Determination of the Ultimate Tensile Strength of Common Household Materials by a Loading Method

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Abstract

An experiment was carried out to determine the ultimate tensile strength of four different household materials: extruded polystyrene, porcelain tiles, printer paper, and wood. Tensile strength was evaluated using the method of loading the materials until they catastrophically failed, and then calculating the force applied when the failure occurred and measuring the cross-sectional area of the failure zone. Paper was determined to have the highest ultimate tensile strength, followed in decreasing order by wood, porcelain tiles, and extruded polystyrene.

Introduction

The mechanical properties of common materials are extremely important to their application. These mechanical properties encompass what might be colloquially thought of as the strength of the material, though in reality strength is too one-dimensional a word, since under different types of stress most materials respond differently. As a result, the compressional, shear, bending, and tensional strength of the material must all be examined separately. Each of these stresses corresponds to a type of force application. Compression represents a pushing force on the material, where the material fails perpendicular to the direction of applied force. Tension is the opposite of compression, in that it corresponds to a pulling force on the material [1]. Shearing occurs when the failure is in the direction parallel to the applied force, while bending occurs when the material is subjected to a force that bends it. The strength of a given object in terms of each of these forces can predict how the object will respond to different situations and loads, and it is very essential to understand the limitations of a material when using it to build structures or to perform another function that will put it under stress. As a result, extensive research has been conducted on the strengths of various materials, from the mechanical strength of steel compounds [2] to the tensile strength of ceramic dental fittings bonded to teeth [3]. In fact most major industries supply data for materials commonly in use; for example there is a large amount of data relating to steel, concrete, and other building materials published in various engineering sources. However, for some lesser known or non-building related materials, less research has been done.

This experiment therefore examined some moderately researched materials, with a particular focus on one aspect of their strength: their ultimate tensile strength. The ultimate tensile strength is a measure of how strongly or an object holds together when subjected to a tensile force. Ultimate tensile strength is mathematically defined by the formula

$$T = \frac{P_c}{A}, \quad (1)$$

where P_c is the critical loading force under which the object fails catastrophically, and A is the cross-sectional area of the failure zone. Throughout the course of this paper, the terms "ultimate tensile strength" and "tensile strength" will be used

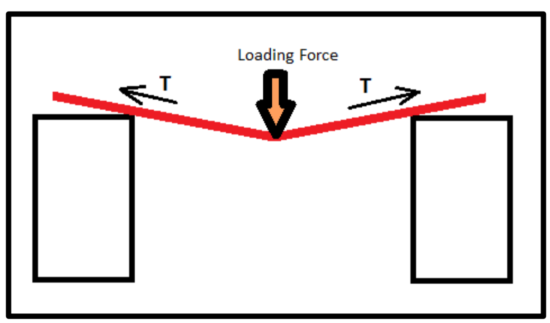


Figure 1: The tensile forces acting on the object under a loading force. The bend in the object is exaggerated for effect.

interchangeably to represent this same quantity. Ultimate tensile strength can be measured in a number of ways, and the method chosen in this experiment is a fairly novel one; while other methods are generally used in place of the method used in this experiment, they almost universally require more by way of specialized equipment in order to perform. In previous studies, the object in question would be put under a bending load in order to determine its tensile strength [4]; instead, in this project the objects were put under tension by loading them at their centers while supporting them from each end, as demonstrated in Figure 1. The ultimate tensile strength can thus be determined by measuring the critical load P_c in terms of the loaded mass and the acceleration due to gravity, and then dividing it by the cross-sectional area A of the failure zone.

Methods and Design

The method used for testing the ultimate tensile strength of various materials is modeled on that which was proposed by Bao, Zhang, and Zhou in their 2002 paper. However, instead of testing the strength of the bond between two pieces of material, this experiment tested the ultimate tensile strength of the material itself. The materials that were tested were wood, extruded polystyrene, printer paper, and porcelain bathroom tiles. Each sample of each material was prepared so that it formed a bar-like shape which could be supported from each end by a stack to raise it off the work surface. This ensured that once the material had deformed somewhat, or begun to fail, it was able to do so to completion. Each material was also scored to an appropriate depth for its thickness, so that the failure zone would be uniform and thus easier to calculate. This meant that the polystyrene, for example, was cut into rectangular sections of approximately 20cm in length by 5cm in width by 2.5cm in depth. A score was then made to decrease its total depth from 2.5cm to 1.5cm, and to ensure the polystyrene failed along that line. The sample was then placed across the two supports of equal height, which together supported approximately 10% of the sample's total area, as shown in Figure 2. Finally, the sample was loaded until it suffered a catastrophic failure. This catastrophic failure was defined as being the total separation of the two halves of the material broken along the score line.

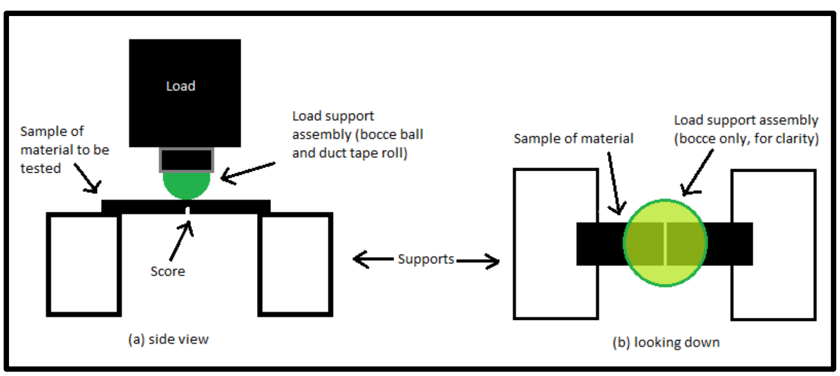


Figure 2: Two views of the experimental set up.

The sample material was loaded in a consistent manner, such that the forces involved were all similarly distributed. This was achieved by balancing the load on top of a sphere. In the case of wood, tile, and polystyrene, a bocce ball of known mass was used as the sphere, while in the case of the paper, a cricket ball of known mass was used. To each of these spheres a ring-shaped structure with a flat top (a duct tape roll and the bottom of a Gatorade bottle respectively) was added so that the loading objects could be balanced adequately on top of the sphere. The loading objects were miscellaneous items that were easily at hand, each of which were weighed and catalogued (See Appendix 2) so that the load could be easily adjusted and manipulated. Since the stack of loading objects was quite unstable as a result of the spherical nature of its support assembly, the sides were supported by applying only a lateral force so that the loading force itself did not change.

The critical loading force was first estimated by increasing the mass of the load in relatively large jumps until the material failed. This trial was not counted. For the next five trials, the material was loaded to near the initial critical load (within 30%), after which smaller objects were added to determine as precisely as possible a load which caused the material to fail. After the failure had occurred, the actual cross sectional area of the failure zone was measured and recorded using a meter stick. All of the samples for a given material were of approximately the same dimensions. However, these final measurements of the cross-sectional area were necessary to ensure that the final measured area was accurate. Additionally, if the area of the failure zone was irregular, it had to be otherwise estimated by measuring the area of sections of the failure zone and then summing them (See Figure 3 for examples of typical failure zones).

Data Collection and Analysis:

Tables containing the raw data collected during the experiment for each material are presented in Appendix 1.

Data tables including the results of manipulating the raw data from the tables in Appendix 1 are shown below:

Extruded Polystyrene:

Critical load [P_c] (N)	**δ(load) [δP_c] (N)**	**Cross-Sectional Area [A] $(\mathrm{m^2})$**	**δ(area) [δA] $(\mathrm{m^2})$**	**Ultimate Tensile Strength [T] (Pa)**	**δ(tensile strength) [δT] (Pa)**
29.932272	$\pm$0.003102194	0.00075	$\pm 2.61 * 10^{-5}$	39909.70	$\pm$1388.904
30.328596	$\pm$0.003253609	0.00075	$\pm 2.61 * 10^{-5}$	40438.13	$\pm$1407.295
29.712528	$\pm$0.002774687	0.00075	$\pm 2.61 * 10^{-5}$	39616.70	$\pm$1378.707
29.677212	$\pm$0.002595482	0.00075	$\pm 2.61 * 10^{-5}$	39569.62	$\pm$1377.067
29.677212	$\pm$0.002595482	0.00075	$\pm 2.61 * 10^{-5}$	39569.62	$\pm$1377.067

The calculations required to obtain the quantities in the above table are listed below. These same methods were used to obtain these quantities whenever they were calculated during the experiment.

- The formula for calculating the critical load (P_c) of the material in terms of the mass of the loaded objects (m) and the acceleration due to gravity (g) is as follows:

  $$P_c = mg = m(9.81\ \mathrm{m/s^2})$$

- Using the uncertainty formula $\delta f(x,y) = \sqrt{\left(\frac{\partial f}{\partial x} * \delta x\right)^2 + \left(\frac{\partial f}{\partial y} * \delta y\right)^2}$, the formula for the uncertainty in the critical load (δP_c) can be derived:

  $$\delta P_c(m,g) = \sqrt{\left(\frac{\partial f}{\partial m} * \delta m\right)^2 + \left(\frac{\partial f}{\partial g} * \delta g\right)^2} = \sqrt{(g * \delta m)^2 + \left(m * (0)\right)^2} = g * \delta m$$

- The formula for the cross-sectional area (A) of the split in the material can potentially take a number of different forms, depending on the geometrical shape of the portion of the split. The formula for calculating the area if the split is a rectangle, triangle, or divided into a number of different cross-sections is as follows:

  $$A = l * w = \frac{1}{2}bh = \sum_{i=1}^{N} A_i$$

- Using the uncertainty formula $\delta f(x,y) = \sqrt{\left(\frac{\partial f}{\partial x} * \delta x\right)^2 + \left(\frac{\partial f}{\partial y} * \delta y\right)^2}$, the formula for the uncertainty in the cross-sectional area (δA) can be derived:

  $$\delta A(l,w) = \sqrt{(w * \delta l)^2 + (l * \delta w)^2}$$

  $$\delta A(0.5, bh) = \sqrt{\left(bh * (0)\right)^2 + \left(0.5 * \sqrt{(h * \delta b)^2 + (b * \delta h)^2}\right)^2} = 0.5 * \sqrt{(h * \delta b)^2 + (b * \delta h)^2}$$

  $$\delta A_{\mathrm{total}} = \sqrt{(\delta A_1)^2 + (\delta A_2)^2 + \cdots + (\delta A_N)^2}$$

- The formula to calculate the ultimate tensile strength (T) of the materials is given by Equation 1, which is as follows:

  $$T = \frac{P_c}{A} \tag{1}$$

- Using the uncertainty formula $\delta f(x,y) = \sqrt{\left(\frac{\partial f}{\partial x} * \delta x\right)^2 + \left(\frac{\partial f}{\partial y} * \delta y\right)^2}$, the formula for the uncertainty in the ultimate tensile strength (δT) can be derived:

  $$\delta T(P_c, A) = \sqrt{\left(\frac{1}{A} * \delta P_c\right)^2 + \left(-\frac{P_c}{A^2} * \delta A\right)^2}$$

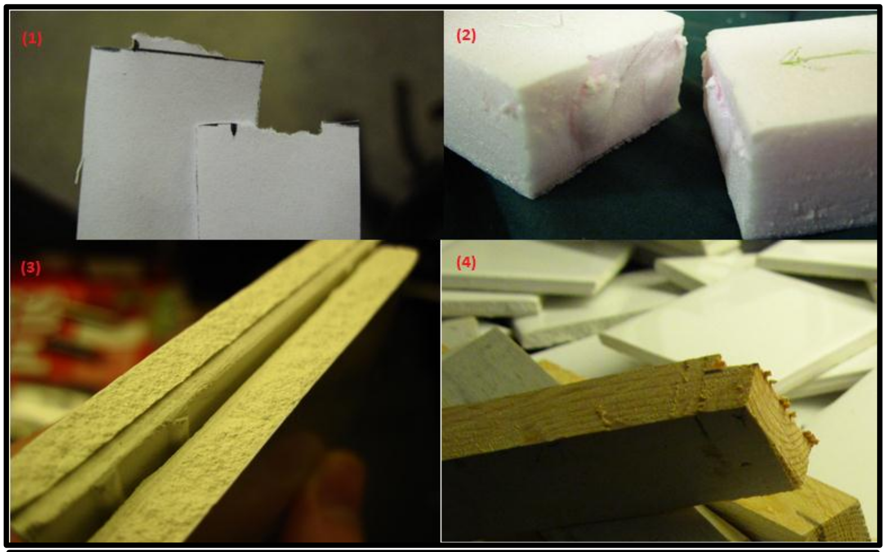


Figure 3: The failure zones of samples from each different material type, paper (1), extruded polystyrene (2), tile (3), and wood (4).

Porcelain Tiles:

Critical load [P_c] (N)	**δ(load) [δP_c] (N)**	**Cross-Sectional Area [A] (m^2)**	**δ(area) [δA] (m^2)**	**Ultimate Tensile Strength [T] (Pa)**	**δ(tensile strength) [δT] (Pa)**
127.3191	$\pm$0.098120	0.000418	$\pm 3.81 * 10^{-5}$	304591.1	$\pm$27763.51
171.1276	$\pm$0.098169	0.000522	$\pm 4.36 * 10^{-5}$	327830.7	$\pm$27384.76
148.4273	$\pm$0.098154	0.000473	$\pm 4.31 * 10^{-5}$	313799.7	$\pm$28586.28
146.9901	$\pm$0.098144	0.000451	$\pm 4.11 * 10^{-5}$	325920.4	$\pm$29696.50
153.4000	$\pm$0.098159	0.000468	$\pm 4.26 * 10^{-5}$	328128.2	$\pm$29892.96

Printer Paper:

Critical load [P_c] (N)	**δ(load) [δP_c] (N)**	**Cross-Sectional Area [A] (m^2)**	**δ(area) [δA] (m^2)**	**Ultimate Tensile Strength [T] (Pa)**	**δ(tensile strength) [δT] (Pa)**
17.64917	$\pm$0.002943	0.00000125	$\pm 2.14 * 10^{-7}$	14119337	$\pm$2420048
17.00073	$\pm$0.002595	0.00000120	$\pm 2.06 * 10^{-7}$	14167275	$\pm$2433883
13.90666	$\pm$0.002403	0.00000115	$\pm 1.98 * 10^{-7}$	12092744	$\pm$2082909
16.65934	$\pm$0.002775	0.00000110	$\pm 1.90 * 10^{-7}$	15144856	$\pm$2616333
12.14870	$\pm$0.002194	0.00000100	$\pm 1.74 * 10^{-7}$	12148704	$\pm$2113938

Wood:

Critical load $[P_c]$ (N)	**δ(load) $[\delta P_c]$ (N)**	**Cross-Sectional Area $[A]$ (m^2)**	**δ(area) $[\delta A]$ (m^2)**	**Ultimate Tensile Strength $[T]$ (Pa)**	**δ(tensile strength) $[\delta T]$ (Pa)**
140.7186	$\pm$0.098129	0.000239	$\pm 1.78 * 10^{-5}$	588780.6	$\pm$43774.87
143.7754	$\pm$0.098134	0.000266	$\pm 1.64 * 10^{-5}$	540255.0	$\pm$33362.55
111.4416	$\pm$0.098100	0.000231	$\pm 1.15 * 10^{-5}$	482431.2	$\pm$24071.91
116.7979	$\pm$0.098115	0.000234	$\pm 1.60 * 10^{-5}$	499136.2	$\pm$34094.43

Graphs displaying the ultimate tensile strength of each of these materials as measured in each individual trial are included in Appendix 3.

Further manipulation of the data from each of these tables enabled the determination of a weighted mean ultimate tensile strength for each material, which are included in the table below:

Material	**Weighted Average Ultimate Tensile Strength $[T_w]$ (Pa)**	**δ(weighted average) $[\delta T_w]$ (Pa)**
Polystyrene	$4.0 * 10^4$	$\pm 3.10 * 10^3$
Tiles	$3.2 * 10^5$	$\pm 6.41 * 10^4$
Printer paper	$1.3 * 10^7$	$\pm 5.24 * 10^6$
Wood	$5.1 * 10^5$	$\pm 6.91 * 10^4$

The calculations required to obtain the quantities in the above table are listed below. These same methods were used to obtain these quantities whenever they were calculated during the experiment.

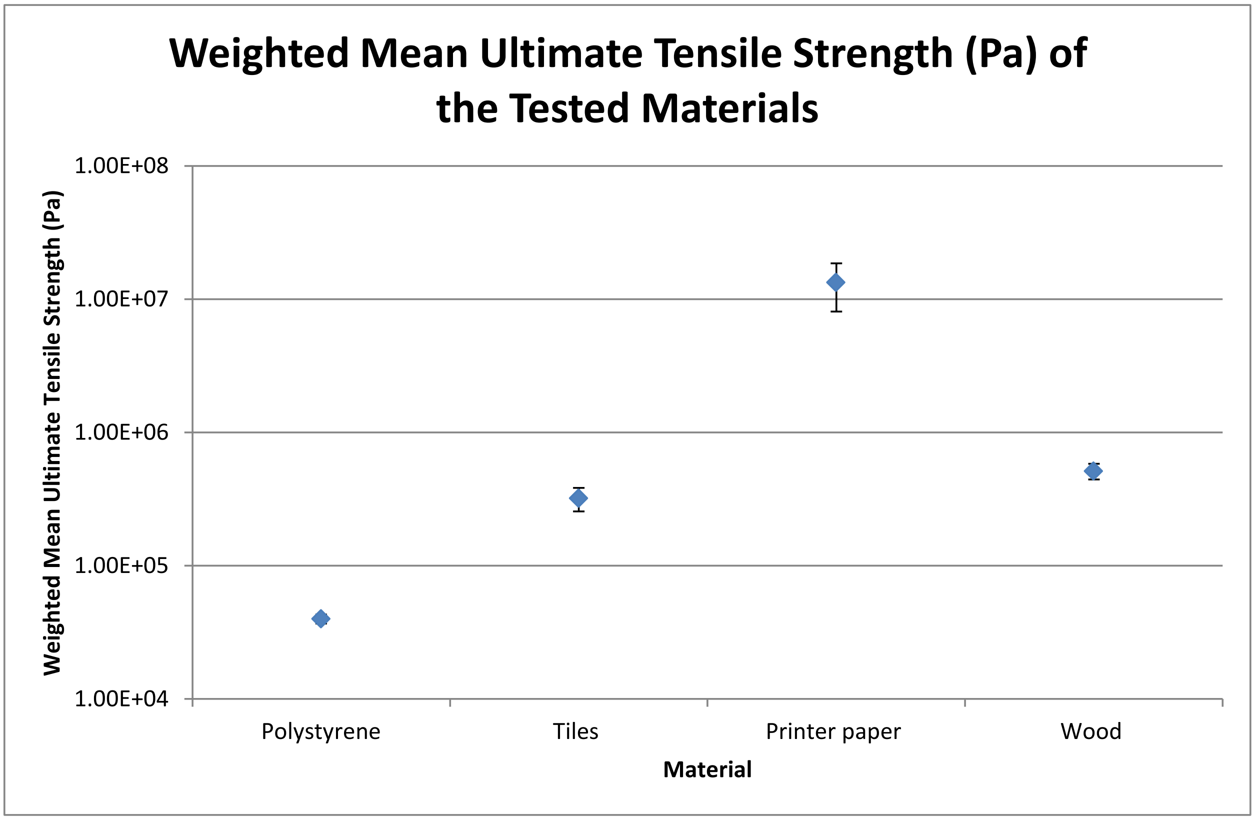
- The formula for calculating the weighted mean ultimate tensile strength (T_w) of a material is as follows:

$$T_w = \frac{\sum_{i=1}^{N}\left(T_i * \frac{1}{(\delta T_i)^2}\right)}{\sum_{i=1}^{N}\left(\frac{1}{(\delta T_i)^2}\right)}$$

- Using the uncertainty formula $\delta f(x,y) = \sqrt{\left(\frac{\partial f}{\partial x} * \delta x\right)^2 + \left(\frac{\partial f}{\partial y} * \delta y\right)^2}$, the formula for the uncertainty in the weighted mean ultimate tensile strength (δT_w) can be derived:

$$\delta T_w(m,g) = \sqrt{\sum_{i=1}^{N}(\delta T_i)^2}$$

A graph displaying the data in the above table is included below:



This graph depicts the weighted mean ultimate tensile strengths of all four tested materials, in addition to the uncertainty in each quantity in the form of vertical error bars. In this graph, some of the vertical error bars, such as those for the data point for polystyrene, are too small to be seen on the graph. The graph clearly displays the trend in the weighted mean ultimate tensile strengths of the four materials in relation to one another: the largest weighted mean tensile strength is that of the printer paper, which was found to be the greatest by a considerable margin; the next largest was that of wood, which is followed closely by that of the porcelain tiles; finally, the lowest tensile strength is that of the extruded polystyrene, which was found to be considerably lower than those of the other three tested materials.

<u>Discussion:</u>

The data show a clear, significant, and measurable difference in the ultimate tensile strengths of all the materials tested. Polystyrene was measured to have the lowest ultimate tensile strength ($4.0 * 10^4$ ($\pm 3.10 * 10^3$ Pa)), porcelain tile the next lowest ($3.2 * 10^5$ ($\pm 6.41 * 10^4$ Pa)), followed by wood ($5.1 * 10^5$ ($\pm 6.91 * 10^4$ Pa)), and then paper with the highest ($1.3 * 10^7$ ($\pm 5.24 * 10^6$ Pa)). This trend towards increasing tensile strengths is a result of the different compositions of the materials. The term "tensile bond strength," a quantity measuring the strength with which the bonds in a material resist a tensile force (thereby making it similar and related to ultimate tensile strength), is somewhat evocative in this respect, in that the strength with which these materials hold together is dependent entirely upon the composition of the molecular bonds that are present in each type of material. Therefore, the relative strengths of the intermolecular forces in each of these materials can therefore be inferred from the conducted measurements of their ultimate tensile strengths.

The uncertainty in the weighted mean ultimate tensile strengths of the tiles, polystyrene, and wood are all of relatively similar magnitudes (10^4, 10^3, and 10^4, respectively). However, the measured uncertainty in the weighted mean ultimate tensile strength of paper breaks this trend; it is much larger than any of the uncertainties for the other materials, having a magnitude of 10^6. The major source of estimable error in this experiment came as a result of the scale resolution of the equipment used. The uncertainties in the length measurements reported were a result of imprecision in the ruler used, and those in the mass measurements reported were a result of imprecisions in the analog and digital measuring scales (the larger error in the largest mass measurement was due to the use of the less precise analog scale). The potential sources of error will now be discussed at some length due to their illumination of the complex nature of the materials that were being examined in this experiment.

Additionally, there were further errors unique to the trials performed for each different material. The much larger magnitude of the paper's uncertainty was due to the much larger proportionality of the scale resolution uncertainty compared to the small measured cross sectional area, causing the uncertainty to become very large through propagation. The method by which the paper was secured to the supporting stacks also affected the accuracy of the results. Several times, the tape holding the paper sample to the supports slipped, causing the paper to release without failing. The experimental setup thus had to be reset, potentially restarting the trial with an already weakened piece of paper. The paper was also secured with varying levels of tension to the blocks. When there was tension applied to the paper by the securing method, it would decrease the critical loading force required to cause the paper to fail, resulting in a lower value for the tensile strength of the paper. Further experiments could be improved by standardizing this initial tension and the method of securing the paper.

Wood is a poor material for testing using the method in this experiment due to the geometrically irregular nature of its failure zones. Wood is an orthotropic material [5], meaning it has different mechanical properties depending on the axis along which the force is applied. This presents difficulties, particularly when attempting to examine its properties along one particular axis, in this case its strength when faced with a force applied perpendicular to the grain. While in theory these properties should be independent and not affect other axes, in practice, force applied in one direction may result in radiation into other axes, producing an irregular result. Particularly in this experiment, failure was observed parallel to the grain, a direction in which the wood is actually failing in shear (i.e. parallel to the axis of the applied force). Wood fails more easily in shear with the grain [5], thus decreasing the measured load required to break the sample as well as skewing the experimental data collected for wood. Additionally, failures occurring in shear with the grain lead to an extremely irregular failure zone, making it very difficult to accurately determine the cross-sectional area of the failure.

These difficulties could account for the small amount of research conducted on wood's strength in the axis radial to its grain.

Ultimately, not even literature sources present confident results with regard to the ultimate tensile strength of wood in any one axis. The sample used in this experiment was not identifiable in terms of its species, although visually it appeared to be a member of either the pine or spruce family. Thus the experimentally measured values for ultimate tensile strength of the wood samples can be compared to values for the Loblolly pine and Sitka spruce. The measured values of tension strength perpendicular and parallel to the grain for each of these are 88.0MPa and 3.2Mpa for the pine [6], and 75.8MPa and 2.6MPa for the spruce [6]. Both of these values are given as a combination of failure perpendicular and parallel to its grain due to the fact that the wood ultimately failed in a very complex manner. The measured value in this experiment is a full order of magnitude outside of both these ranges. This suggests that either the wood used in this experiment was from a species with very different characteristics than those of pine or spruce woods, or that there were large elements of the failure that were inadequately examined. The varied and inconsistent nature of wood is largely due to its layered composition, with different seasons and ages producing different cellulitic structures [7]. Wood is therefore of wildly varying densities and strengths throughout any one sample and these variations and their interfaces produce complex interactions. Wood is held together by London dispersion forces between cellulose molecules which are the principle structural constituents in wood [7], forming fibers called tracheids and libriform fibers. Given that these are large molecules, a high strength of interaction can be expected.

No literature value was found for the specific type of paper tested in this experiment; however, paper is composed of a more a more organized form of the fibers that make up wood. This matrix can be expected to have even greater intermolecular forces due to its purer, less amorphous nature. This is supported by the data gathered by the experiment, with paper having the greatest tensile strength of the tested materials ($1.3 * 10^7$ ($\pm 5.24 * 10^6$ Pa)).

Extruded polystyrene displayed interesting behavior under a loading force; this interesting behavior contributed to the error in measurement of its ultimate tensile strength, but was also revealing of the mechanism by which it failed. The polystyrene slowly peeled apart while it was under a loading force, with the fracture spreading from the lower edge of the polystyrene, which was under greater stress due to the bending of the sample. This meant that the time over which it failed was in fact quite long. Initial trials did not take this into account, meaning additional loading force was applied while it was still "settling" (in reality peeling apart). This would have resulted in an overestimation of the actual required force. Further experiments could minimize this error by waiting for increased, standardized periods of time before adding load.

Literature sources place the value of the tensile strength of polystyrene foams, similar to the sort tested in this experiment, in a range of 230-330 kPa [8]. The measured value in this experiment was significantly lower than this, at around 40 ($\pm$3.10 kPa). As the uncertainty range of the data collected in this experiment does not include the literature value, there is no agreement between these measurements, and as such it is possible that different polymeric forms or polystyrene that had been formed and foamed differently were used. Polystyrene is a polymer of moderate length [8], and is therefore also held together by London dispersion forces. This should produce a force similar to that of wood and paper. However, the polystyrene is very amorphous, having little internal organization, which would contribute to the material's observed lower tensile strength than those of wood and paper. Additionally, the presence of air bubbles within the material due to the manufacturing process of extruded polystyrene (it is foamed) can disrupt its internal strength and lead to an even lower observed tensile strength, further skewing the experimental results.

Tile suffered from no unique sources of error in its testing, and thus was subject only to the systematic errors. The manufacturer provides information on the breaking strength of the tiles, computed by an industry standard test [9]. Manipulating this strength, the tensile strength according to the company is greater than or equal to $2.0 * 10^5$Pa. The actual measured value in this experiment was $3.2 * 10^5$ ($\pm 6.41 * 10^4$ Pa), which is in good agreement with the literature value. Ceramics are brittle materials held together in an ionic lattice, much like crystals are [10]. Failure due to tensile forces is caused by imperfections or irregularities in the lattice [10]. The fact that in this experiment the tile was observed to have a larger tensile strength than reported in the literature value indicates that the manufacturing company was taking a lower estimate of the tile's strength and that the tile had fewer imperfections than were expected in the worst case.

Another large source of error is the superposition of the errors, through propagation, of the summation of the non-standard masses used to load each sample. Each mass was measured separately and had an associated uncertainty, thereby amplifying the propagated uncertainty value of the overall mass required to cause the sample to fail. A method to reduce this source of error would be weighing the final total masses all at once. Finally, the non-standard nature of the loading masses contributed to the error. In essence, these made it difficult to precisely, accurately, and consistently dial in the mass required to break the material, resulting in an overestimate of the actual required mass in each trial. The use of standard masses would rectify this source of error.

It is important to note that all of the data points obtained for each material, with the exception of those collected for wood, agreed with each other. Agreement is defined as an overlap of their uncertainty ranges with one another. As previously mentioned, the trials performed for wood contained significant variation and random error as a result of the inherently irregular failure process of wood. This means that the collected data for wood is less reliable and statistically significant than that for the other three materials.

Conclusion

The ultimate tensile strengths of the four examined materials were determined to be as follows: printer paper was found to have the highest tensile strength ($1.3 * 10^7$ ($\pm 5.24 * 10^6$ Pa)), followed in decreasing order by wood ($5.1 * 10^5$ ($\pm 6.91 * 10^4$ Pa)), porcelain tiles ($3.2 * 10^5$ ($\pm 6.41 * 10^4$ Pa)), and finally by extruded polystyrene ($4.0 * 10^4$ ($\pm 3.10 * 10^3$ Pa)).

This decrease in tensile strength correlates to the individual materials' chemical makeup and the nature of their internal structural bonding. The large uncertainties in the calculated values are the result of propagation of error through several calculations, and the relative magnitude of the uncertainties resulted from the differences in the properties of the materials. The measured ultimate tensile strength of the porcelain tiles was found to agree with the reported literature values for this quantity, while the measured values for extruded polystyrene and wood disagreed with their respective literature values and no literature values were found for printer paper.

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Appendix 1 – Raw Data Tables:

Extruded Polystyrene:

Trial #	Mass to break (kg)	δ[mass] (kg)	Length (m)	δ[length] (m)	Width (m)	δ[width] (m)
1	3.0512	±0.000316228	0.05	±0.0005	0.015	±0.0005
2	3.0916	±0.000331662	0.05	±0.0005	0.015	±0.0005
3	3.0288	±0.000282843	0.05	±0.0005	0.015	±0.0005
4	3.0252	±0.000264575	0.05	±0.0005	0.015	±0.0005
5	3.0252	±0.000264575	0.05	±0.0005	0.015	±0.0005

Porcelain Tiles:

Trial #	Mass to break (kg)	δ[mass] (kg)	Length (m)	δ[length] (m)	Width (m)	δ[width] (m)
1	12.9785	±0.010002000	0.076	±0.0005	0.0055	±0.0005
2	17.4442	±0.010006998	0.087	±0.0005	0.0060	±0.0005
3	15.1302	±0.010005498	0.086	±0.0005	0.0055	±0.0005
4	14.9837	±0.010004499	0.082	±0.0005	0.0055	±0.0005
5	15.6371	±0.010005998	0.085	±0.0005	0.0055	±0.0005

Printer Paper:

Trial #	Mass to break (kg)	δ[mass] (kg)	Length (m)	δ[length] (m)	Width (m)	δ[width] (m)
1	1.7991	±0.000300000	0.0125	±0.0005	0.0001	$\pm 1.67 * 10^{-5}$
2	1.7330	±0.000264575	0.0120	±0.0005	0.0001	$\pm 1.67 * 10^{-5}$
3	1.4176	±0.000244949	0.0115	±0.0005	0.0001	$\pm 1.67 * 10^{-5}$
4	1.6982	±0.000282843	0.0110	±0.0005	0.0001	$\pm 1.67 * 10^{-5}$
5	1.2384	±0.000223607	0.0100	±0.0005	0.0001	$\pm 1.67 * 10^{-5}$

Wood:

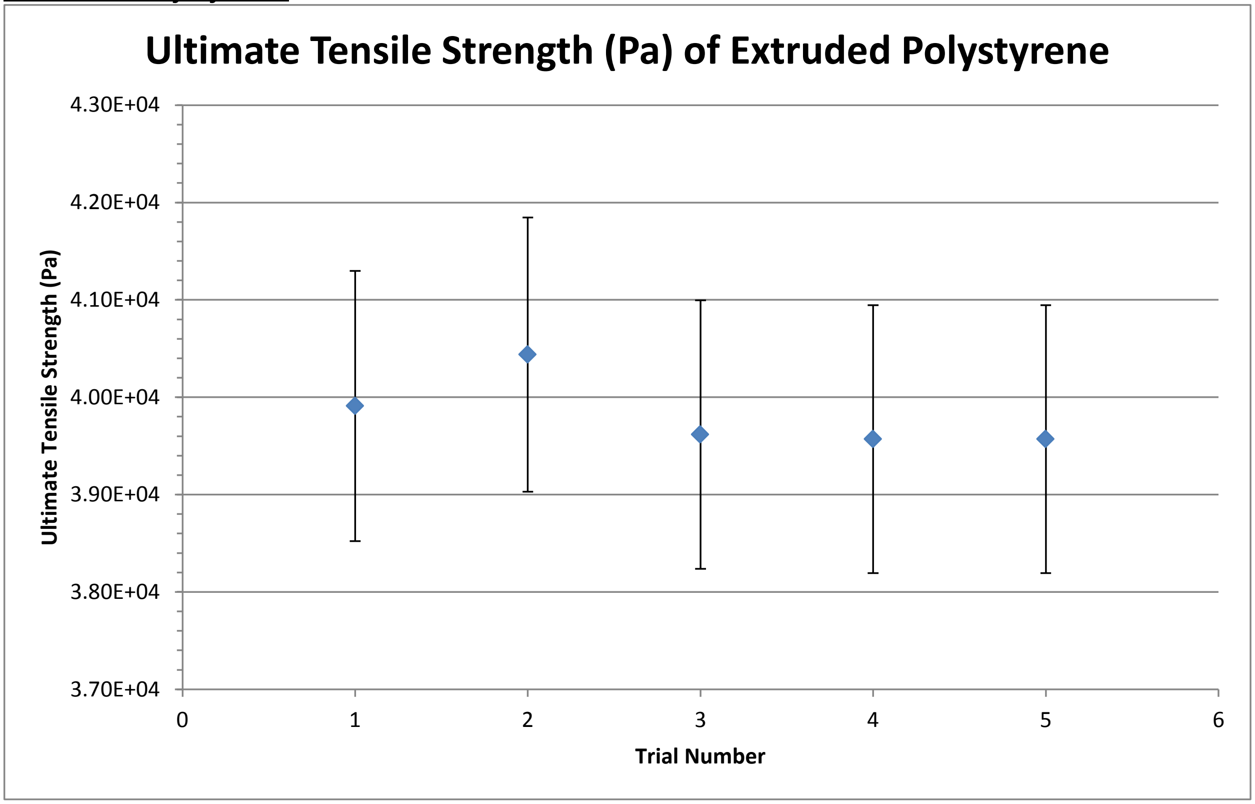
Trial #	Mass to break (kg)	δ[mass] (kg)	Cross-Sectional Area (m^2)
1	14.344	±0.010003000	0.00023900
2	14.656	±0.010003499	0.00026613
3	11.360	±0.010000000	0.00023100
4	11.906	±0.010001500	0.00023400

Appendix 2 – Masses of Objects Used for Loading Tests:

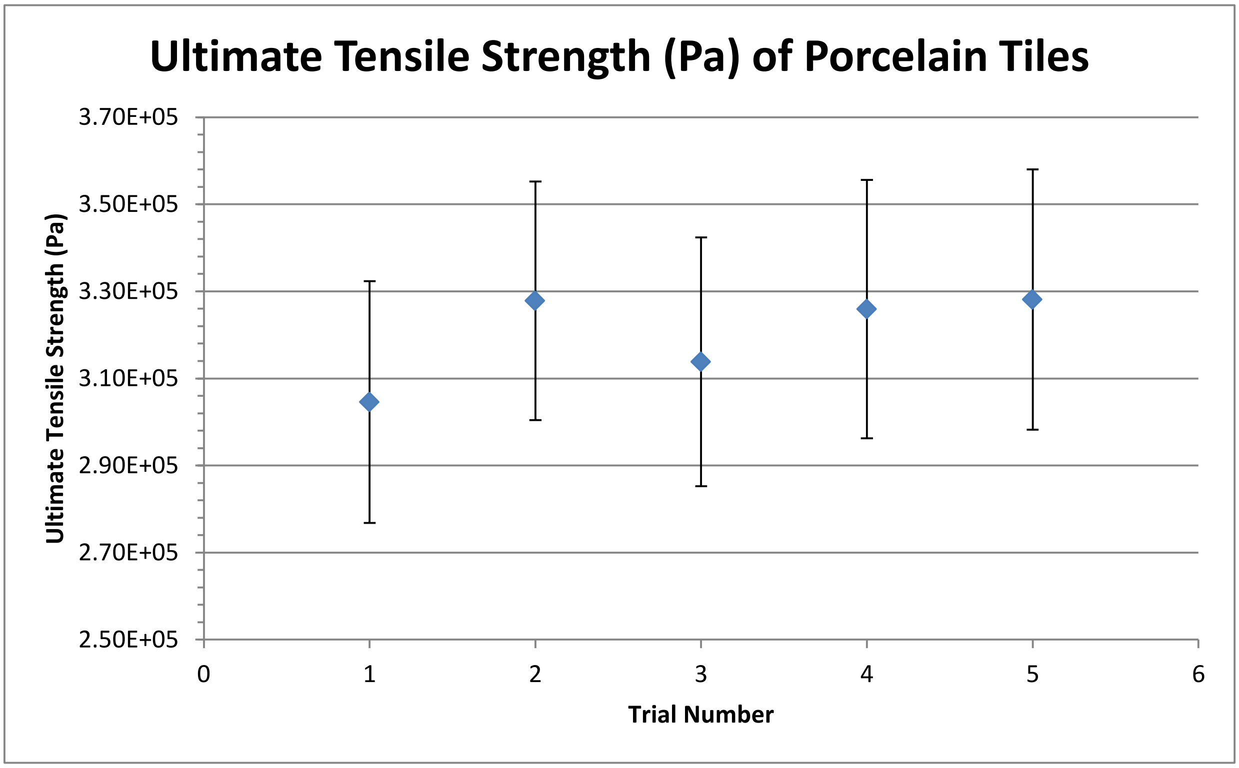
Object	Mass (±0.0001kg unless otherwise noted)
Pencil #2	0.0029
Scrap polystyrene #2	0.0034
Pencil #1	0.0036
Scrap polystyrene #1	0.0050
Chapstick	0.0104
AAA battery (Kirkland brand)	0.0112
Tile fragment #5	0.0187
Tile fragment #4	0.0212
AA battery II (Kirkland brand)	0.0244
AA battery I (Kirkland brand)	0.0245
Scotch tape dispenser	0.0442
Tile fragment #3	0.0442
Tile fragment #7	0.0736
Tile fragment #2	0.0746
Tile fragment #1	0.0767
Tile fragment #6	0.0769
Disposable garment box	0.0811
Juggling ball	0.0837
Andrew's phone	0.1265
Exacto Knife	0.1291
Worldwide Communication Book	0.1444
Cricket ball + Bottle portion	0.1658
Wipes	0.1888
Pencil sharpener	0.1999
Cardboard box for scales	0.2382
Paper towel roll	0.2805
Duct tape ring	0.4007
Chalk	0.4059
Driven to Distraction (book)	0.4216
My Day Timer (book)	0.4598
The Intellectual Devotional (book)	0.5177
Brita water filters	0.5260
Bocce ball	0.5303
Made in America (book)	0.5466
Roommate Suggestion Guide (book)	0.5608
Shampoo	0.8883
Bocce ball + Duct tape	0.9310
CD case (post-removal of CD)	1.6185
CD case (pre-removal of CD)	1.6344
All textbooks	11.36 (±0.01kg)

Appendix 3 – Graphs of Ultimate Tensile Strengths of the Materials:

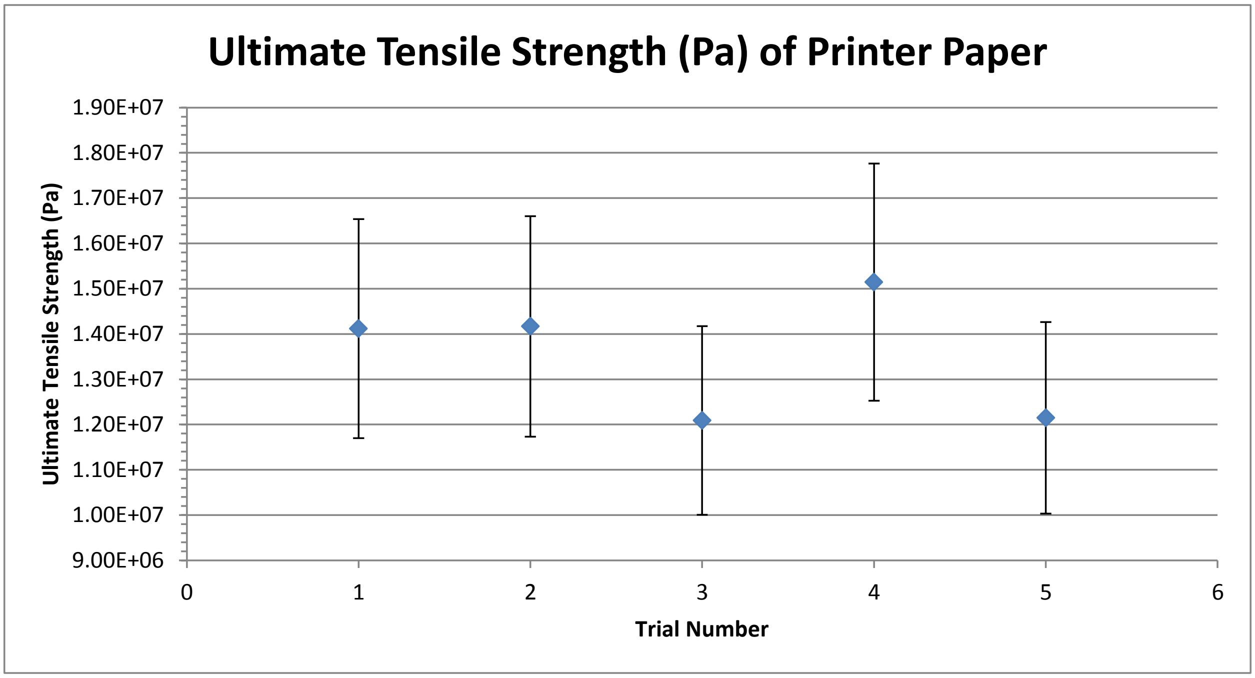
Extruded Polystyrene:



Porcelain Tiles:



Printer Paper:



Wood: