Comparison of Specific Properties of Engineering Materials

by

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Abstract

The purpose of this laboratory experiment was to use basic measurements of several different samples of engineering materials and calculate their specific properties. To this end the radius, length and mass of fourteen different specimens were measured. The yield strength, tensile strength and elastic modulus was provided for each material. From this data as well the measured dimensions the specific yield strength, tensile strength and modulus were calculated. The results of these calculations show that in general the metal specimen have the highest density, the ceramic sample had a relatively mid-range density and the polymer materials had the lowest density.

Introduction

The density of a material can be a crucial factor in determining the material that is best suited for an application [1]. The density can be used to determine the relative weights of materials. This is an extremely important factor to consider if the material in question will be used to construct the frame of an aircraft. A lighter weight material will ultimately translate to greater payload capacity and decreased fuel consumption.

A more important aspect of the density of the material is the role it plays in calculating its specific strength. The specific strength is simply the strength-to-weight ratio of the material [1]. The specific strength of a material is given by the tensile or yield strength divided by the density of the material. A material with a high specific strength will be suitable for applications such as aircraft and automobiles. This means that the material has a light weight with the aforementioned benefits, but it also has a high strength. Both of these factors are important in such safety conscious applications.

The density, and thus the specific strength, of a material can be calculated a number of different ways. The simplest method is to determine the dimensions of a given material specimen and use an applicable formula to determine the volume of the specimen. The formula for the volume of a cylindrical specimen is given in equation 1,

$$V = \frac{\pi D^2}{4} L \qquad (1)$$

where V=Volume of the specimen, D=Diameter of the cylinder and L=Length of the specimen. Once the volume of the specimen is known the mass can be measured with a balance. The density (ρ) is then the mass divided by the volume.

The specific strength also requires a measure of the tensile and/or yield strength of the material. This can be done using a tensile test machine. In this method the sample would be stretched until it failed with a computer calculating the stresses at failure. A separate measurement can be performed to obtain this data but published tensile/yield strength values for most engineering materials is readily available. Such published values are shown in table 1.

Table 1: Mechanical properties and relative costs of engineering material samples [1]

Material	Yield Strength (Map)*	Tensile Strength (MPa)*	Elastic Modulus (GPa)	Relative Cost
Titanium	170	240	103	66.4
AA6061	55	124	69.0	8.7
AA2024	75	185	72.4	14.1
Brass	113	333	110	6.0
C1018	295	395	207	1.0
Ductile Cast Iron	276	414	169	2.4
Pure Cu - Hot Rolled	69.0	220	115	7.9
Nylon 6,6	69.0	94.5	2.69	13.4
Polycarbonate	62.1	67.6	2.38	12.1
Polypropylene	34.1	36.2	1.35	1.8
ABS		45.0	2.40	12.0
PVC	42.8	46.2	3.30	3.0
PTFE	-	27.6	0.50	33.3
High-alumina	-	417	380	2.1

* For metals - annealed condition (O temper)

Experimental Procedure

Fourteen specimens of different engineering materials were obtained from the instructor. The fourteen samples are listed in table 1. Each sample was cylindrical in shape. Using equation 1 the diameter and length of each sample was measured with a set of digital calipers and the volume was calculated. The only sample that was not measured with the calipers was the high-alumina due to its length. The mass of each sample was then obtained using a digital mass balance. Once the mass was obtained the density of each specimen was calculated by dividing the mass by the density. The results of these measurements and calculations are shown in table 2.

After the density of each specimen was calculated the data in table 1 was incorporated to calculate the specific properties of each specimen. This data is shown in table 3. Finally equation 2 was used to determine the cost per unit yield strength and cost per unit tensile strength, i.e.

$$Cost = \frac{C_m \rho}{\sigma_w} \qquad (2)$$

where C_m=cost per unit mass, ρ=density of the material and σ_w=safe working stress of the material [2]. The safe working stress takes into account the factor of safety. In the case of this experiment there was no specified factor of safety so the yield strength and tensile strength were used directly for σ_w. The results of equation 3 are given in table 4.

After the specific properties of each specimen were calculated they were ranked based on their specific tensile strength and their cost per unit tensile strength. This ranking is shown in table 5. Finally the measured densities from the 14 specimen were compared to published values. This comparison is illustrated in figure 4.

Results

Table 2 shows the results of the measurements taken form the 14 specimen and the resulting calculated densities. Figure 1 illustrates the relationship between the densities of the different materials. Figure 1 shows that the metals seem to have the highest density. High-alumina does appear to have a higher density than the 2 aluminum alloys, however. The polymers do appear to be the least dense material.

Table 2: Physical measurement of 14 engineering samples

Material	Diameter (mm)	Length (mm)	Volume (mm^3)	Mass (g)	Density (g/mm^3)
Titanium	12.76	15.79	2019.17	8.8	0.00436
AA6061	25.51	21.27	10871.2	28.6	0.00263
AA2024	25.43	20.8	10564.4	29.2	0.00276
Brass	25.44	12.61	6409.72	53.9	0.00841
C1018	19.02	19.37	5503.52	42.7	0.00776
Ductile Cast Iron	27.63	18.73	11230.3	78.0	0.00695
Pure Cu - Hot Rolled	25.43	18.36	9325.14	81.6	0.00875
Nylon 6,6	25.48	49.38	25179.1	28.5	0.00113
Polycarbonate	25.44	45.69	23224.4	27.6	0.00119
Polypropylene	26.84	48.93	27684.1	24.6	0.00089
ABS	25.25	37.85	18953	19.7	0.00104
PVC	25.97	47.23	25018	34.5	0.00138
PTFE	19.51	49.66	14846.1	10.8	0.00073
High-alumina	8.06	350	17857.8	61.5	0.00344

Once the density values for each specimen was calculated the specific properties were calculated using the data in table 1. The specific properties were calculated using equations 3, 4 and 5:

$$\sigma_{Sy} = \frac{\sigma_y}{\rho} \quad (3)$$

$$\sigma_{St} = \frac{\sigma_t}{\rho} \quad (4)$$

$$E_S = \frac{E}{\rho} \quad (5)$$

where σ_{Sy}, σ_{St} and E_S = specific yield strength, specific tensile strength and specific modulus respectively, σ_y, σ_t and E = yield strength, tensile strength and elastic modulus respectively and ρ = density of the material [1]. The results of these calculations are given in table 3.

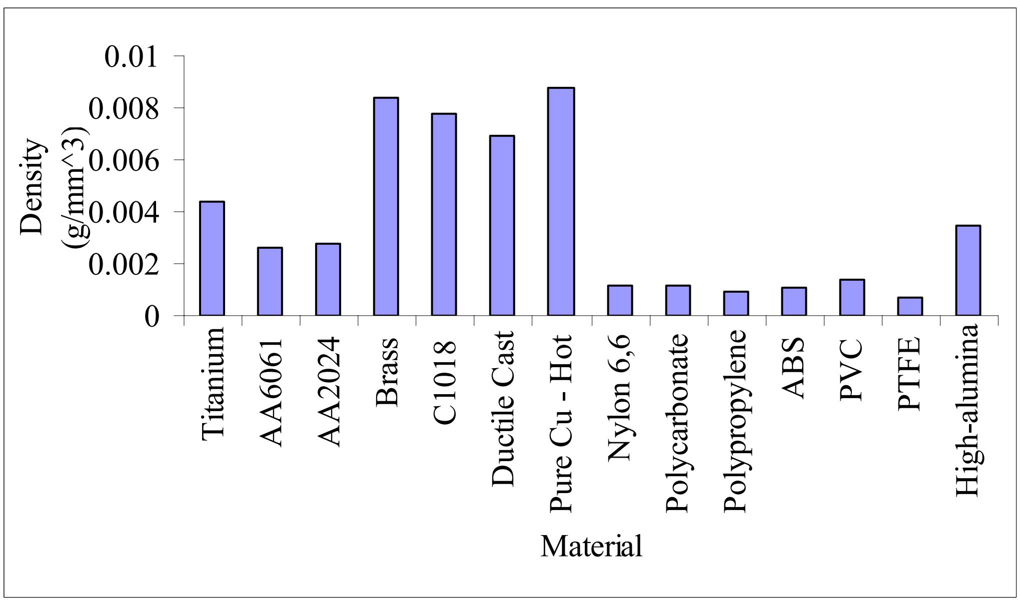


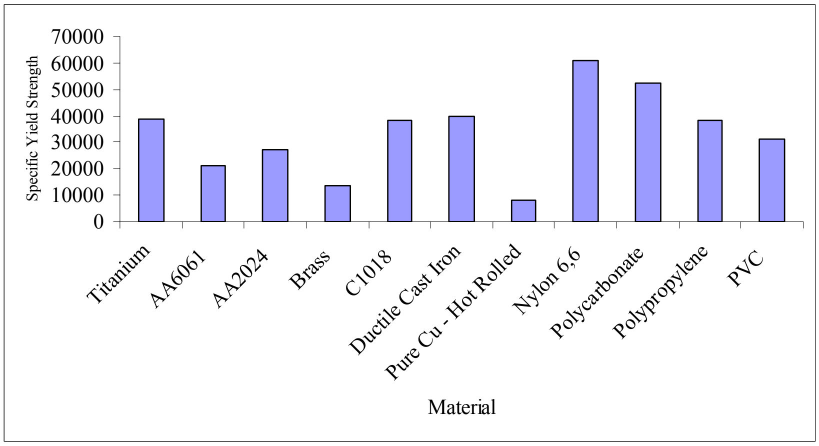
Figure 1: Calculated densities of the engineering material specimens

The data given in table 3 is illustrated graphically in figure 2. Overall the apparent trends in figure 1 that show the difference in the densities of the three material groups do seem to be present in specific strength plots in figure 2. The only noticeable trend in either of the specific strength plots appears to be in the specific yield strength plot. The polymer materials appear to have slightly higher specific yield strengths than the metals. There is also a visible trend in the specific modulus plot. High-alumina ceramic has the highest specific modulus, the metals appear to have a higher specific modulus than the polymers and the polymers have the lowest specific modulus values of the three groups.

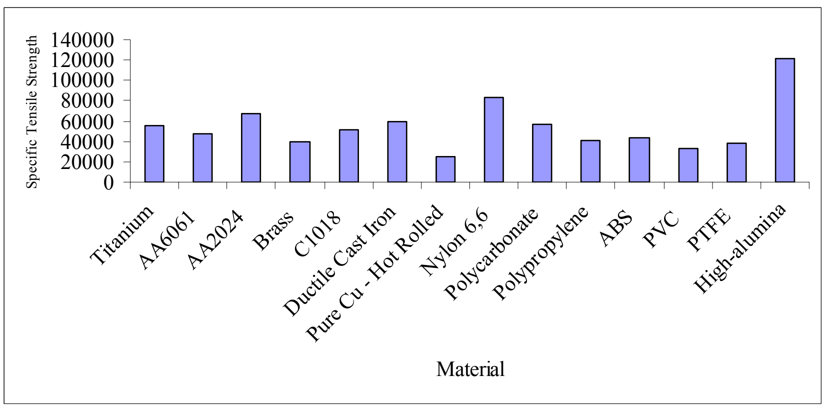
Table 3: Specific properties of engineering material specimen

Material	Specific Yield Strength	Specific Tensile Strength	Specific Modulus
Titanium	39007	55068	23633
AA6061	20906	47134	26228
AA2024	27135	66932	26194
Brass	13438	39600	13081
C1018	38022	50911	26680
Ductile Cast Iron	39738	59607	24332
Pure Cu - Hot Rolled	7885	25141	13142
Nylon 6,6	60960	83489	2377
Polycarbonate	52255	56883	2003
Polypropylene	38375	40738	1519
ABS		43294	2309
PVC	31037	33502	2393
PTFE	-	37940	687
High-alumina	-	121085	110341

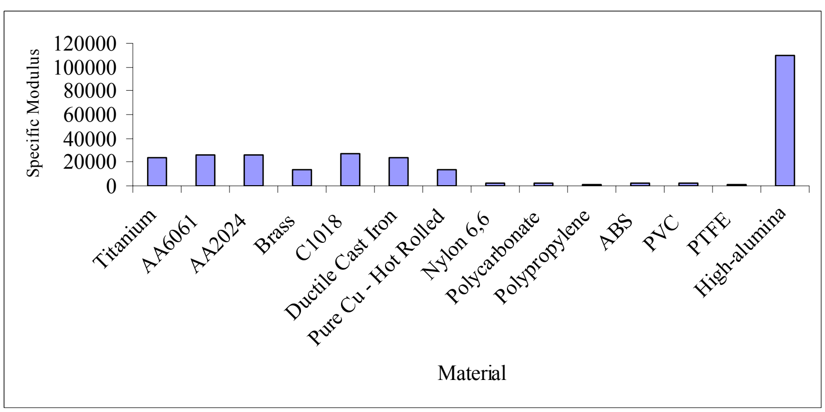
Because the specific properties are ratios they are unit-less values. Table 3 shows the raw data illustrated in figure 2. There are no values for specific yield strength of ABS, PTFE or high-alumina because of their stiffness. The yield strength deals with the point of maximum deformation, but these materials are stiff enough that they do not deform prior to failure at the tensile strength point.



(a)



(b)



(c)

Figure 2: Specific yield strength (a), specific tensile strength (b) and specific modulus (c) of engineering materials specimen

The difference in the specific modulus suggests the stiffness of the different material classes. The polymers have the lowest specific modulus values and thus have the greatest elongation. The metals appear to have higher specific modulus values than the polymers and will exhibit less elongation under stress. The high-alumina ceramic specimen has the highest specific modulus. This modulus value is far enough beyond the other material classes to suggest that it will have almost no elongation under stress. This is reinforced by the data in table 1.

After the specific properties comparison the cost per unit strength for each specimen was calculated using equation 2. Table 4 shows the results of these calculations. The comparison of the cost per unit yield strength and cost per unit tensile strength is illustrated in figure 3. Figure 3 seems to show that in most cases the cost per unit yield strength is higher than the cost per unit tensile strength. Again ABS, PTFE and high-alumina do not have a cost per yield strength value associated with them because they do not yield.

Table 4: Cost per unit strength values for engineering material specimens

Material	Cost per Unit Yield Strength	Cost per Unit Tensile Strength
Titanium	0.001702	0.001206
AA6061	0.000416	0.000185
AA2024	0.000520	0.000211
Brass	0.000447	0.000152
C1018	0.000026	0.000020
Ductile Cast Iron	0.000060	0.000040
Pure Cu - Hot Rolled	0.001002	0.000314
Nylon 6,6	0.000220	0.000161
Polycarbonate	0.000232	0.000213
Polypropylene	0.000047	0.000044
ABS		0.000277
PVC	0.000097	0.000090
PTFE	-	0.000878
High-alumina	-	0.000017

Because each of the specimens has a tensile strength, the specific tensile strength and the cost per unit tensile strength were the values used to rank the materials. These rankings are shown in table 4. The two different sets of rankings are quite different from one another. However high-alumina did rank highest on both scales.

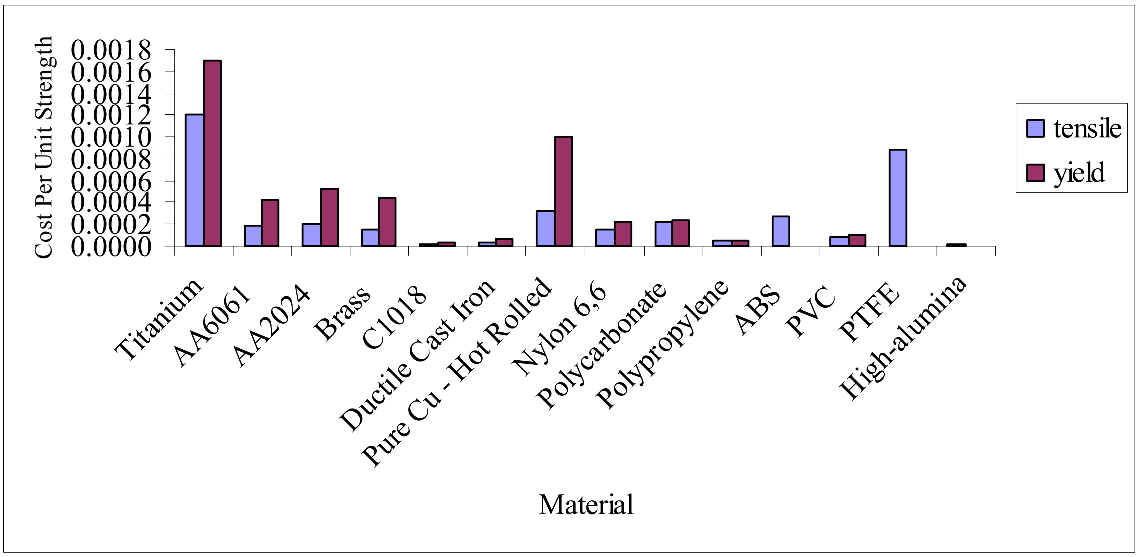


Figure 3: Cost per unit strength comparison for 14 engineering material specimens

The final test of the engineering materials was to compare the measured densities to published density values. Table 5 shows the values being compared for each material. The published values for the densities of the engineering materials are not accepted as standard values. Because of this they were not use to perform any formal discrepancy analysis between the measured and published values. Table 5 does seem to show that the measured densities are relatively close to the published values. This is further illustrated in figure 4.

Table 4: Rankings of the 14 specimen based on specific tensile strength and cost per unit tensile strength

Material	Ranking by Specific Tensile Strength*	Ranking by Cost per Unit Tensile Strength^
Titanium	6	14
AA6061	8	8
AA2024	3	9
Brass	11	6
C1018	7	2
Ductile Cast Iron	4	3
Pure Cu - Hot Rolled	14	12
Nylon 6,6	2	7
Polycarbonate	5	10
Polypropylene	10	4
ABS	9	11
PVC	13	5
PTFE	12	13
High-alumina	1	1

* Materials ranked from greatest tensile strength to lowest tensile strength

^ Materials ranked from least cost per unit strength to greatest cost per unit strength

Table 5: Calculated density values and published density values for engineering materials [3]

Material	Calculated Density (g/cm^3)	Published Density (g/cm^3)
Titanium	4.3582	4.51
AA6061	2.6308	2.7
AA2024	2.7640	2.78
Brass	8.4091	8.75
C1018	7.7587	7.87
Ductile Cast Iron	6.9455	7.1
Pure Cu - Hot Rolled	8.7505	8.96
Nylon 6,6	1.1319	1.16
Polycarbonate	1.1884	1.17
Polypropylene	0.8886	0.9
ABS	1.0394	1.02
PVC	1.3790	1.45
PTFE	2.0746	2.18
High-alumina	3.4439	3.96

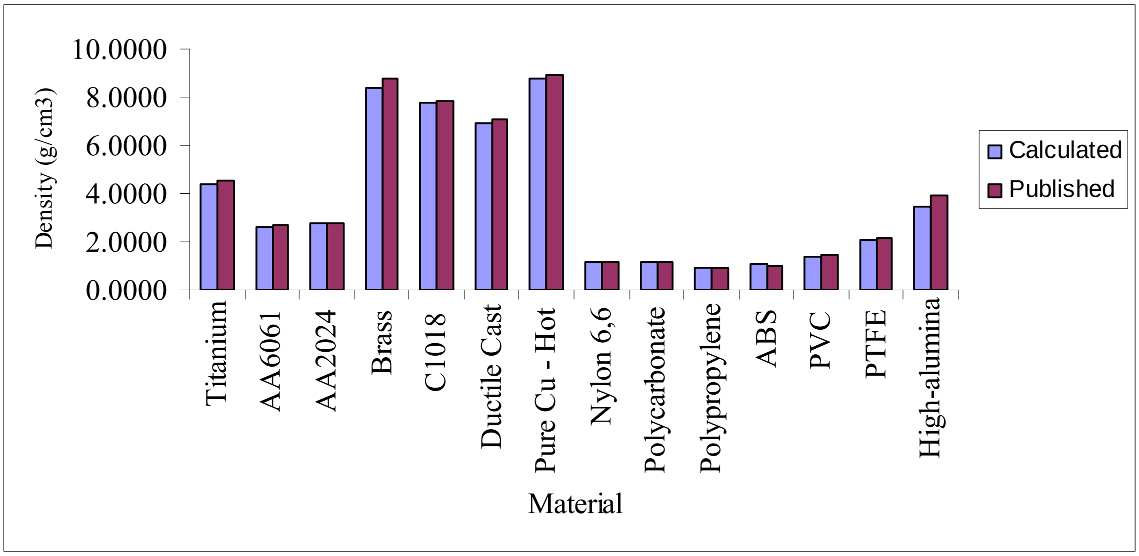


Figure 4: Comparison of calculated and published density values [3]

Discussion

Figure 1 shows the overall relationship between the densities of the different materials. For the most part it appeared as if the metals had the highest densities of the materials measured. The only exceptions appear to be the two aluminum samples. They each had a density below the high-alumina ceramic. The polymer materials all had densities well below both the metals and the ceramic.

Figure 2 seems to show no discernable difference between the specific tensile strengths of metals and polymers. The difference is in the specific modulus values for each group. Figure 2 shows that the metal samples have higher specific modulus values than the polymers. This means that the metals are less likely to deform under and equal amount of force than the polymers. This would likely be the deciding factor between the two material types in a transportation application. The added stiffness of the metals would mean that a vehicle is more likely to be able to withstand any impact it may encounter. It also means that the vehicle's structure will not be as likely to deform under normal operating conditions, i.e. lift forces under a wing. Based on this data the best choice for the structure of a transportation vehicle would be a metal. The polymers also appear to have slightly higher specific yield strengths than the metals. This would also influence the material selection as it also translates to greater deformation on the part of the polymers.

Table 4 shows the ranking of the materials based on two different criteria. There is quite a difference between the two rankings. The only similarity is high-alumina, which ranked first on both scales. The scale that would probably be the bets suited to be used in material selection would be the cost per unit tensile strength scale. Even if this scale were used it would probably be wise to reconsider choosing high-alumina for a given application. Even though the alumina specimen ranked highest on both scales its lack of deformation under stress means it would fail under a load before showing any signs on fatigue. Besides this note the rest of the cost per unit tensile strength ranking is probably a safe selection method. Using this scale would mean the material selected would have the best value for the desired strength. It also allows a budget to be taken into consideration. If the cost is not as important as the strength then the highest ranking materials can be neglected in favor of higher strength based on this ranking.

The comparison of measured and published density values is shown in figure 4. This figure shows that the measured and published values were relatively close for a given material. The slight discrepancy between the values can probably be attributed to method by which the density was measured. As previously stated the method used to calculate the density in this laboratory was one of the simpler methods. It is likely that the published values were not found by measuring the dimensions of the specimen but by displacement. This method works by suspending the material in a fluid of known density, i.e. pure water's density is one. The material will overflow the container of fluid. When the material is removed from the container the amount of water that it displaced will be equal to the volume. Both methods appear to produce the same results but the slight difference in density values can be attributed to the difference in data collection methods.

Conclusions

1. Metals appear to have the highest density and polymers the lowest, with the ceramic materials between the two.

2. Metals appear to have a higher specific modulus than polymers and are therefore less prone to deformation.

3. The two different ranking systems for the materials are quite different. Despite the difference between the rankings, high-alumina ranked first on both scales.

4. The densities calculated in this experiment were relatively close to the published density values.

Reference

1. Dr. P.N. Anyalebechi: "Materials Science and Engineering Laboratory Manual," School of Engineering, Padnos College of Engineering and Computing, Grand Valley State University, January 2005, pp. 59-60, 85.

2. Dr. P.N. Anyalebechi: "Essentials of Materials Science and Engineering (EGR 250)," School of Engineering, Padnos College of Engineering and Computing, Grand Valley State University, May 2005, pp. 32.

3. Matweb – Material Property Data, www.matweb.com, June 27, 2005.