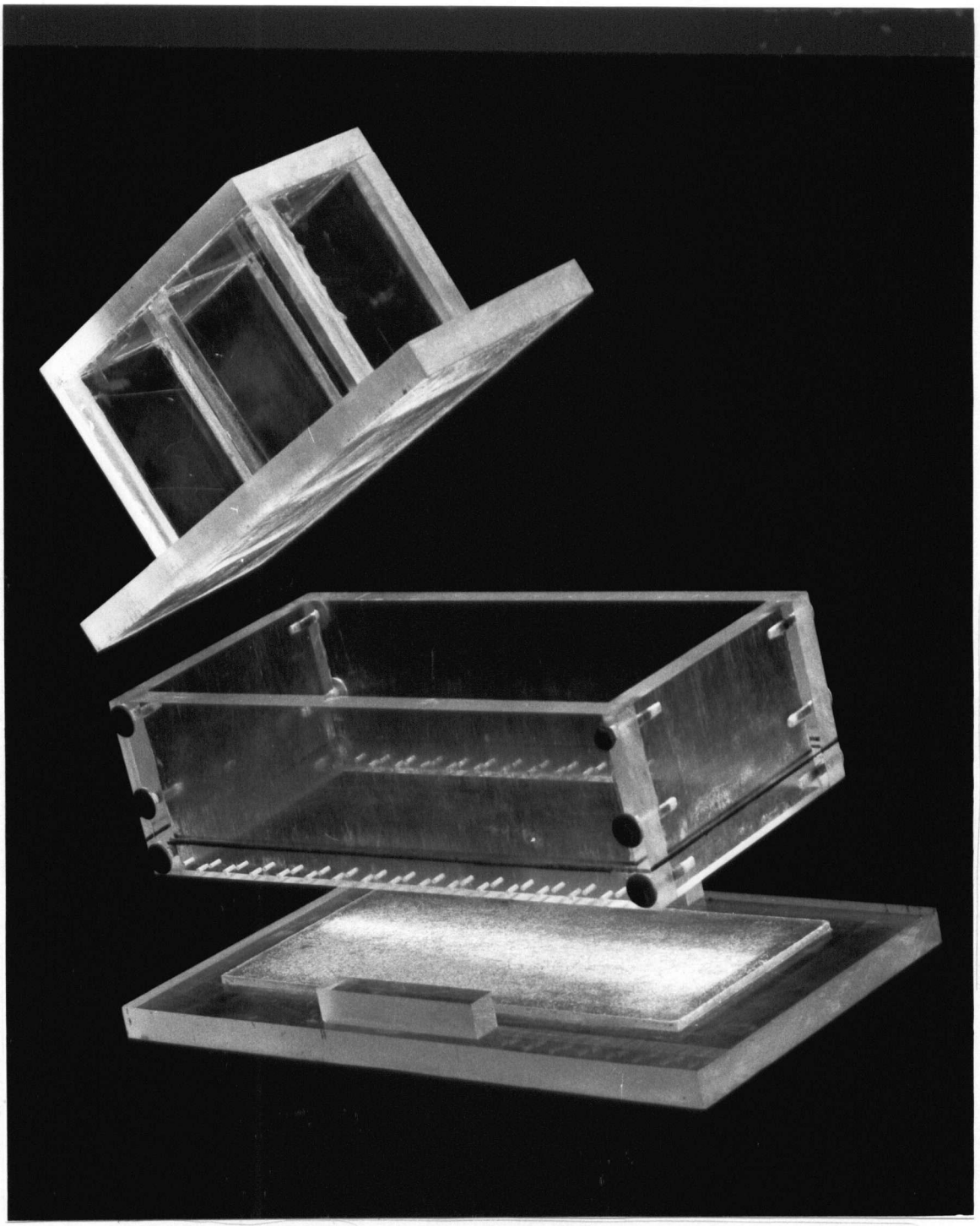

Figure 2. Parts of Mold

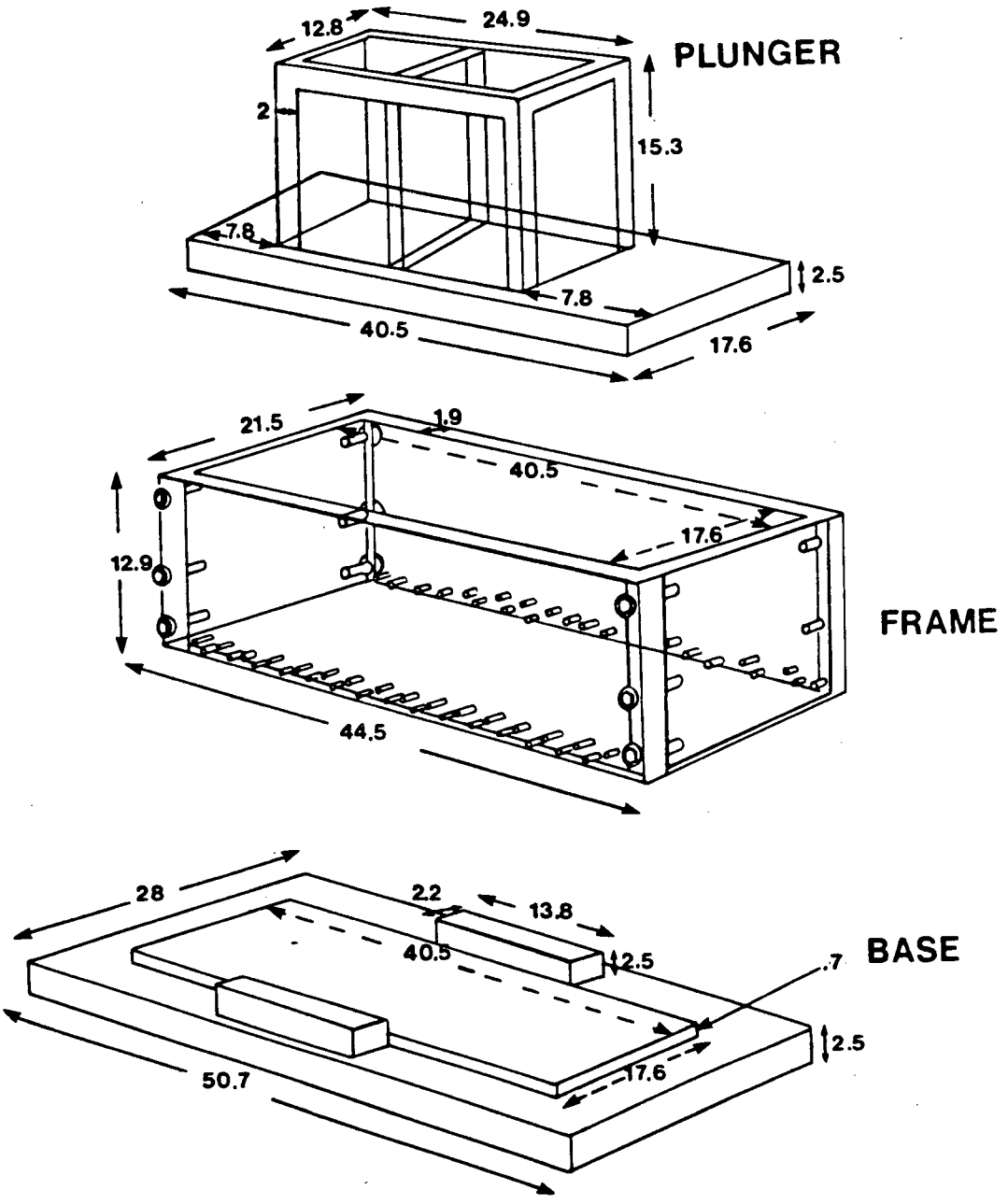

Figure 3. Dimensions of mold

Figure 4. Single opening press

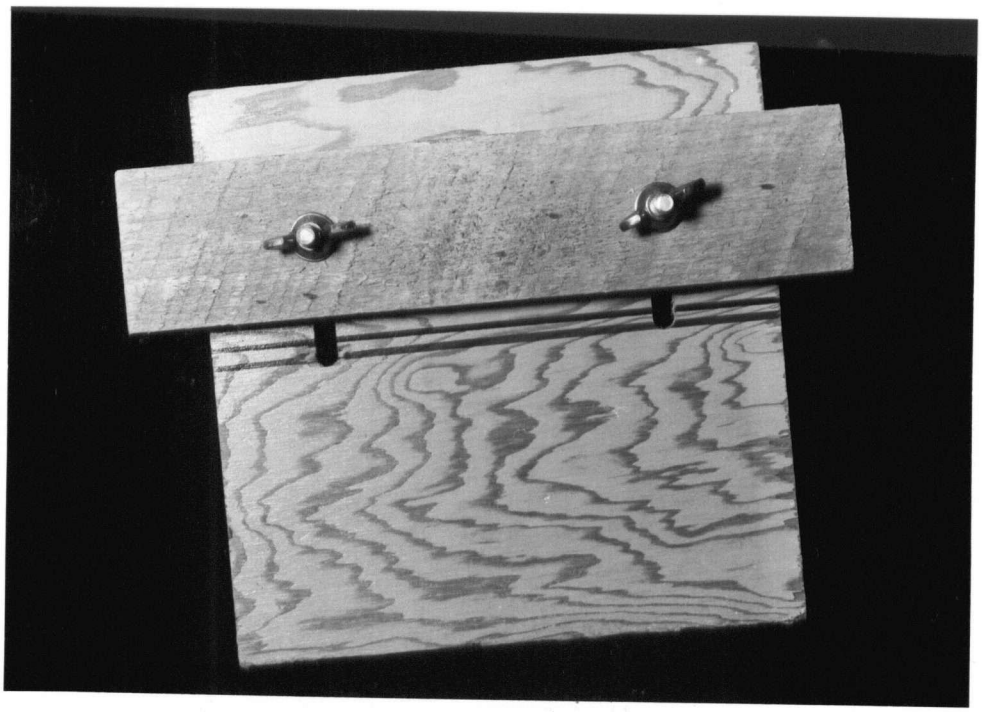

Figure 5. Leveller

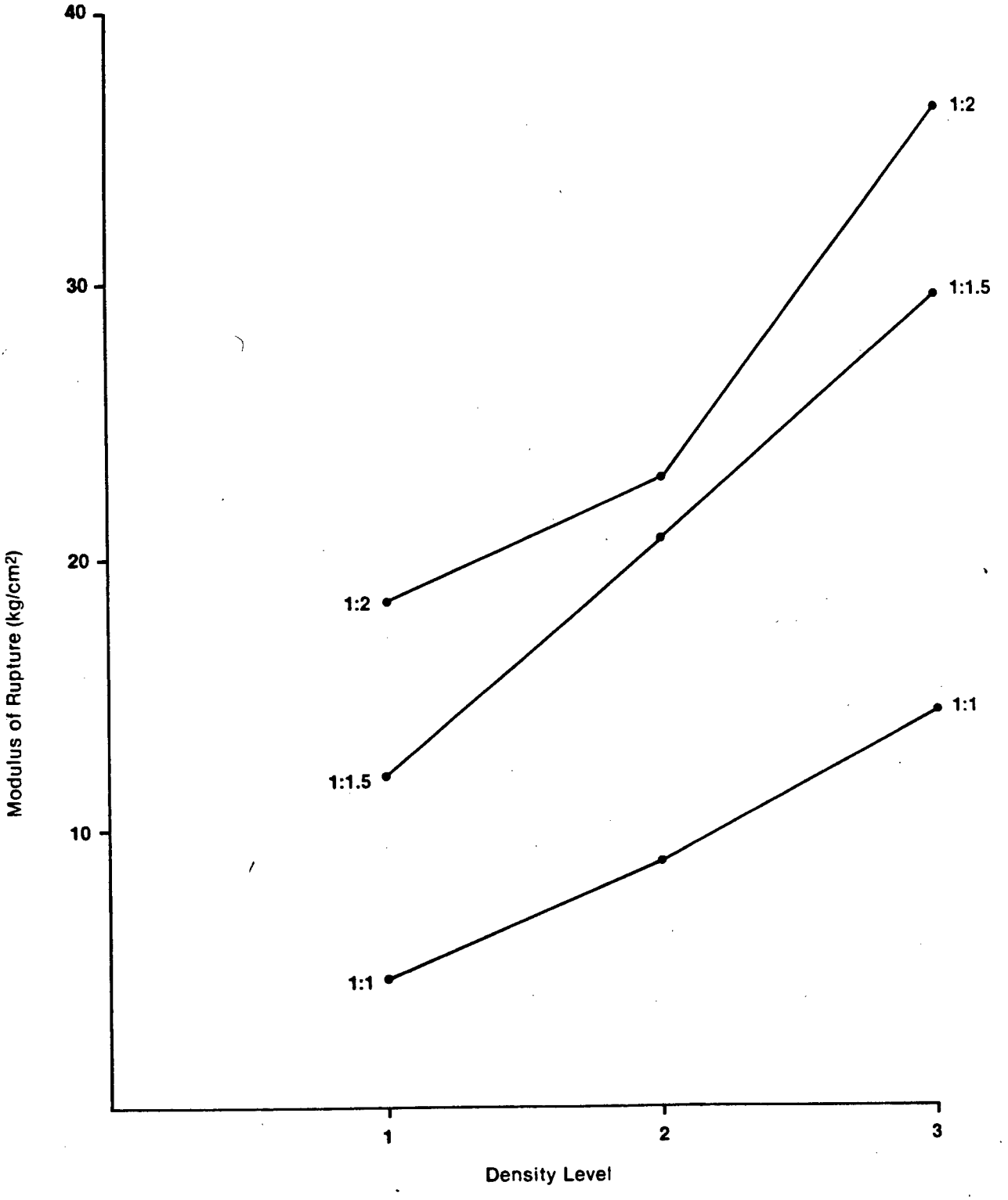

Fig. 6

Dependence of Modulus of Rupture on Density and Wood-Cement ratio interaction.

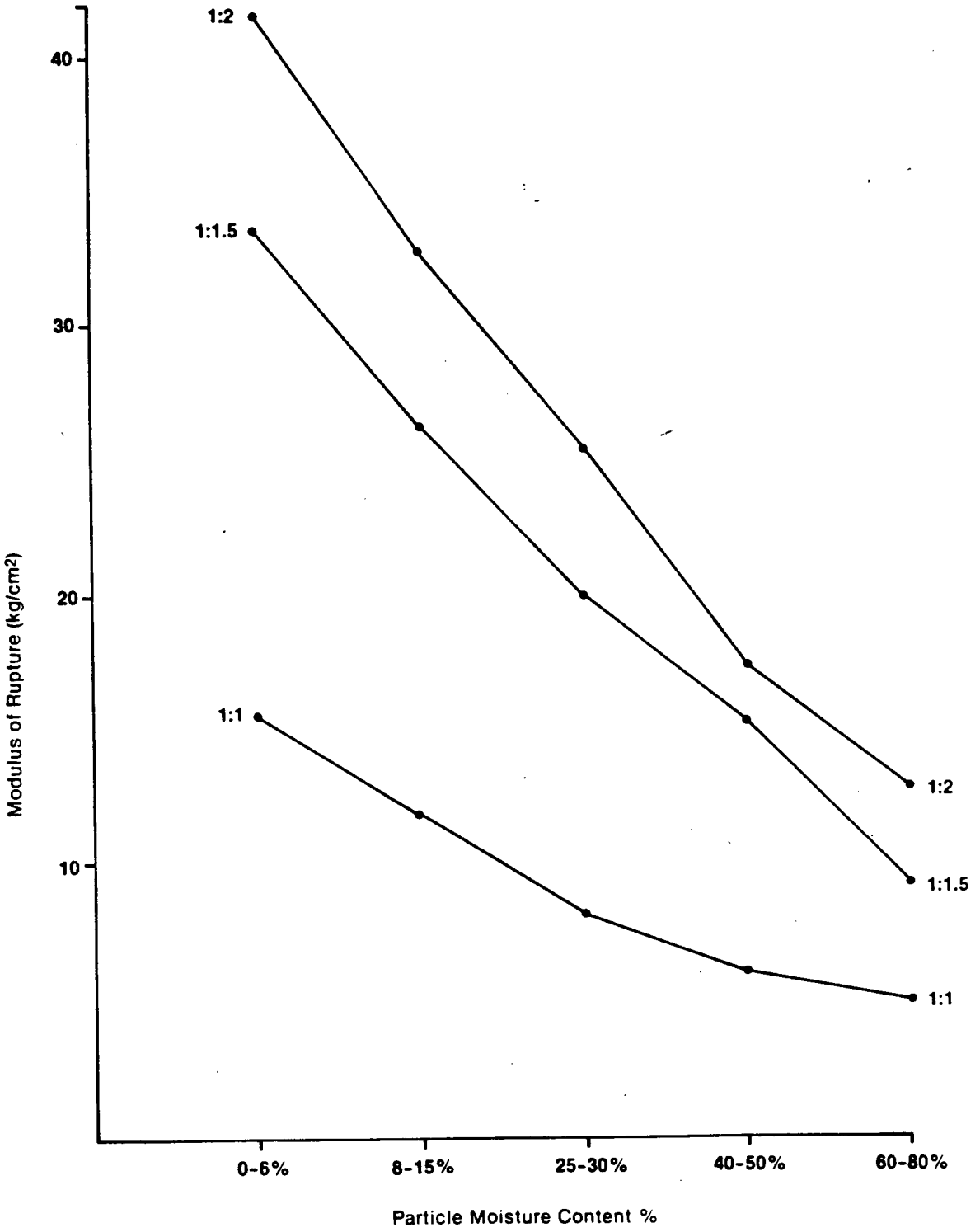

Fig. 7

Dependance of Modulus of Rupture on Particle Moisture Content and Wood-Cement ratio interaction.

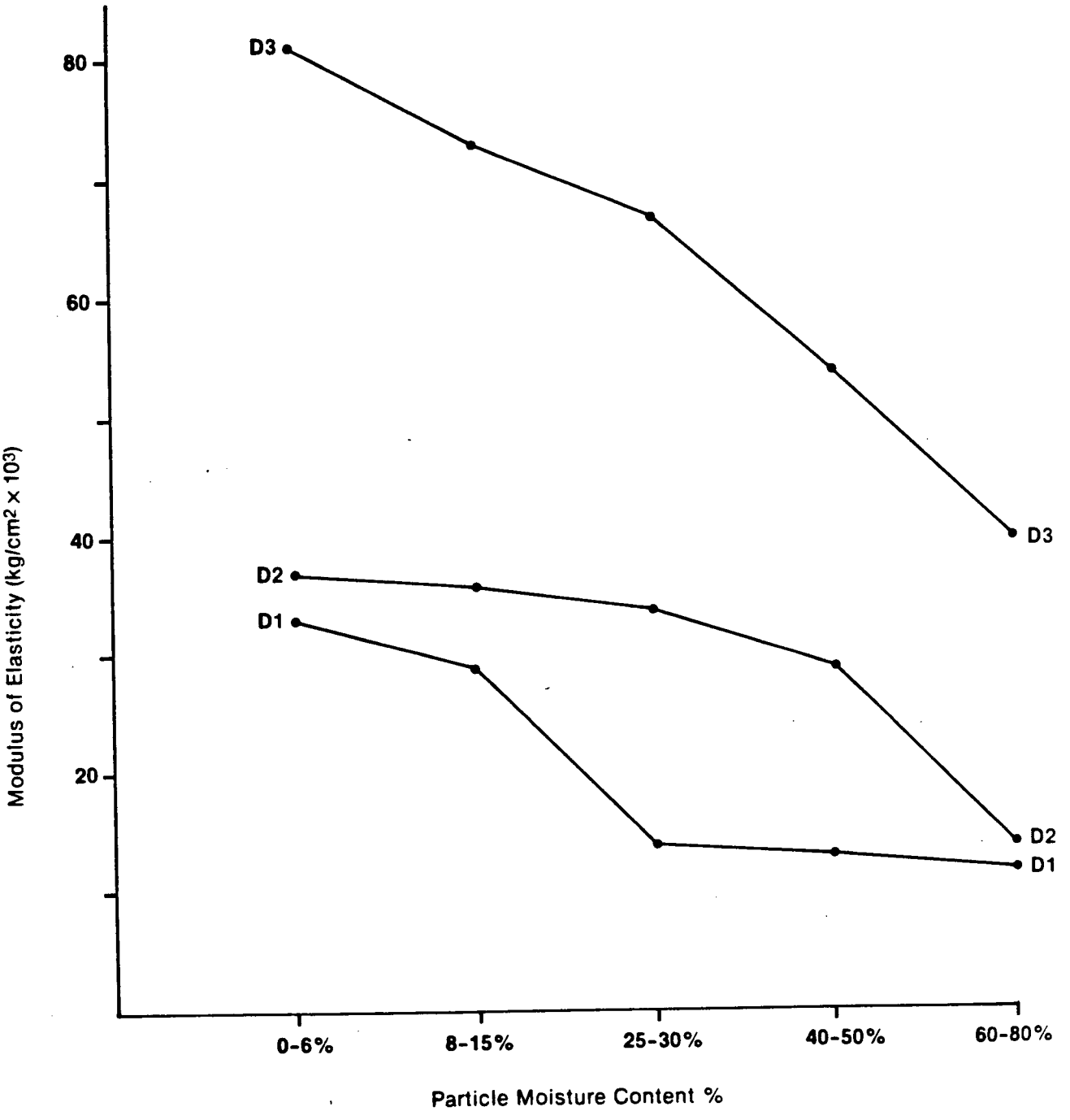

Fig. 8

Dependence of Modulus of Elasticity on Particle Moisture Content and Density interaction (*at 1:1 Wood-Cement Ratio*). (Wood-Cement ratios: 1:1.5 and 1:2 held constant.)

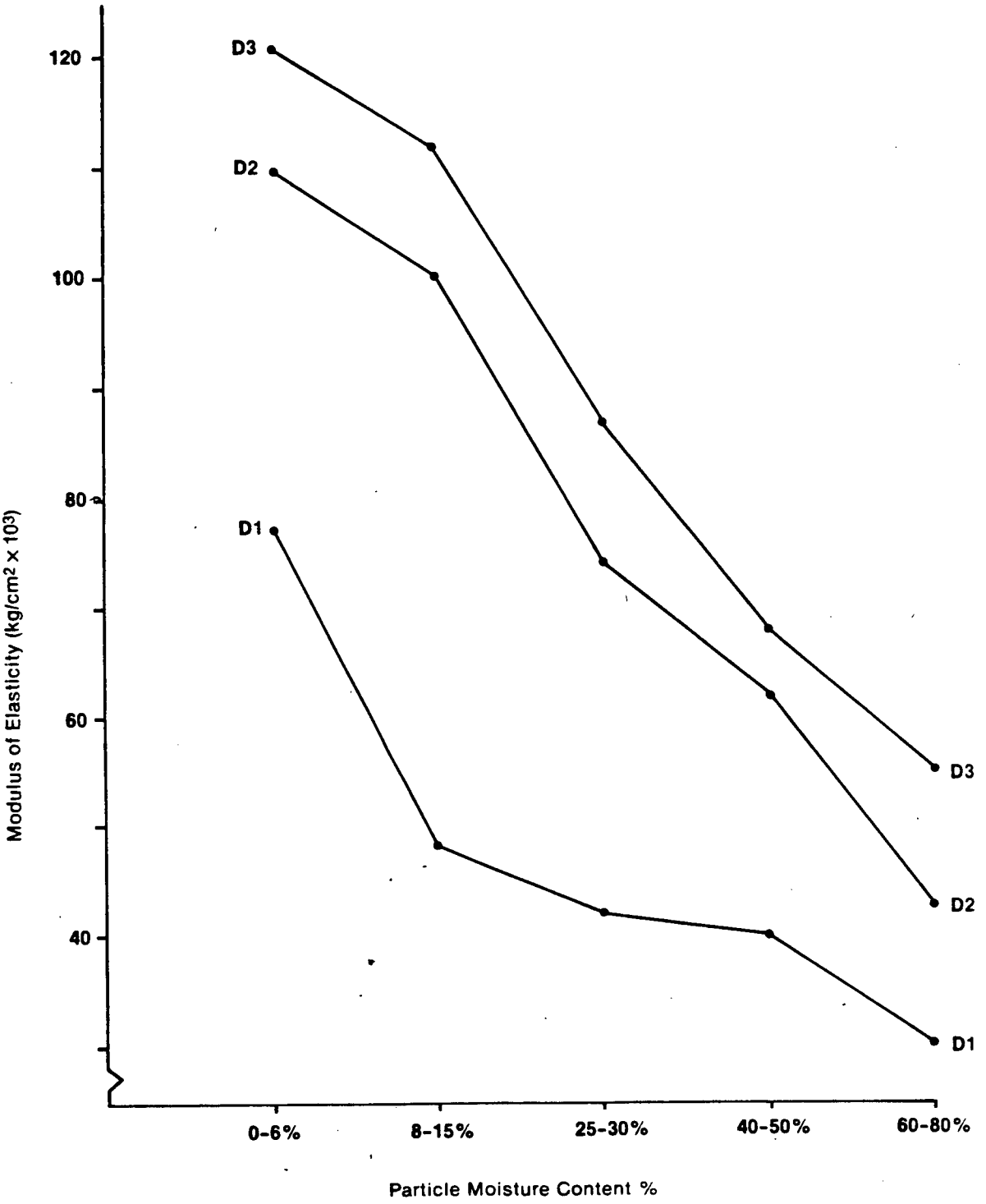

Fig. 9

Dependence of Modulus of Elasticity on Particle Moisture Content and Density *at 1:1.5 Wood-Cement Ratio.*(Wood-Cement ratios: 1:1 and 1:2 are held constant.)

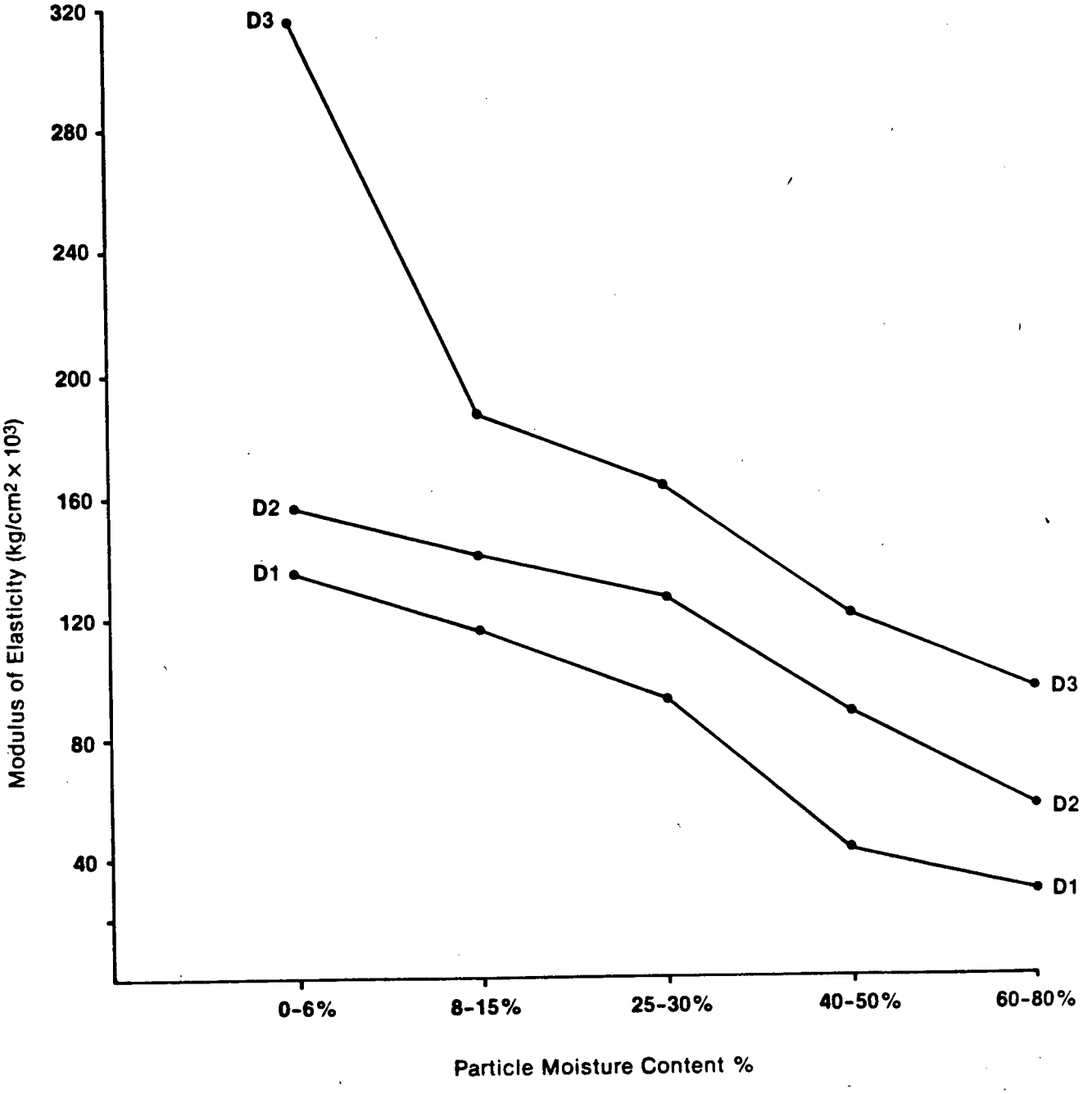

Fig. 10

Dependence of Modulus of Elasticity on Particle Moisture Content and Density *at 1:2 Wood-Cement Ratio.* (Wood-Cement ratios 1:1.5 and 1:1 held constant.)

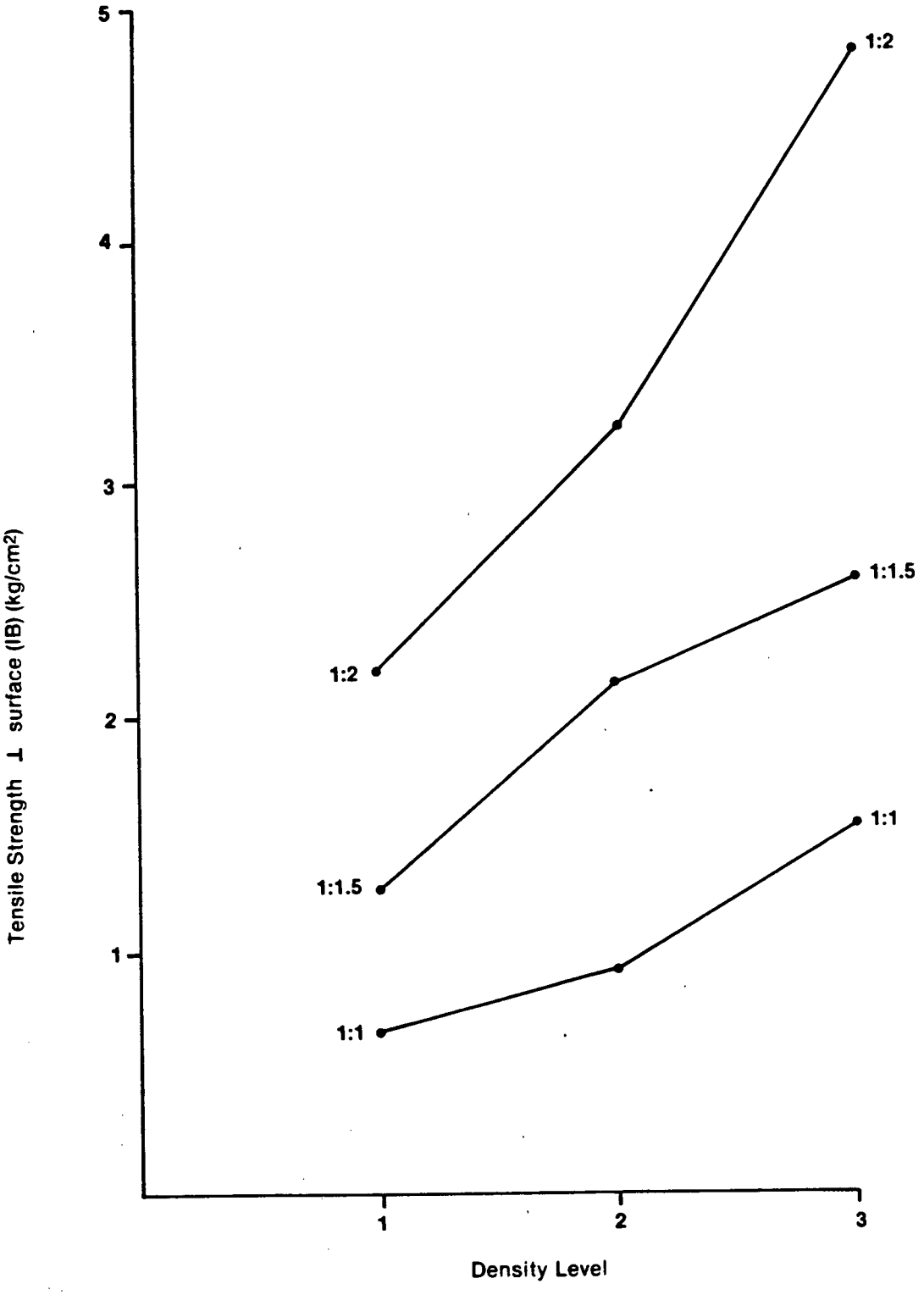

Fig. 11

Dependence on Tensile Strength ⊥ surface (IB) on Density and Wood-Cement ratio interaction.

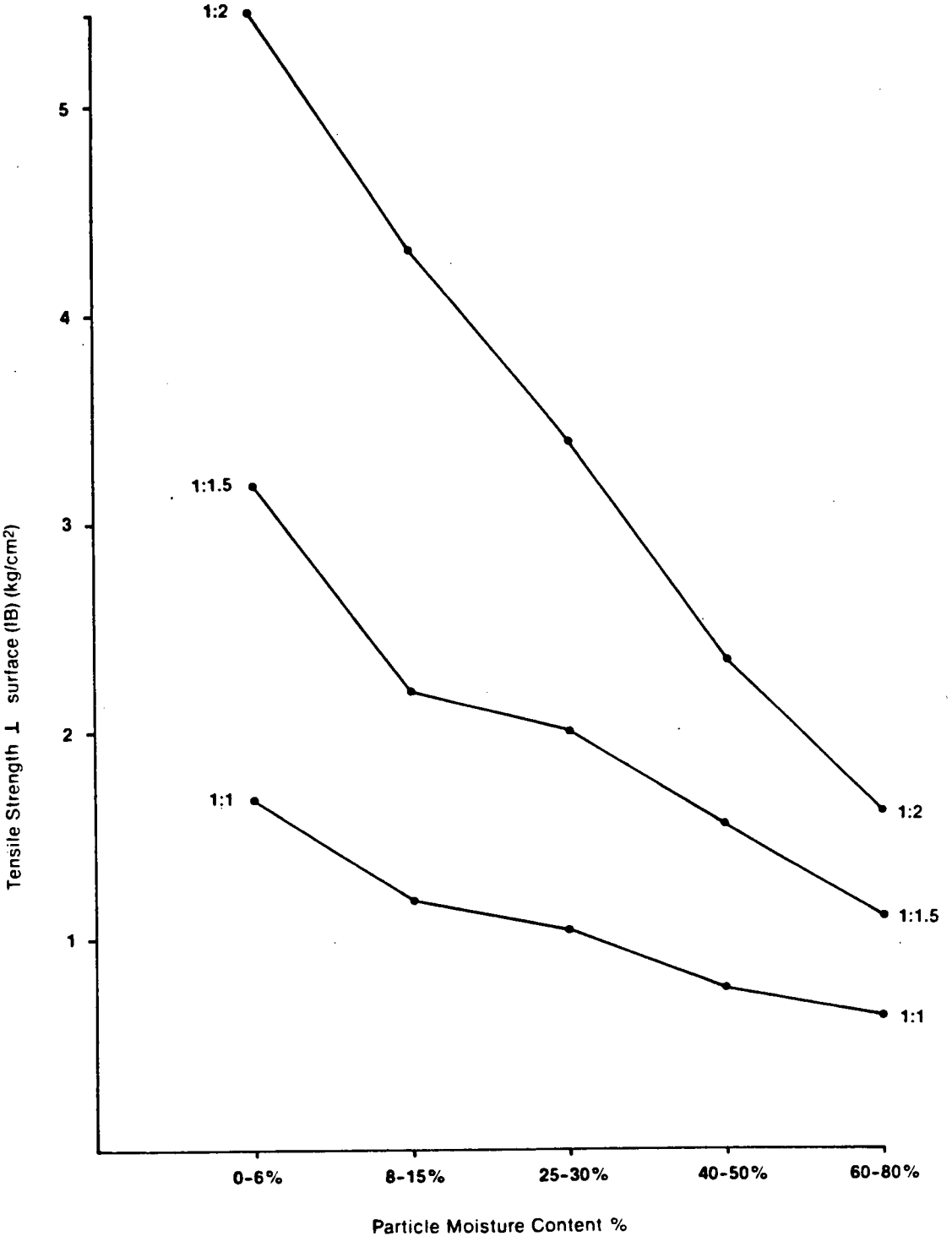

Fig. 12

Dependence of Tensile Strength ⊥ surface on Particle Moisture Content and Wood-Cement ratio interaction.

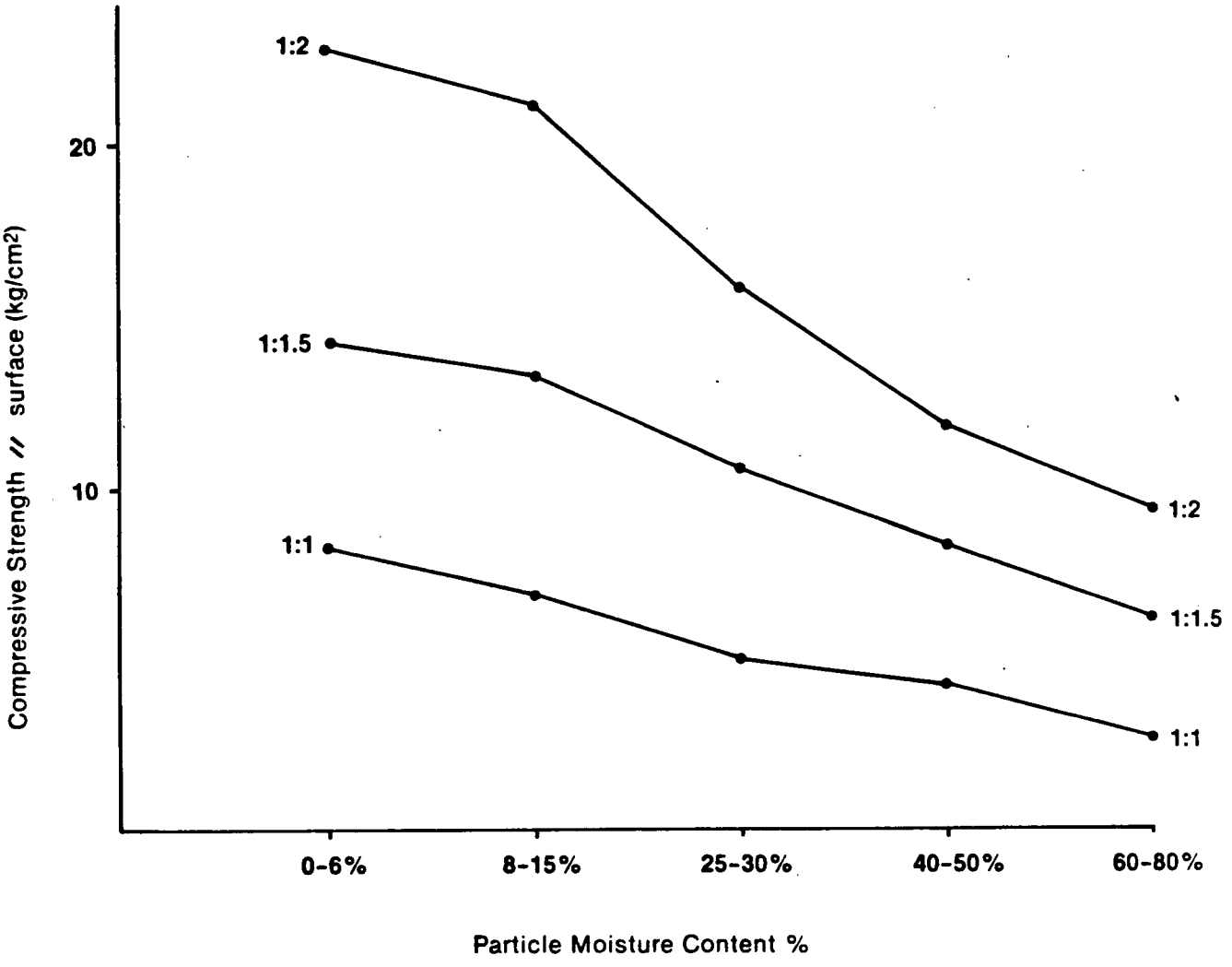

Fig. 13

Dependence of Compressive strength // surface on Particle Moisture Content and Wood-Cement ratio interaction.

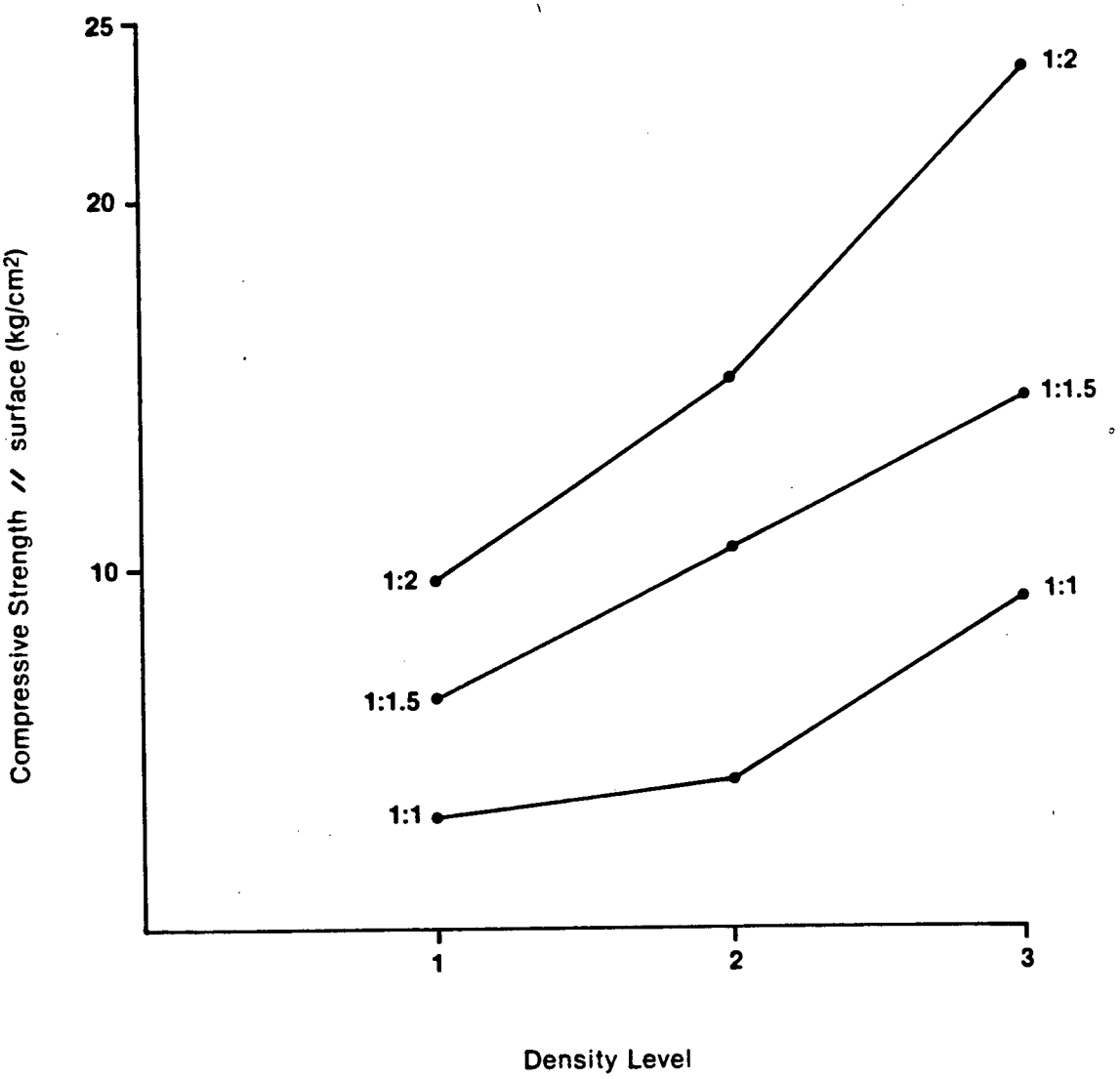

Fig. 14

Dependence of Compressive strength // surface on Density and Wood-Cement ratio interaction.

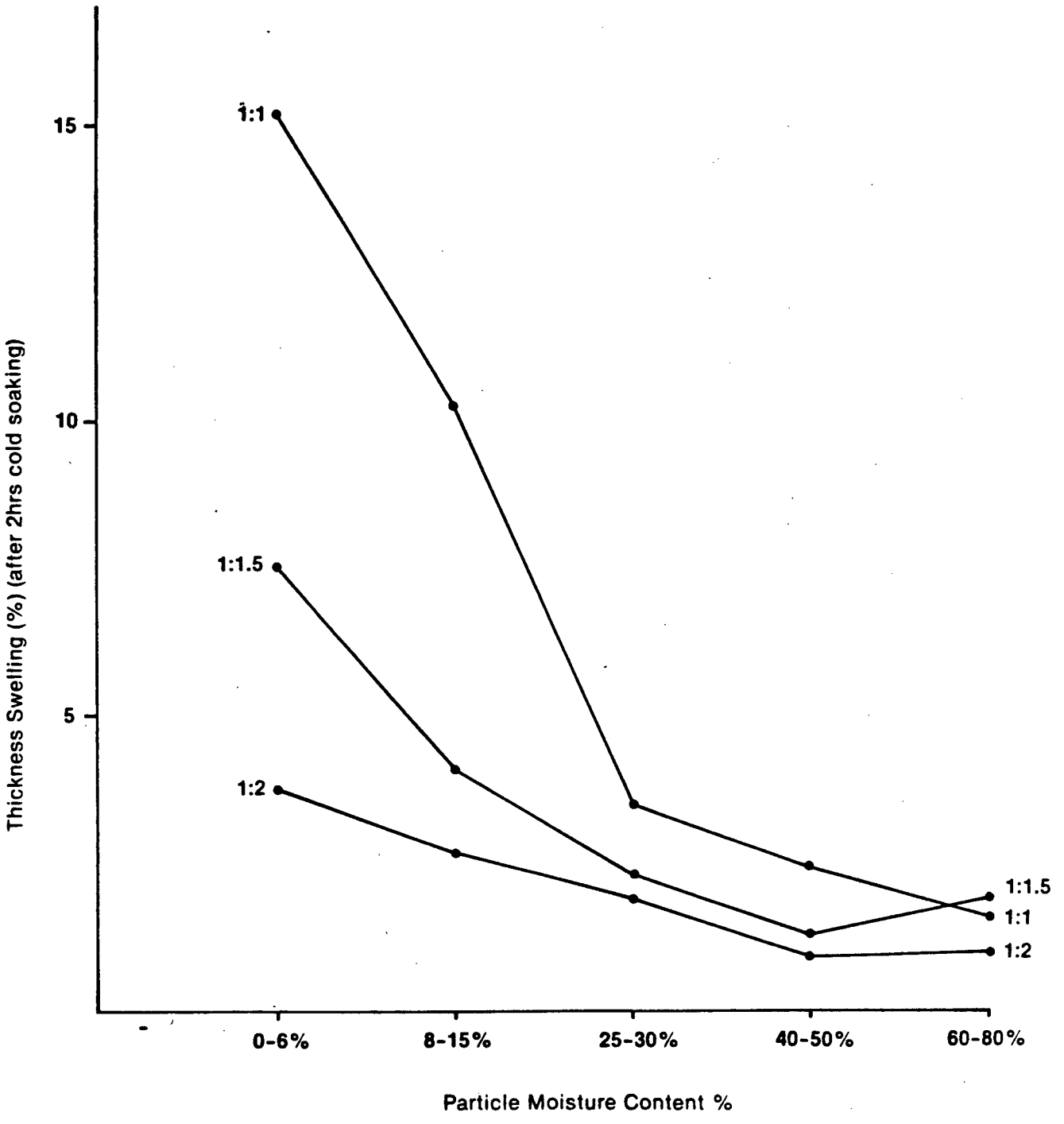

Fig. 15

Dependence of Thickness Swelling (after 2h cold soaking) on Wood-Cement ratio and particle moisture content interaction.

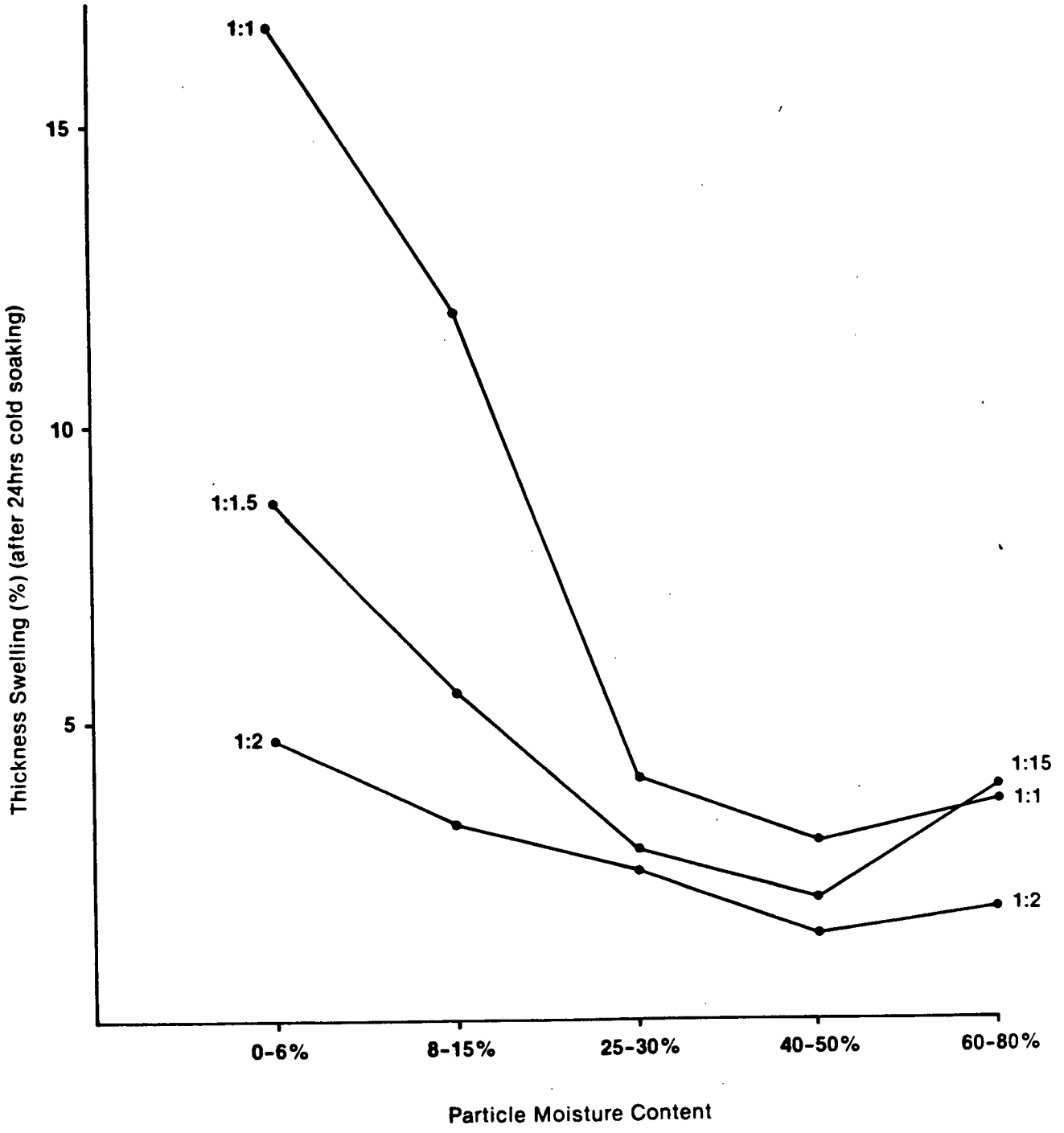

Fig. 16

Dependence of Thickness Swelling (after 24h cold soaking) on Particle Moisture Content and Wood-Cement ratio interaction.

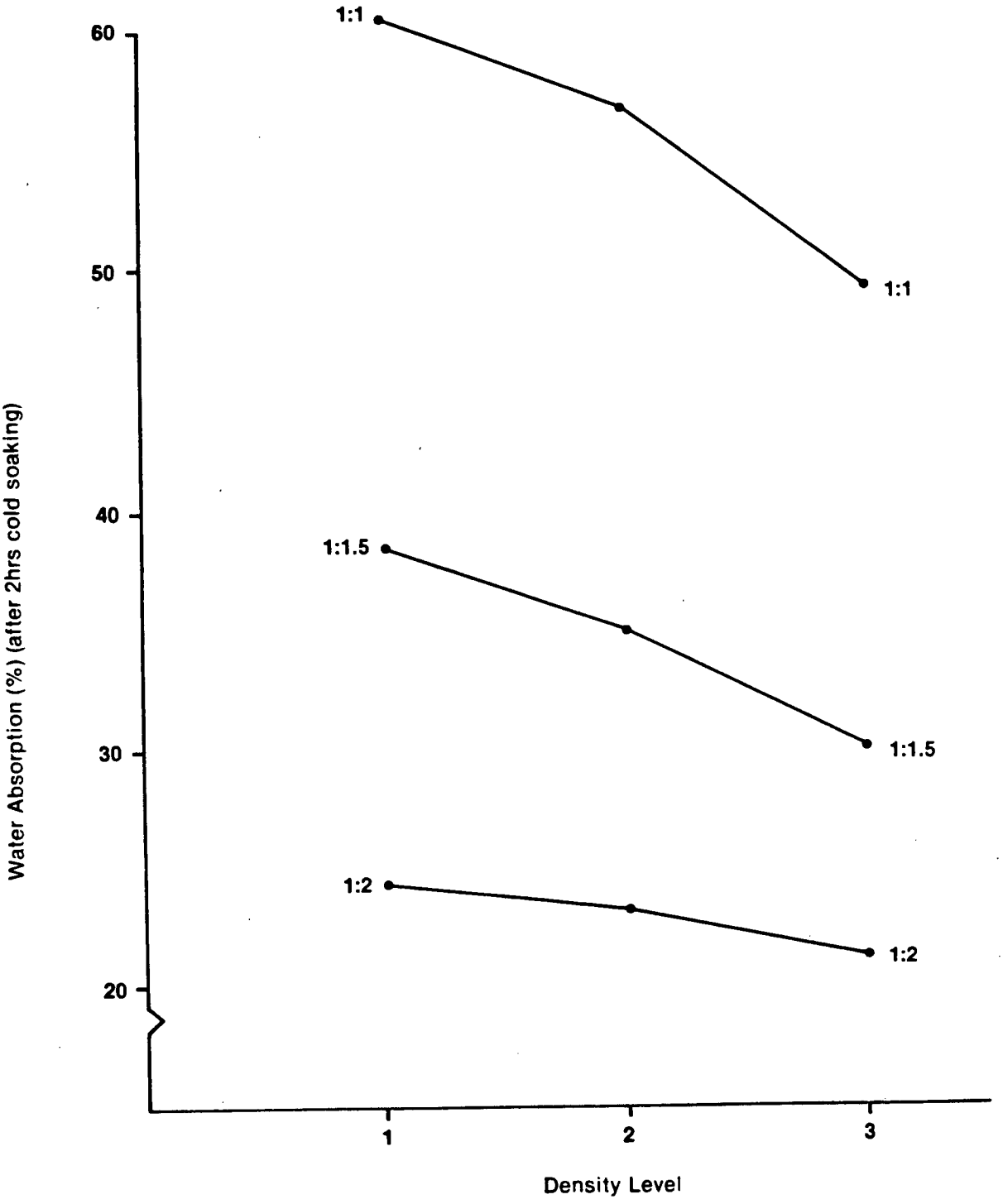

Fig. 17

Dependence of Water Absorption (after 2h. cold soaking) on Density and Wood-Cement ratio interaction.

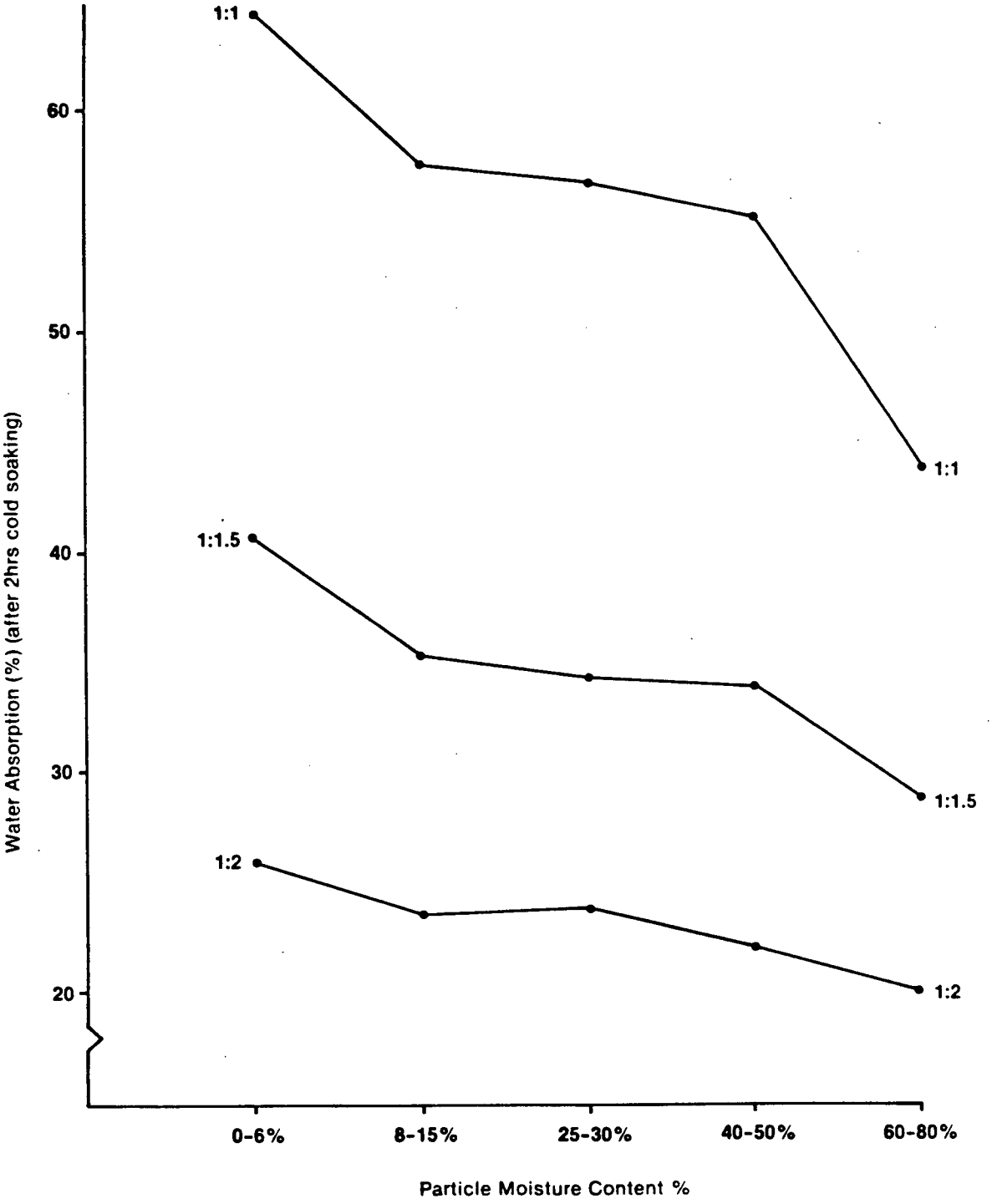

Fig. 18

Dependence of Water Absorption (after 2h cold soaking) on Particle Moisture Content and Wood-Cement ratio interaction.

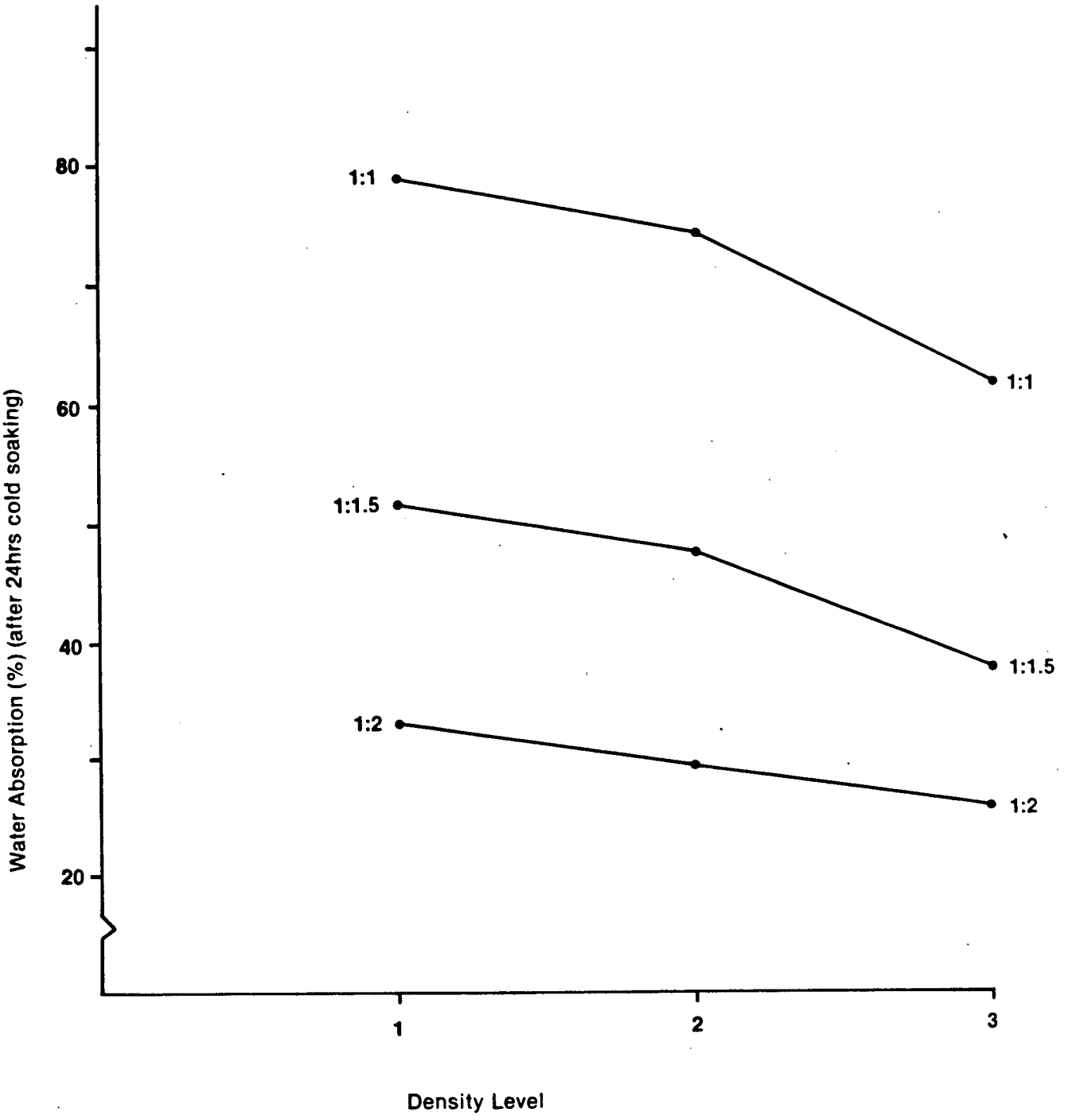

Fig. 19

Dependence of Water Absorption (after 24h cold soaking) on Density and Wood-Cement ratio interaction.

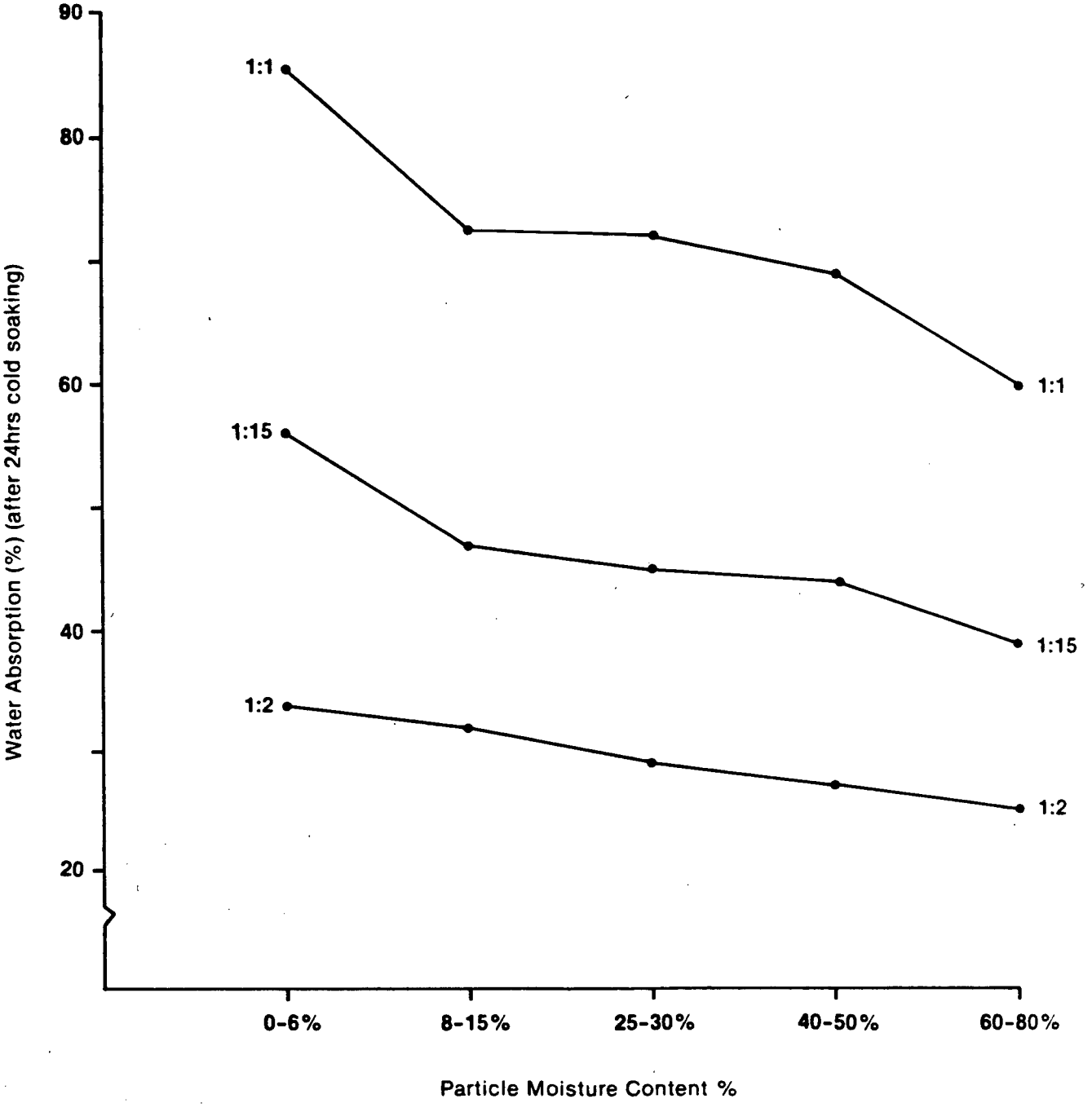

Fig.20.

Dependence of Water Absorption (after 24h cold soaking) on Particle Moisture Content and Wood-Cement ratio interaction.

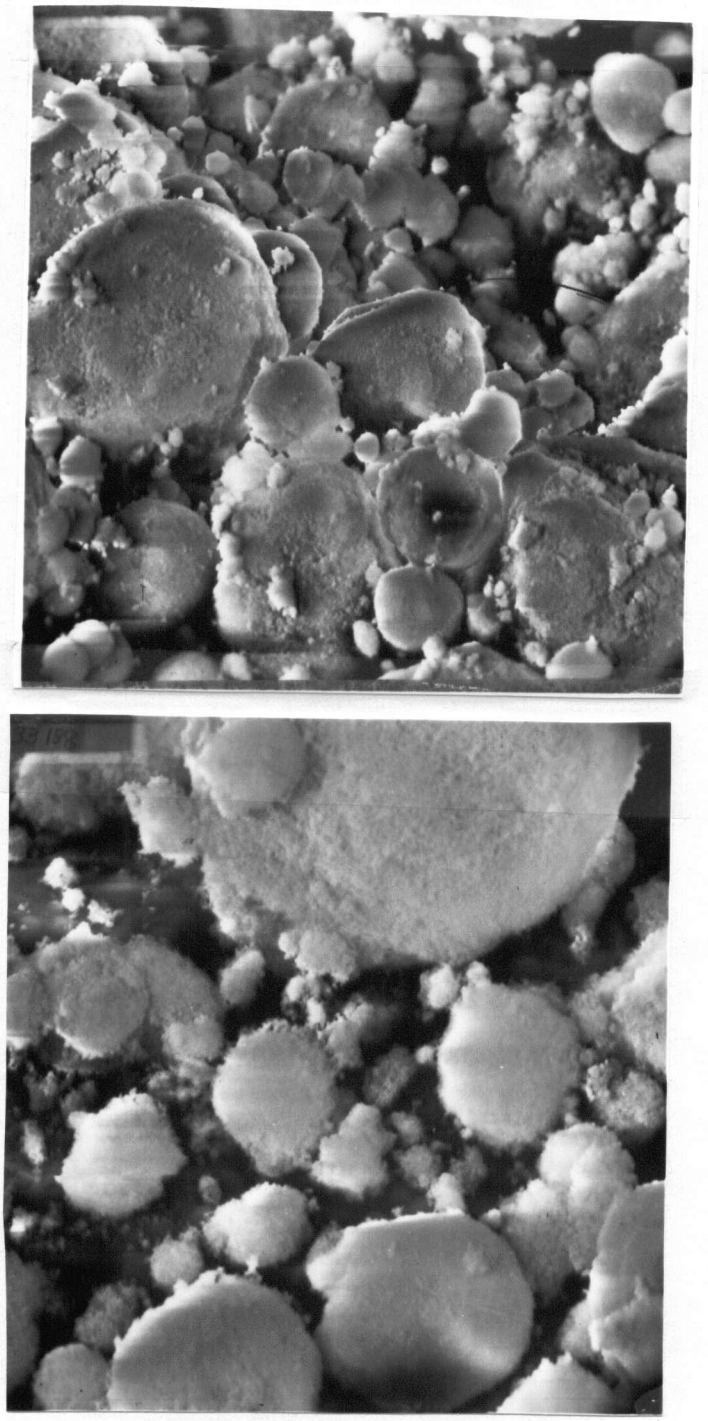

Figure 21. Electron micrographs of crystals of pure magnesium oxide powder

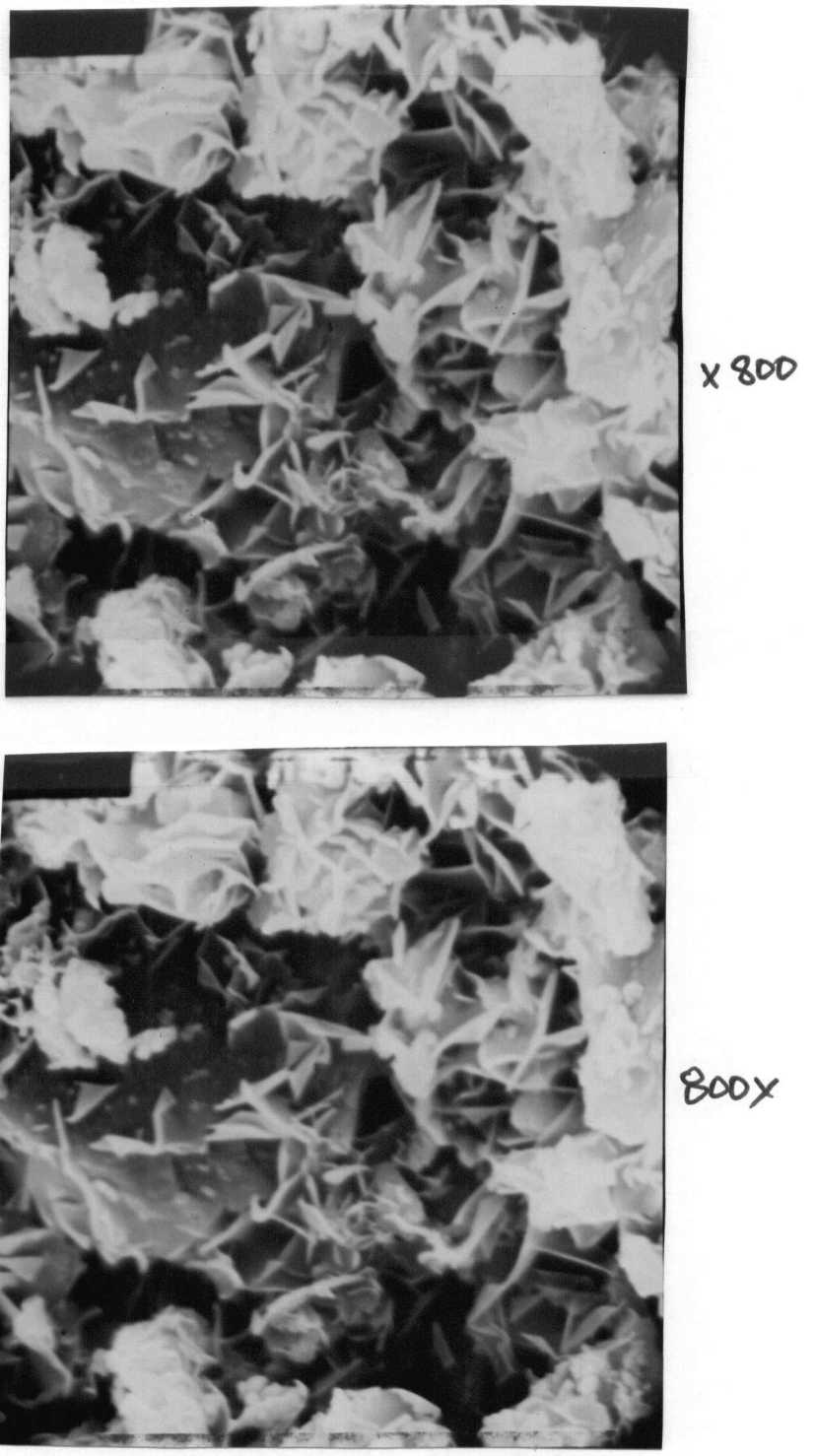

Figure 22. Electron micrographs of crystals of dead burnt magnesite cement powder

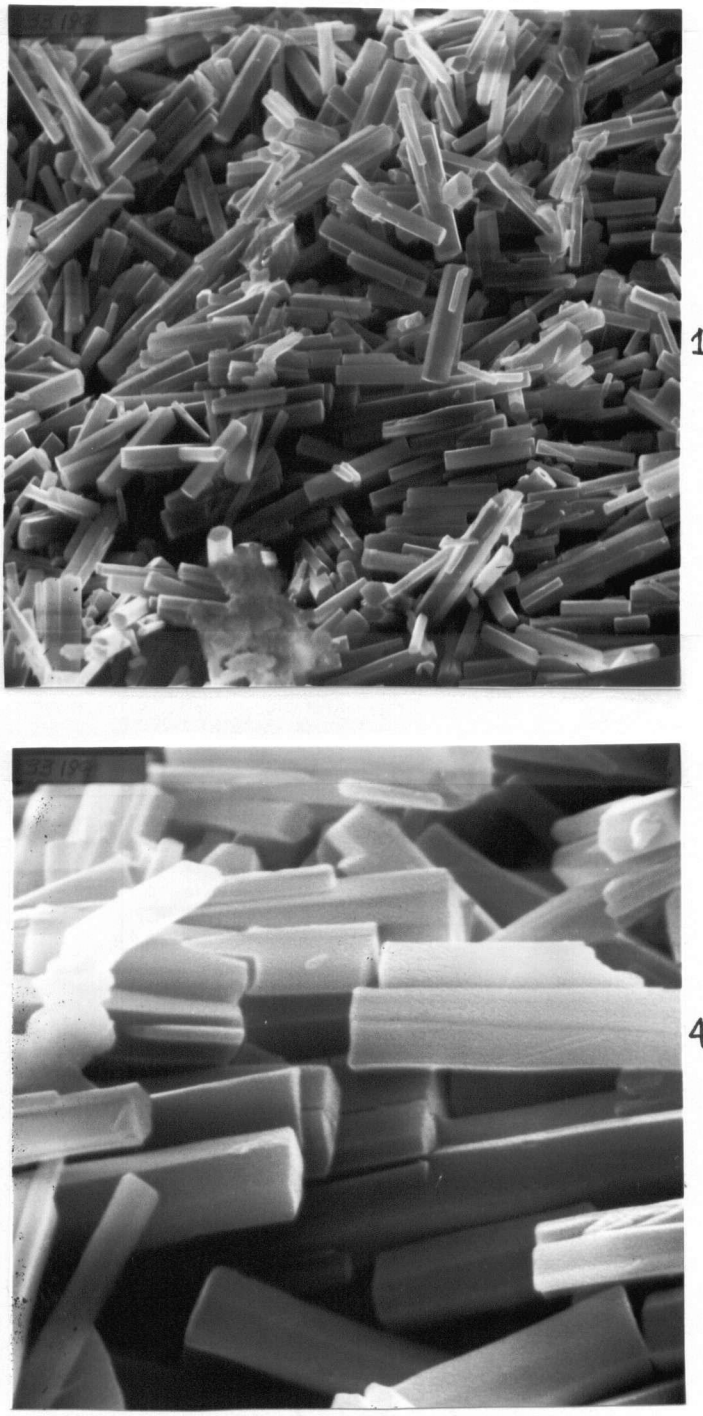

Figure 23. Electron micrographs of crystals of Ammonium Polyphosphate (reactant)

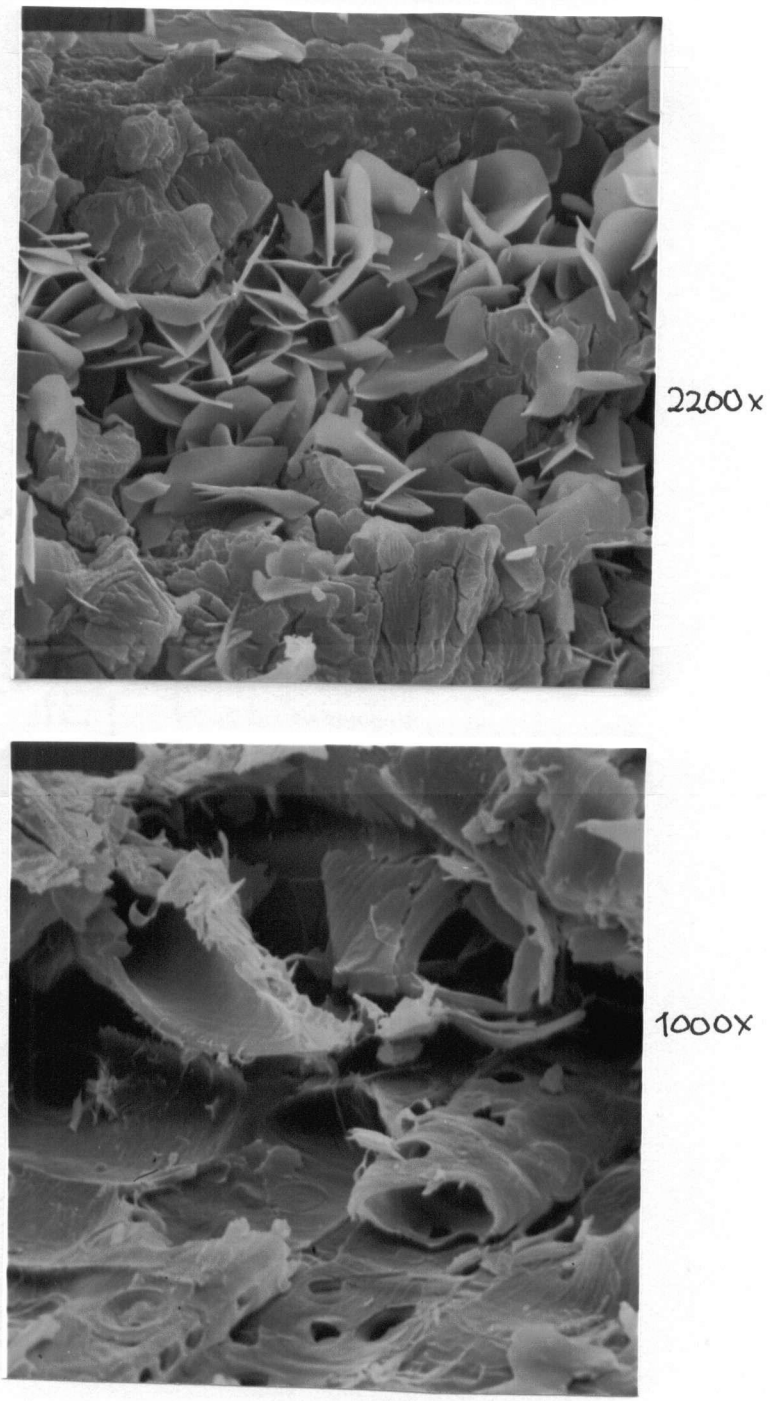

Figure 24. Electron micrographs of magnesite cement boards manufactured using; 0-6% initial particle moisture content, 1:1 wood-cement ratio and density level 1

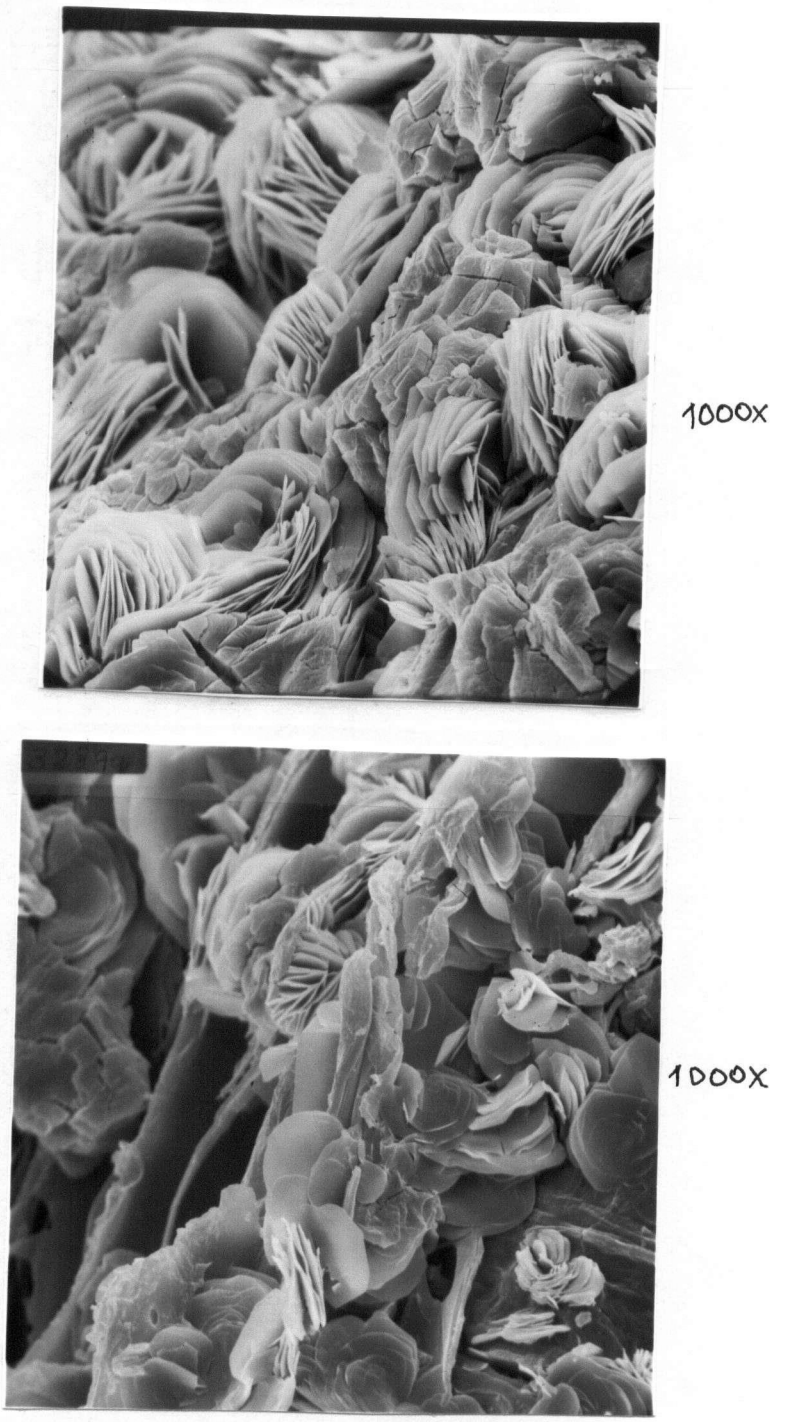

Figure 25. Electron micrographs of magnesite cement boards manufactured using; 8-15% initial particle moisture content, 1:1 wood-cement ratio and density level 1

Figure 26. Electron micrographs of magnesite cement boards manufactured using; 25-30% initial particle moisture content, 1:1 wood-cement ratio and density level 1

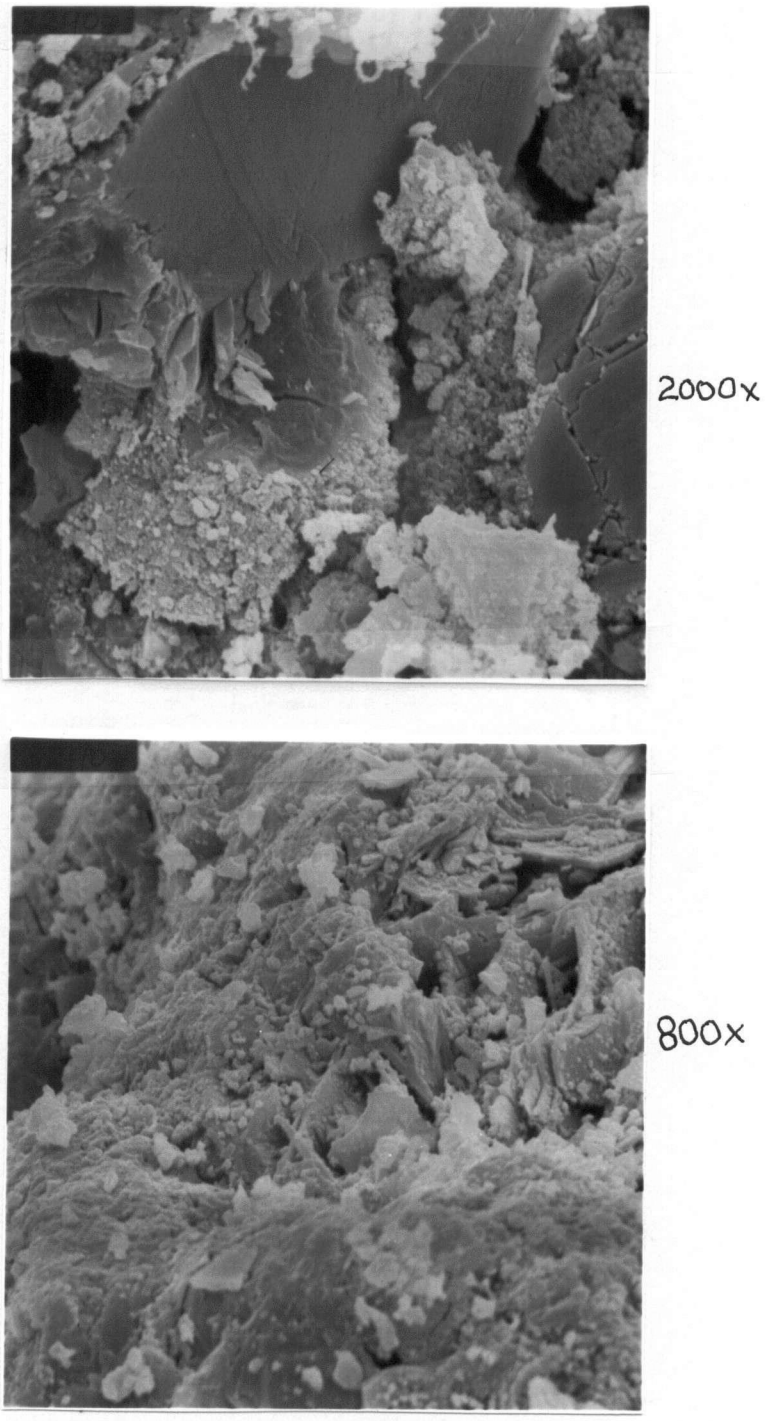

Figure 27. Electron micrographs of magnesite cement boards manufactured using; 40-50% initial particle moisture content, 1:1 wood-cement ratio and density level 1

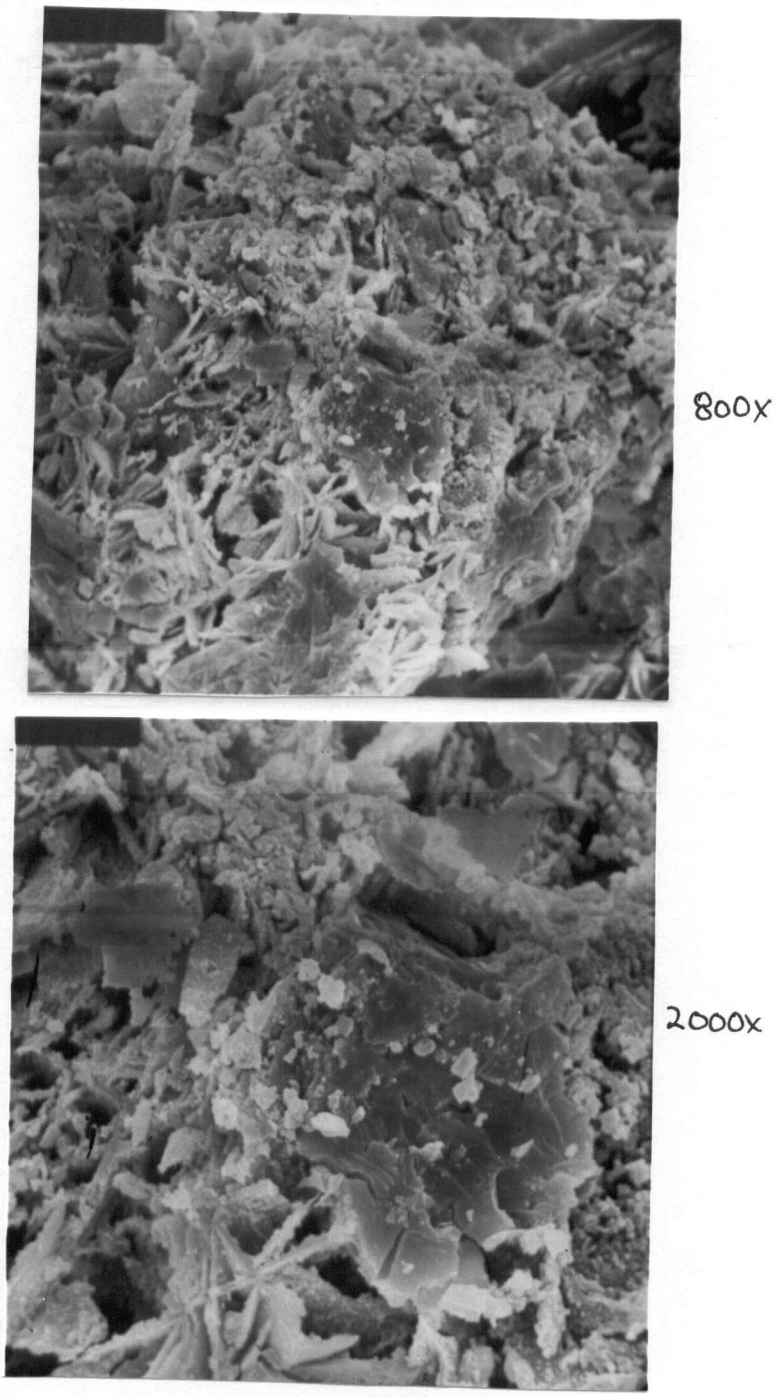

Figure 28. Electron micrographs of magnesite cement boards manufactured using; 60-80% initial particle moisture content, 1:1 wood-cement ratio and density level 1

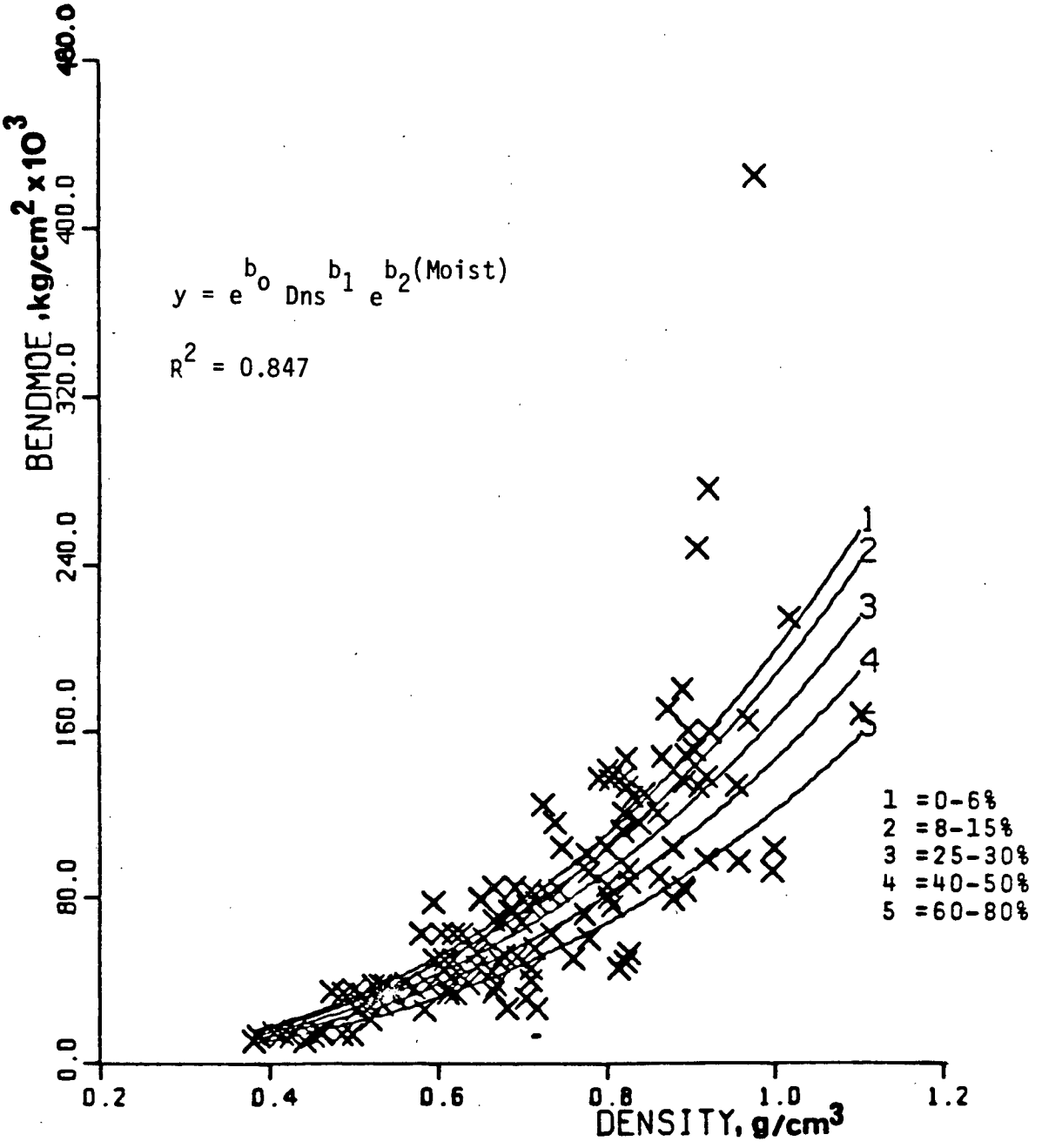

Fig.29 Relationship between MOE and density at different initial particle moisture contents.

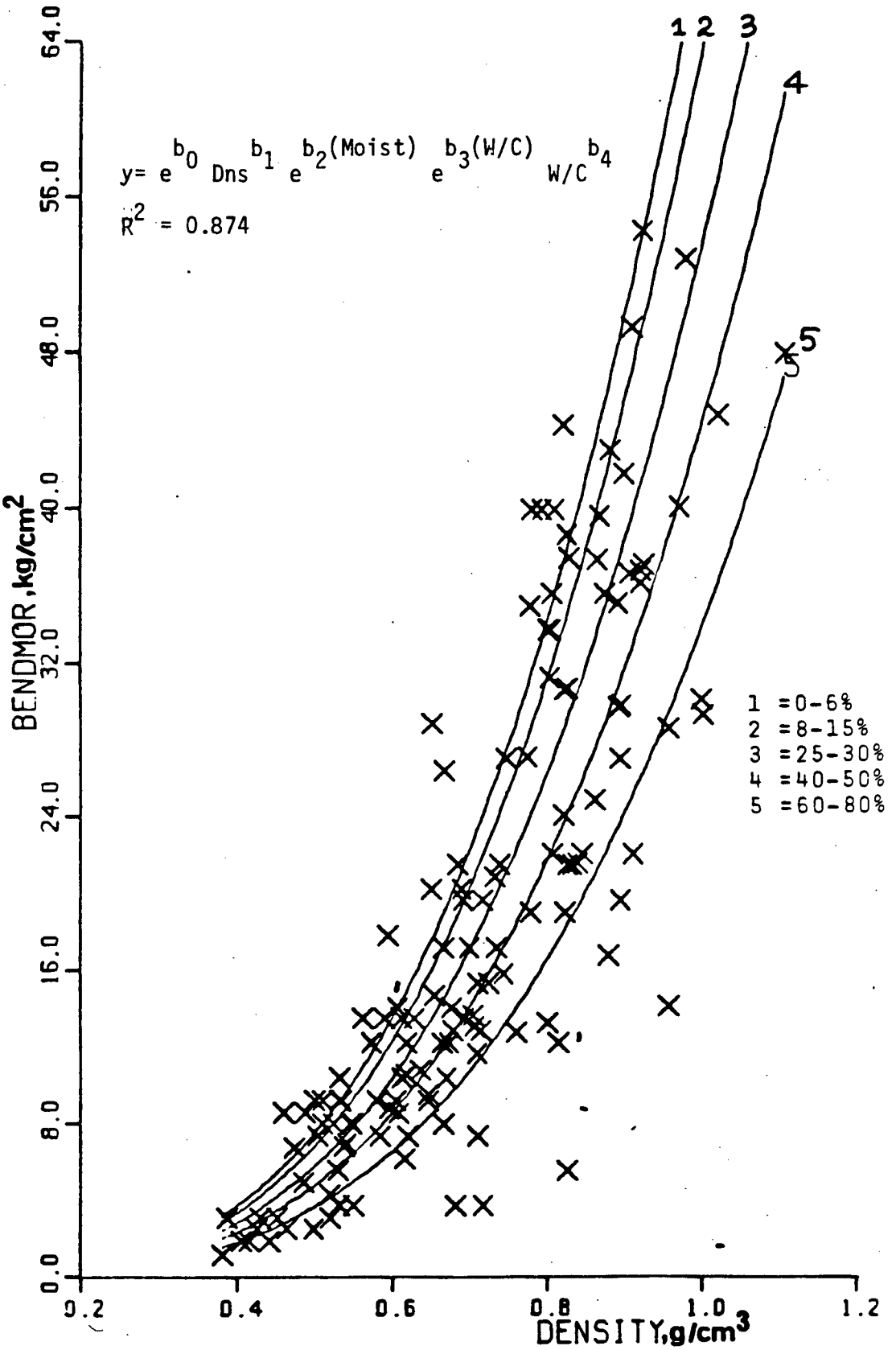

Fig.30 Relationship between MOR and density at different initial particle moisture contents.

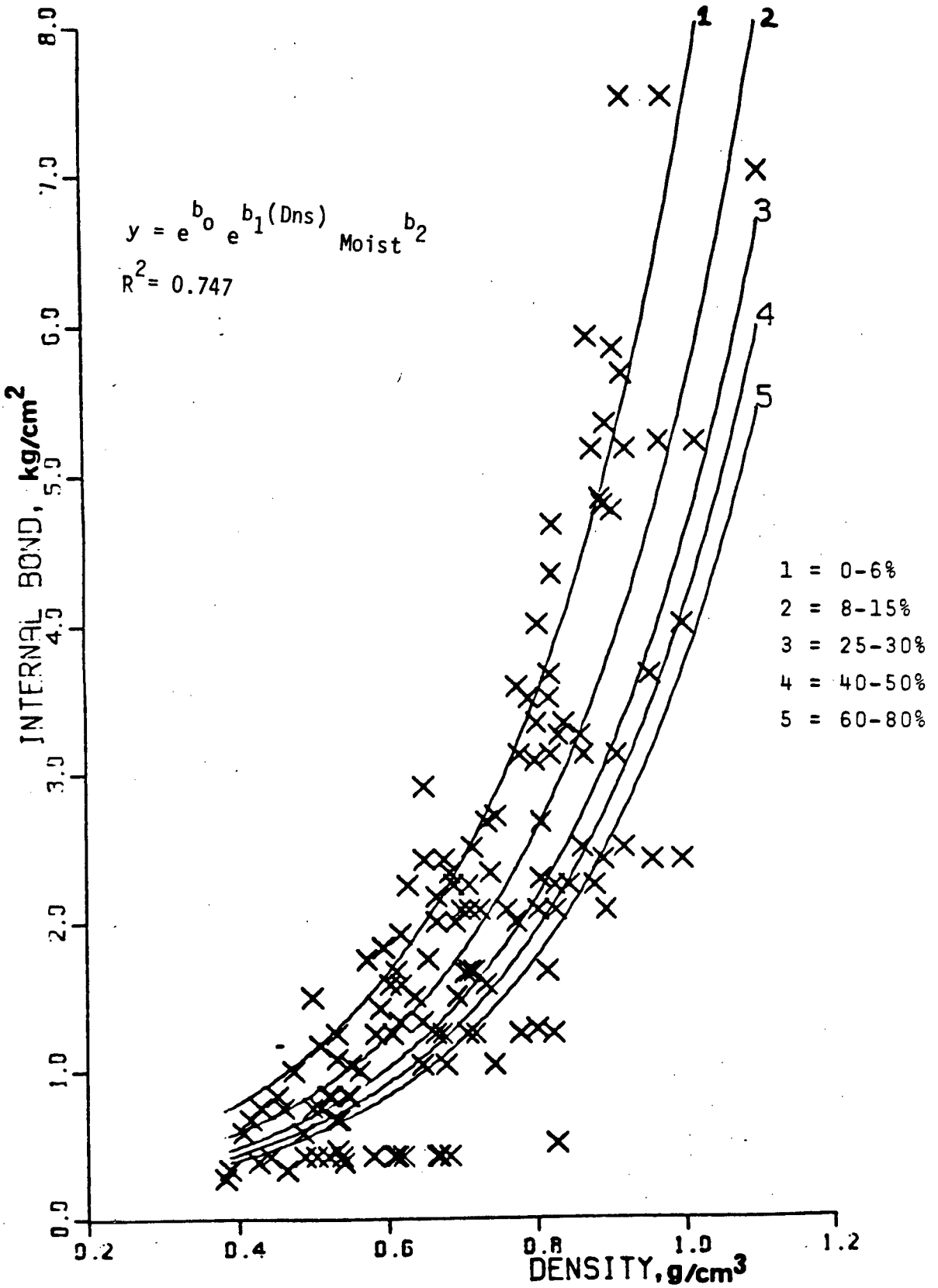

Fig.31 Relationship between IB strength and density at different initial particle moisture contents.

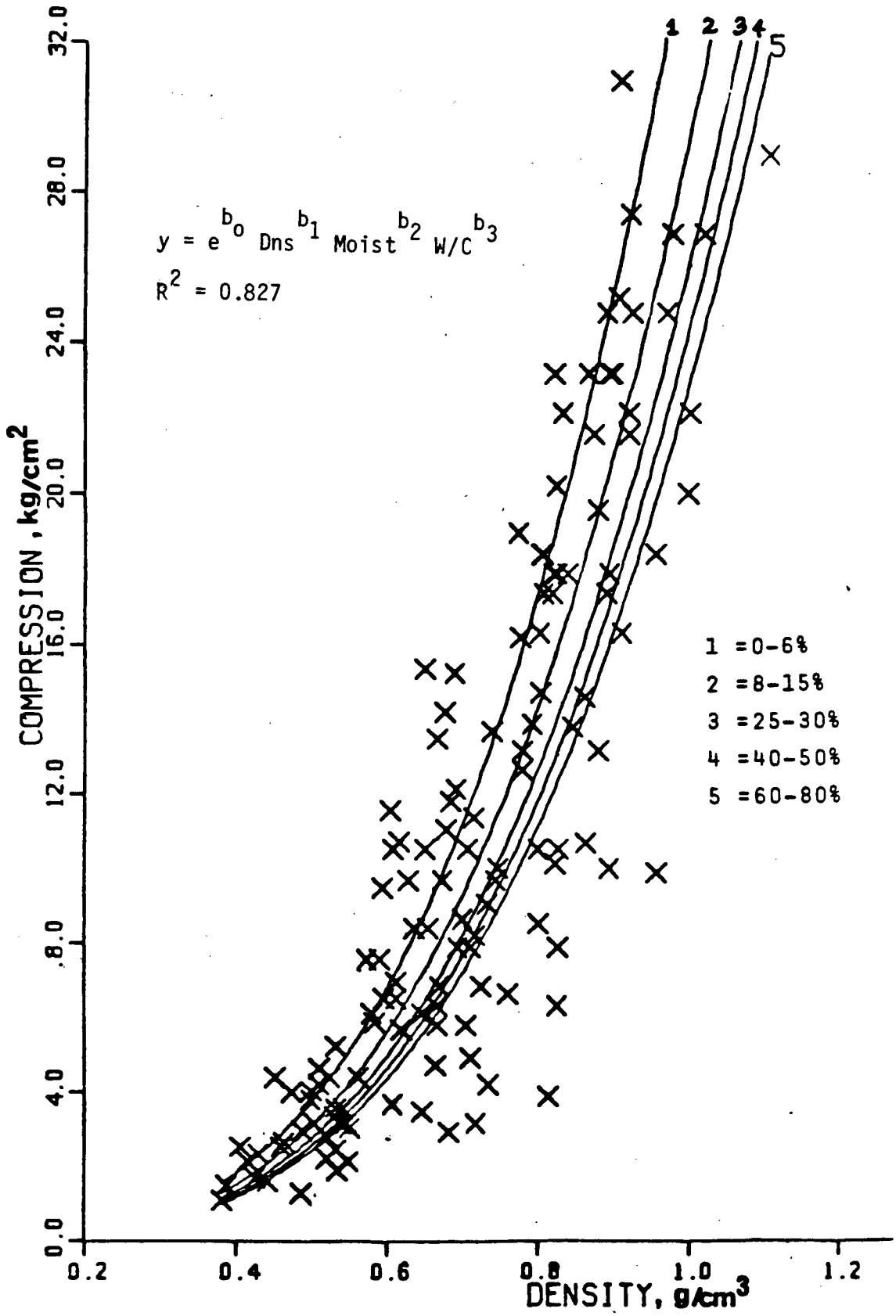

Fig.32 Relationship between edgewise compression strength and density at different initial particle moisture contents

ducing compounds, C_3S and C_3A, are present in lesser amounts, resulting in 60 to 70 cal per g heat liberation.

The American Society for Testing and Materials gives a specification (ASTM C 150-61) covering five types of portland cements which are intended to cover the principal areas where special properties are needed. A further modification of the properties of portland cement concrete can be achieved by the use of admixtures. This topic will be discussed in a later section.

Table 1·3 shows typical compound composition for the five types of portland cement covered by ASTM Specifications, and a brief description of each follows.

Table 1·3 Compound Composition of Portland Cements

Type of cement	Compound composition, %			
	C_3S	C_2S	C_3A	C_4AF
I. Normal	45	27	11	8
II. Modified	44	31	7	13
III. High early strength	53	19	10	7
IV. Low heat	20	52	6	14
V. Sulfate resistant	38	43	4	8

Type I This is ordinary portland cement for use where special properties are not required. When ordinary portland cement is to be exposed to severe frost action, then Type IA may be specified. This is similar to Type I except that an air-entraining agent has been added.

Type II This type is a moderate variation of Type I and is used where some sulfate action is indicated or where a somewhat lower heat of hydration is needed. Type IIA should be used for combined frost and sulfate attack.

Type III Type III cement is designed for use where high early strength is needed because of a particular construction situation. Several factors can contribute to this high early strength. First, early strength can be improved chemically by using a higher percentage of C_3S. Second, the hydration and hardening can be improved by physically grinding the cement finer. The surface area of the cement exposed to the action of water and therefore the rate of hydration partially depend on the fineness of the individual cement particles. For a given weight of cement, the surface area, measured in square centimeters per gram, will be greatest for the finer material. Not only will the hydration proceed more rapidly for the fine cement, but it will also be more complete in a given period of time. The limit to fineness occurs when the particles are so small that minute amounts of moisture will prehydrate and thereby destroy the cement during handling and storage. Again, Type IIIA is available for situations where fast hardening and resistance to frost action are required.

Type IV Type IV cement is for use where the heat of hydration must be kept to an absolute minimum. As has already been mentioned, this is accomplished chemically by using minimum amounts of tricalcium silicate and tricalcium aluminate. While the cement can be modified to reduce the heat liberated, other steps may also be necessary to control temperatures in mass concrete. Among the steps taken in heat control are the following: controlling placement temperatures of the constituent materials in the concrete and use of a cooling solution circulated through pipes embedded in the concrete.

Type V Type V cement is specified for use where there is extensive exposure to sulfates. This condition occurs most often in hydraulic structures carrying waters with a high alkali content. Sulfate resistance can be improved chemically by reducing the tricalcium aluminate content.

Of the five types available Type I is the most widely used and is best for the normal situation. Chemical or physical alteration of this type of cement can improve certain specific properties, but at the same time other properties may be adversely affected. For example, strength is reduced somewhat for Type IV and V. Table 1·4 compares the strengths of the various types of cement with Type I at three different moist curing intervals.

Table 1·4 Approximate Relative Strengths of Concrete as Affected by Type Cement

Type of portland cement	Compressive strength, % of normal portland cement concrete		
	3 days	28 days	3 months
I. Normal	100	100	100
II. Modified	80	85	100
III. High early strength	190	130	115
IV. Low heat	50	65	90
V. Sulfate resistant	65	85	85

APPENDIX II

BRITISH STANDARD SPECIFICATION

METHODS OF TEST FOR
WOOD CHIP BOARDS
WOOD WASTE BOARDS
& SIMILAR BOARDS

B.S. 1811 : 1952

Price 2/- net, post free

BRITISH STANDARDS INSTITUTION
Incorporated by Royal Charter
Telegrams : Standards, Sowest, London Telephone : Abbey 3333
Sales Branch Telephone : Victoria 0522
24 VICTORIA STREET, LONDON, S.W.1

If precise data are required as to the condition of the test pieces at the time of testing, a small portion shall be cut from each of the test pieces and weighed immediately after the test has been carried out. The volatile content of each of these portions shall be determined in accordance with Test 6, Part 2, and reported with the results of the particular test to which they refer.

PART 2. METHODS OF TEST

1. TEST FOR FLEXURAL STRENGTH (TRANSVERSE)

Six test pieces, each 8 in. × 4 in. shall be prepared and conditioned as specified in Clauses 2 and 3.

Each test piece shall be simply supported on parallel rollers having a radius of ⅜ in. to ½ in., spaced at 6 in. centre-to-centre and free to rotate in ball or roller bearings. A load shall then be applied at the centre of the span along a line parallel with the end supports by means of a bar rounded to a radius of between ⅜ in. and ½ in. (See Fig. 1.)

The load shall be applied at an even rate, or at a rate such as will produce an even rate of increase in strain, and shall be so adjusted that the test will be completed in a period of not less than half a minute and not more than 4 minutes. The load which each test piece fails to support shall be reported, together with the mean ultimate failing load.

The effective modulus of rupture, f, shall be calculated as follows :—

If W = mean ultimate failing load in pounds to the nearest pound or to within ½ per cent of the load

s = measured span between centres of supports (6 in.)

b = mean width of test pieces in inches, determined in accordance with Test 5, Part 2

d = mean thickness of test pieces in inches, determined in accordance with Test 5, Part 2

$$\text{then } f = \frac{3Ws}{2bd^2} \text{ lb/sq. in.}$$

NOTE 1. If the faces of the test pieces have different finishes, they shall be tested with the load applied to the fair face.

NOTE 2. If a board has a distinct grain it will be necessary to repeat the strength tests and record separate results for test pieces cut parallel with, and at right angles to, the grain.

NOTE 3. If the flexural strength when wet is required, the test pieces shall be immersed in water for 24 hours and the water absorption determined in accordance with Test 7, Part 2 of this standard. The test pieces shall then be tested immediately for flexural strength and the effective modulus of rupture determined as above.

NOTE 4. This test is designed for determining the breaking load of boards up to about 1¼ in. in thickness. When testing materials of greater thicknesses an appropriate depth/span ratio should be chosen.

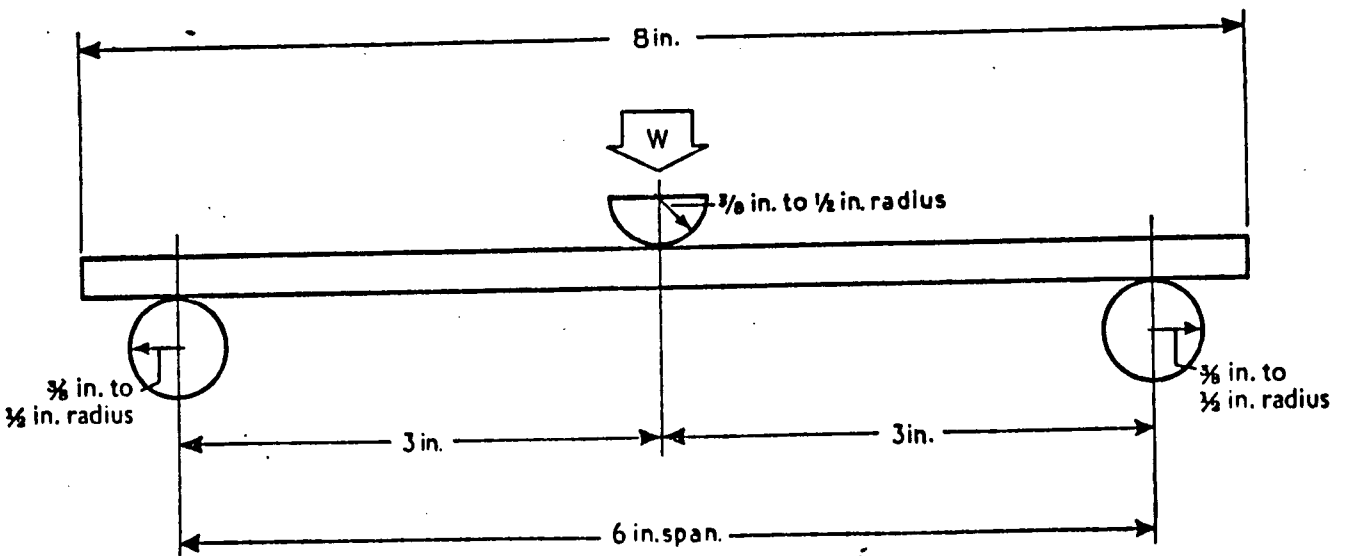

Fig. 1. Typical diagram showing application of test for flexural strength and deflection

2. TEST FOR DEFLECTION AND EFFECTIVE MODULUS OF ELASTICITY

Six test pieces, each 8 in. × 4 in., shall be prepared and conditioned as specified in Clauses 2 and 3.

Each test piece shall be simply supported on parallel rollers having a radius of ⅜ in. to ½ in. spaced at 6 in. centres and free to rotate in ball or roller bearings. A load shall then be applied at the centre of the span along a line parallel with the end supports by means of a bar rounded to a radius of between ⅜ in. and ½ in. (See Fig. 1.) An initial load shall be applied equivalent to 10 per cent of the ultimate failing load* and the deflection under this load shall be treated as the zero condition. The load shall then be increased to 33⅓ per cent of the ultimate failing load and after a lapse of 30 seconds the deflection at the centre shall be measured to an accuracy of ± 0·005 in. The increase in deflection for each of the test pieces shall be reported together with the mean increase.

The effective modulus of elasticity, E, in bending shall be calculated as follows :—

If W = increase in load in pounds

s = measured span between centres of supports (6 in.)

Δ = mean increase in deflection, in inches

b = mean width of test pieces in inches, determined in accordance with Test 5, Part 2

d = mean thickness of test pieces in inches, determined in accordance with Test 5, Part 2

then $$E = \frac{Ws^3}{4bd^3\Delta} \text{ lb/sq. in.}$$

3. TEST FOR DEFLECTION UNDER SUSTAINED LOAD

Six test pieces each $(36d + 4)$ in. long by 6 in. wide, where d is the nominal thickness of the board, shall be prepared and conditioned as specified in Clauses 2 and 3.

Each test piece shall be simply supported on horizontal parallel rollers having a radius of ⅜ in. to ½ in., spaced at a distance centre to centre of 36 times the nominal thickness of the board. The test load shall be applied at the mid-point of the span along a line parallel to the end supports by means of a bar rounded to a radius of ⅜ in. to ½ in. and carrying a stirrup, from which a weight shall be suspended so that the total weight including the bar and stirrup shall be 2 lb. The position

* For the purposes of this test, if the ultimate failing load has not already been determined in accordance with Test 1, Part 2, it will be permissible to adopt the mean of the results of at least two tests, carried out in accordance with Test 1, Part 2, on test pieces cut from the same, or similar, boards as those being tested for deflection.

APPENDIX III

each specimen as specified in Sections 9, 126 and 127.

TENSILE STRENGTH PERPENDICULAR TO SURFACE

28. Scope

28.1 The test for tensile strength perpendicular to the surface shall be made on specimens in the dry condition to determined cohesion of the fiberboard in the direction perpendicular to the plane of the board.

NOTE 13—This test is included because of the increased use of fiberboards and particle boards where wood, plywood, or other materials are glued to the board, or where the internal bond strength of the board is an important property. Tests in the soaked condition shall be made if the material is to be used under severe conditions.

29. Test Specimen

29.1 The test specimen shall be 2 in. (50 mm) square and the thickness shall be that of the finished board. Loading blocks of steel or aluminum alloy 2 in. square and 1 in. (25 mm) in thickness shall be effectively bonded with a suitable adhesive (Note 14) to the 2-in. square faces of the specimen as shown in Fig. 5, which is a detail of the specimen and loading fixtures. Cross-sectional dimensions of the specimen shall be measured to an accuracy of not less than ±0.3 percent. The maximum distance from the center of the universal joint or self-aligning head to the glued surface of the specimen shall be 3 in. (76 mm).

NOTE 14—Any suitable adhesive that provides an adequate bond may be used for bonding the fiberboard specimen to the loading blocks. Epoxy resins are recommended as a satisfactory bonding agent. The pressure required to bond the blocks to the specimen will depend on the density of the board and the adhesive used, and should not be so great as to measurably damage the fiberboard. The resulting bond shall be at least as strong as the cohesive strength of the material perpendicular to the plane of the fiberboard.

30. Procedure

30.1 Engage the loading fixtures, such as are shown in Fig. 5, attached to the heads of the testing machine, with the blocks attached to the specimen. Stress the specimen by separation of the heads of the testing machine until failure occurs. The direction of loading shall be as nearly perpendicular to the faces of the fiberboard as possible, and the center of load shall pass through the center of the specimen.

31. Speed of Testing

31.1 Apply the load continuously throughout the test at a uniform rate of motion of the movable crosshead of the testing machine of 0.08 in./in. (cm/cm) of thickness per min.

NOTE 15—It is not intended that the testing machine speed shall be varied for small differences in fiberboard thickness, but rather that it shall not vary more than ±50 percent from that specified above (see Note 9).

32. Test Data and Report

32.1 Obtain maximum loads from which calculate the stress at failure. Calculate strength values in pounds per square inch (or kilograms per square millimeter), for which the measured dimensions of the specimen shall be used. Include the location of the line of failure in the report.

33. Moisture Content

33.1 Determine the moisture content of each specimen on a separate sample prepared from the same material, as specified in 126.2 and Section 127.

COMPRESSION STRENGTH PARALLEL TO SURFACE

34. Scope

34.1 The test for compression strength parallel to the surface shall be made on specimens both in the dry and in the soaked condition. Tests shall be made of specimens both with the load applied parallel and perpendicular to the long dimension of the board to determine whether or not the material has directional properties.

34.2 Because of the large variation in character of wood-base fiber and particle panel materials and the differences in manufactured thicknesses, one procedure is not applicable for all materials. One of the three procedures detailed as follows shall be used depending on the character and thickness of the board being evaluated:

34.2.1 *Procedure A* (*Laminated Specimen*) shall be used for materials 3/8 in. (10 mm) or more but less than 1 in. (25 mm) in nominal thickness, particularly when modulus of elasticity and stress at proportional limit are re-

quired. In this procedure when materials less than 1 in. in thickness are evaluated, two or three thicknesses shall be laminated to provide a nominal thickness of at least 1 in. but no amount more than that amount than necessary. The nominal size of the specimen shall be 1 by 4 in. (25 by 101 mm) (with the 4-in. dimension parallel to the applied force) by the thickness as laminated.

34.2.2 *Procedure B* (*Lateral Support*) shall be used for materials less than $^3/_8$ in. in thickness, particularly when modulus of elasticity and stress at proportional limit are required. Specimens shall be 1 by 4 in. by the thickness as manufactured and evaluations made in a suitable lateral support device. The 4-in. long dimension shall be parallel to the applied force.

34.2.3 *Procedure C* (*Short Column*) shall be used when maximum crushing strength only is required or where the thickness of the board material is 1 in. or more and either maximum crushing strength modulus of elasticity, and stress at proportional limit or only maximum crushing strength is required. When the material being evaluated is 1 in. or less in thickness, the width of the specimen shall be 1 in., the thickness shall be as manufactured, and the length (height as tested) shall be four times the thickness. When the material being evaluated is more than 1 in. in thickness, the width shall be equal to the nominal thickness and the length (height as loaded) shall be four times the nominal thickness.

35. Test Specimen

35.1 The test specimens shall be carefully sawed with surfaces smooth and planes at right angles to the faces of the boards as manufactured. For the laminated specimens (Procedure A), pieces of board at least 1 in. (25 mm) larger in length and width than the finished size of specimen shall be laminated using thin spreads of epoxy resin (Note 16) and pressures not exceeding 50 psi (3.5 kg/cm^2). Specimens shall be sawed from the laminated pieces after at least 8 h of curing of the resin at room temperature. The width and thickness shall be measured to at least the nearest 0.001 in. (0.025 mm). These two dimensions shall be used to calculate net cross-sectional area for modulus of elasticity, and stress at proportional limit and maximum load.

NOTE 16—The epoxy resin is required because it contains no water or other swelling agent that might produce initial stresses adjacent to the glue lines.

36. Specimens Soaked Before Test

36.1 Specimens to be tested in the soaked condition shall be prepared in accordance with Section 13.

37. Procedure

37.1 Load the specimens through a spherical loading block, preferably of the suspended self-aligning type. Center them carefully in the testing machine in a vertical plane as shown in Figs. 18 (unsupported 4-in. (101-mm specimen) and 19 (laterally supported pack device).[4] Apply loading at a uniform rate of head travel of the testing machine of 0.005 in. (0.12 mm)/in. of length/min.

NOTE 17—Speed of test therefore for the 4-in. specimen of Methods A and B shall be 0.020 in. per minute (see Note 9 for permitted variation in testing speed).

38. Load-Deformation Curves

38.1 When required, obtain load-deformation curves for the full duration of each test. Figure 18 shows a Lamb's Roller Compressometer on an unsupported specimen. Figure 19 shows a Marten's Mirror Compressometer on a laterally supported specimen. Use these or equally accurate instruments for measuring deformation. Choose increments in loading so that not less than 12 and preferably at least 15 readings are obtained before proportional limit. Read deformation to the nearest 0.0001 in. (0.002 mm). Attach compressometers over the central portion of the length; points of attachment (gage points) shall be at least 1 in. (25 mm) from the ends of specimens.

39. Moisture Content and Specific Gravity

39.1 Use the entire compression parallel to surface specimen for moisture content determination except when the capacity of the drying oven is too small for convenient drying

[4] The lateral support device is detailed in Fig. 2 of ASTM Methods D 805, Testing Veneer, Plywood, and Other Glued Veneer Constructions, *Annual Book of ASTM Standards*, Part 22.

APPENDIX IV

each specimen as specified in Sections 9, 126 and 127.

TENSILE STRENGTH PERPENDICULAR TO SURFACE

28. Scope

28.1 The test for tensile strength perpendicular to the surface shall be made on specimens in the dry condition to determined cohesion of the fiberboard in the direction perpendicular to the plane of the board.

NOTE 13—This test is included because of the increased use of fiberboards and particle boards where wood, plywood, or other materials are glued to the board, or where the internal bond strength of the board is an important property. Tests in the soaked condition shall be made if the material is to be used under severe conditions.

29. Test Specimen

29.1 The test specimen shall be 2 in. (50 mm) square and the thickness shall be that of the finished board. Loading blocks of steel or aluminum alloy 2 in. square and 1 in. (25 mm) in thickness shall be effectively bonded with a suitable adhesive (Note 14) to the 2-in. square faces of the specimen as shown in Fig. 5, which is a detail of the specimen and loading fixtures. Cross-sectional dimensions of the specimen shall be measured to an accuracy of not less than ±0.3 percent. The maximum distance from the center of the universal joint or self-aligning head to the glued surface of the specimen shall be 3 in. (76 mm).

NOTE 14—Any suitable adhesive that provides an adequate bond may be used for bonding the fiberboard specimen to the loading blocks. Epoxy resins are recommended as a satisfactory bonding agent. The pressure required to bond the blocks to the specimen will depend on the density of the board and the adhesive used, and should not be so great as to measurably damage the fiberboard. The resulting bond shall be at least as strong as the cohesive strength of the material perpendicular to the plane of the fiberboard.

30. Procedure

30.1 Engage the loading fixtures, such as are shown in Fig. 5, attached to the heads of the testing machine, with the blocks attached to the specimen. Stress the specimen by separation of the heads of the testing machine until failure occurs. The direction of loading shall be as nearly perpendicular to the faces of the fiberboard as possible, and the center of load shall pass through the center of the specimen.

31. Speed of Testing

31.1 Apply the load continuously throughout the test at a uniform rate of motion of the movable crosshead of the testing machine of 0.08 in./in. (cm/cm) of thickness per min.

NOTE 15—It is not intended that the testing machine speed shall be varied for small differences in fiberboard thickness, but rather that it shall not vary more than ±50 percent from that specified above (see Note 9).

32. Test Data and Report

32.1 Obtain maximum loads from which calculate the stress at failure. Calculate strength values in pounds per square inch (or kilograms per square millimeter), for which the measured dimensions of the specimen shall be used. Include the location of the line of failure in the report.

33. Moisture Content

33.1 Determine the moisture content of each specimen on a separate sample prepared from the same material, as specified in 126.2 and Section 127.

APPENDIX V

materials with the materials most commonly used alternately to them.[6]

97. Test Specimen

97.1 The area of the test specimen to be abraded shall be 2 by 3 in. (50 by 76 mm), and the specimen shall be fabricated from a piece of the board 2 by 4 in. (50 by 101 mm) by the thickness of the material (Note 32) as shown in Fig. 16. The specimens shall be conditioned before test (see Section 4) and the test made in the same conditioned atmosphere. The actual dimensions of the abrading area of the specimen shall be measured to the nearest 0.01 in. (0.2 mm). The thickness of the test specimen shall be measured to at least the nearest 0.001 in. (0.02 mm) near each corner and the center.

NOTE 32—When the board tested is less than 1/2 in. (12 mm) thick, either sufficient thicknesses shall be laminated together to provide the 1/2-in. thickness or the specimen shall be backed by a thickness of wood or plywood sufficient or provide the 1/2-in. total thickness of specimen required.

98. Procedure

98.1 Conduct the test on the Navy-type abrasion machine[7] as shown in Fig. 17, using as the abrading medium new No. 80 grit aluminum oxide, or equivalent. Apply the grit continuously (Note 33) to the 14-in. (355-mm) diameter steel disk, which serves as a platform supporting the specimen and rotates at the rate of 23 1/2 rpm. Rotate the specimen in the same direction as the steel disk at the rate of 32 1/2 rpm. Superimpose a load of 10 lb (4.5 kg) on the test specimen. The machine is designed so that twice each revolution the specimen is raised 1/16 in. (1.6 mm) above the steel disk and immediately lowered. Determine the decrease in the thickness of the specimen at the end of each 100 revolutions of the steel disk by measuring the thickness of the specimen to the nearest 0.001 in. (0.02 mm) near each corner and at the center, after brushing to remove any dust or abrading material adhering to the surface of the specimen. The mean of the five recordings shall be taken as the loss in thickness. Repeat this procedure until the specimen has 500 revolutions of wear or as required (Note 34).

NOTE 33—The Navy wear tester is so designed that there is an excess of grit on the abrading disk at all times. During all parts of the abrading action, except when the specimen is in the raised position, the specimen is pushing a small amount of grit a head of it.

NOTE 34—When values of accumulated wear are plotted as ordinates against revolutions, the slope of the curve is a straight line for wear through uniform materials. When the rate of wear per 100 revolutions of the abrading disk is not uniform after the first 200 revolutions, it is probably due to a change in abrasion resistance with depth from the original surface of the material being tested.

99. Report

99.1 The report shall include the following:

99.1.1 Loss in thickness in inches per 100 revolutions of wear if uniform, and

99.1.2 If the amount of wear changes with depth from the original, surface values for each 100 revolutions.

WATER ABSORPTION AND THICKNESS SWELLING

100. Scope

100.1 A test shall be made to determine the water-absorption characteristics of building boards.

101. Test Specimen

101.1 The test specimen shall be 12 by 12 in. (304 by 304 mm) in size, or 6 by 6 in. (152 by 152 mm) in size with all four edges smoothly and squarely trimmed.

102. Conditioning Prior to Test

102.1 The test specimen shall be conditioned as nearly as deemed practical to constant weight and moisture content in a conditioning chamber maintained at a relative humidity of 65 ± 1 percent and a temperature of 20 ± 3 C (68 ± 6 F). The moisture content after conditioning shall be reported.

103. Weight, Thickness, and Volume of Test Specimen

103.1 After conditioning, weigh the specimen to an accuracy of not less than ±0.2

[6] U. S. Forest Products Laboratory Report R 1732, "The Abrasion Resistance of Wood as Determined with the U. S. Navy Wear Test Machine."

[7] The Navy-type wear tester may be constructed from drawings obtainable from the U.S. Navy or the Forest Products Laboratory. It is manufactured commercially by the Tinius Olsen Testing Machine Co., Willow Grove, Pa.

percent and measure the width, length, and thickness to an accuracy of not less than ±0.3 percent. Compute the volume of the specimen from these measurements. Measure the thickness to an accuracy of ±0.3 percent at four points midway along each side 1 in. (25 mm) in from the edge of the specimen and average for the thickness swelling determination.

NOTE 35—Where a common practice or special consideration requires edge thickness determinations at the edge or another distance from the edge (as the present practice for particle board is ½ in. (12 mm)), the edge distance used shall be given.

104. Submersion in Water

104.1 Submerge the specimen horizontally under 1 in. (25 mm) of distilled water maintained at a temperature of 20 ± 1 C (68 ± 2 F). As an alternative to the above method of submersion, specimens may be submerged vertically (Note 36). After a 2-h submersion, suspend the specimen to drain for 10 min, at the end of which time remove the excess surface water and immediately weigh the specimen and determine the thickness. Submerge the specimen for an additional period of 22 h and report the above weighing and measuring procedure (Note 37).

NOTE 36—The amounts of water absorbed for tests of this duration are not the same for the two methods of submersion. Specimens suspended vertically will absorb considerably more water than those suspended horizontally. Therefore, values obtained from the two methods are not comparable.

NOTE 37—Soluble materials in some of the board products may influence water absorption values if the water is reused; therefore fresh water shall be used for each test. When tap water has been proven sufficiently pure so that results of test are not affected, it may be used as an alternative to distilled water.

105. Drying After Submersion

105.1 After submersion dry the specimen in an oven at 103 ± 2 C as outlined in Sections 126 and 127, and calculate the moisture content (based on oven-dry weight) from the weights after conditioning and after 2 and 24-h submersion.

106. Calculation and Report

106.1 Calculate the amount of water absorbed from the increase in weight of the specimen during the submersion, and express the water absorption both as the percentage by volume and by weight based on the volume and the weight, respectively, after conditioning. Assume the specific gravity of the water to be 1.00 for this purpose. Express the thickness swelling as a percentage of the original thickness. When any other size of specimen than the 12-in. (304-mm) square one is used, the report shall include the size used. In addition, give the method of submersion if other than horizontal.

LINEAR VARIATION WITH CHANGE IN MOISTURE CONTENT

107. Scope

107.1 Tests of linear variation with change in moisture content shall be made to measure the dimensional stability of a fiberboard with change in moisture content.

108. Test Specimen

108.1 The test specimens, when possible, shall be 3 in. (76 mm) in width and at least 12 in. (304 mm) in length. Two specimens shall be provided, one cut parallel with the long dimension of each board and one from the same board cut at right angles to the long dimension. When a board does not permit obtaining a 12-in. (304-mm) specimen, the maximum length possible shall be used, but it shall be at least 6 in. (152 mm).

109. Procedure

109.1 Follow the following or any equally or more accurate method for measuring specimens: Condition to practical equilibrium (Note 38) specimens carefully sawed square and smooth at a relative humidity of 50 ± 2 percent and a temperature of 20 ± 3 C (68 ± 6 F). Measure the length of each specimen to the nearest 0.001 in. (0.02 mm) in a comparator like or similar to the one shown in Figs. 13 and 14 using a standard bar of the same nominal length as the specimen for reference. For each measurement orient the specimen in the same way in the comparator, for example, numbered surface up with numbers reading from the side toward the operator. Then condition the specimens to practical equilibrium (Note 39) at a relative humidity of 90 ± 5 percent and a temperature of 20 ± 3 C (68 ± 6 F), place in the comparator

to the surface. Include the size of specimen and necessary details regarding methods of measurements in the report.

MOISTURE CONTENT AND SPECIFIC GRAVITY

126. Procedure

126.1 Determine the specific gravity (or density) of each static bending specimen at time of test from the dimensions, weight, and moisture content, as provided in Sections 9, 19, and 127. When specific gravity determinations are required on specimens of prism form from other tests; like procedure may be used. The moisture content of a specimen may be determined from a coupon cut from the test specimen as in the static bending test, or the entire test specimen may be used for the moisture determination.

126.2 When for any reason additional determinations of moisture content and specific gravity (or density) are required, prepare separate samples for this determination from the same material as is used in preparing the test specimens. These moisture content and specific gravity specimens shall be the full thickness of the material and 3 in. (76 mm) wide and 6 in. (152 mm) long. Smaller specimens may be used when deemed necessary. Condition the specimens in accordance with the provisions of Section 5.

126.3 Measure the dimensions to an accuracy of not less than ±0.3 percent, and the weight to an accuracy of not less than ±0.2 percent. Obtain the oven-dry weight after drying the specimen in an oven at 103 ± 2 C until approximately constant weight is attained.

127. Calculations

127.1 The moisture content shall be calculated as follows:

$$M = 100[(W - F)/F]$$

where:

M = moisture content, percent,
W = initial weight, and
F = final weight when oven-dry.

127.2 Calculate the specific gravity as follows (Note 45):

$$\text{Sp gr} = KF/lwt$$

where:

F = final weight when oven dry, g,
L = length of coupon, in. (or mm),
w = width of coupon, in. (or mm),
t = thickness of coupon, in. (or mm), and
K = 1, when metric units of weight and measurement are used; or
0.061, when metric units of weight and U.S. customary units of measurement are used.

Note 45 – The specific gravity as determined by this equation is based on volume at test and weight when oven dry.

127.3 When desired, the density based on weight and volume of the specimens after conditioning may be calculated.

INTERLAMINAR SHEAR

128. Scope

128.1 Tests in interlaminar shear (shear in the plane of the board) shall be made on specimens bonded between two steel loading plates loaded in compression to obtain strength and deformation properties of wood-base panel materials. One half of the test specimens shall be prepared with the long dimension parallel and the other half with the long dimension perpendicular to the long dimension of the board in order to evaluate any directional properties.

129. Significance

129.1 Shear properties in the plane of the board (interlaminar shear) duplicate the kind of stressing in shear encountered in such glued structural assemblies as structural sandwiches and adjacent to gluelines between flanges and webs in box and I-beams and gusset plates in trusses. The procedure used follows closely the requirements of Method C 273. While it apparently yields values in the same plane as the "block shear" test of Sections 87 to 90, values obtained are not comparable because of effects of friction in the tool and the fact that failure in the block shear test can only occur in a $^{1}/_{8}$-in. (3-mm) thick area in the middle of the board. The interlaminar shear strength test offers the additional advantage that shear deformation data can be obtained when desirable.

130. Test Specimen

130.1 The interlaminar shear tests shall be made on specimens 2 in. (50 mm) wide and 6 in. (150 mm) long by the thickness of the material, when the board material is $^{1}/_{2}$ in. (12.5 mm) in thickness or less. For materials more than $^{1}/_{2}$ in. (12.5 mm) thick, the specimen shall have a width of at least twice the thickness but not less than 2 in. (50 mm) and a length at least 12 times the thickness (Note 46). The edges of the specimen shall be sawed square and smooth. The length, width, and thickness shall be measured to an accuracy of at least ±0.3 percent.

130.2 Steel loading plates $^{3}/_{4}$ in. (about 20 mm) thick, having a width equal to the specimen width and a length equal to the specimen length plus $^{1}/_{4}$ in. (7 mm) shall be bonded to each face of the specimen as shown in Fig. 20 using suitable adhesive (Note 47). The loading ends of the plates shall protect $^{1}/_{4}$ in. (7 mm) beyond the end of the specimen and they shall be beveled at 45 deg and oriented as shown. Extreme care shall be used in applying adhesive so minimum spreads are used to prevent it infusing into the specimen and thus reinforcing the board.

Note 46 – A length ratio of 12:1 is prescribed as a minimum so that secondary normal stresses are minimal.

Note 47 – See Note 14.

131. Loading Procedure

131.1 The load shall be applied through notched fittings such that the line of action of the direct compressive force shall pass through the diagonally opposite corners of the specimen as shown in Fig. 20. The lower fitting shall be placed on a spherical bearing block as shown in Fig. 21 so that the load is uniformly distributed across the width of the specimen.

132. Speed of Testing

132.1 The load shall be applied continuously throughout the test at a uniform rate of motion of the movable crosshead of the testing machine equal to 0.002 times the length (inch or centimeter) per minute (see Note 9).

133. Load-Deformation Data

133.1 When shearing modulus is required, data for plotting load-deformation curves can be obtained by using the dial gage arrangement shown in Fig. 21, which measures the displacement of one plate with respect to the other. The interlaminar shearing modulus is defined as the slope of the straight-line portion of the stress-strain curve. A secant modulus may be calculated for data which do not have an initial straight-line relationship. If shearing modulus values are included in the report, the method used to determine them shall also be reported.

134. Moisture Content and Specific Gravity

134.1 If moisture content or specific gravity, or both, are required, a separate specimen taken from the board adjacent to the shear specimen shall be used and the determinations made as detailed in Sections 126 and 127.

135. Calculations and Report

135.1 The interlaminar shearing strength shall be calculated for each specimen by the following equation, and the values determined shall be included in the report:

$$f_s = P/Lb$$

135.2 The interlaminar shearing modulus shall be calculated for each specimen by the following equation (Note 48), and the values determined shall be included in the report:

$$G = P_1d/Lbr$$

where:

b = width of specimen, in. (or cm),
d = thickness of specimen, in. (or cm),
f_s = interlaminar shearing strength, psi (or kg/cm²),
G = interlaminar shearing modulus, psi (or kg/cm²),
L = length of specimen, in. (or cm),
P = maximum load, lb (or kg),
P_1 = load at proportional limit or point where secant intersects load-deformation curve, lb (or kg), and
r = dial reading or displacement of one plate with respect to the other at load P_1, in. (or cm).

Note 48 – The equation in 129.2 above assumes that the strains in the loading plates and in the bond between the plates and the specimen are negligible.

EDGEWISE SHEAR

136. Scope

136.1 Tests in edgewise shear (shear nor-