An Analysis of Balsa Material Data

NARAM-52 Research and Development Project
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R&D Report from http://nar.org National Association of Rocketry

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Abstract:

For years, rocketeers have been searching for the perfect building materials. This report analyzes data collected by a fellow rocketeer and draws some surprising conclusions about available materials. Data collected and calculated numerical values are presented in tables; these values are made available for general use in model rocketry and model aeronautics.

Previous Research:

Gere, James, and Barry Goodno. *Mechanics of Materials*. 7th Ed. Toronto, ON, Canada: Thomson Engineering, 2009. Print.

Stenberg, Alyssa. "A Scientific Study of Rocket Fin Material." (2009). Print

Objectives

The objective of this project was to provide useful materials data for practical applications, such as the building of model rockets and model aircraft.

Budget

As this was merely an analysis project, only time and effort were required; no funds were expended.

Equipment:

Equipment used was a Dell Latitude D830 running Windows 7. All analysis was done in Microsoft Excel, a spread sheet program.

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Background:

Basic Structural Analysis

All structural analyses rely on a single basic principle: the elastic behavior of materials. This behavior is analogous to the behavior of a spring under tension or compression. Basic physics equations state that the further you stretch a spring, the more force it exerts to return to its original shape. This is demonstrated by Hooke's Law, which states:

$$F = -kx \qquad \text{(Equation 1)}$$

where F is force, k is the spring constant (the measure of the spring's stiffness), and x is the displacement of the spring. Notice the negative sign indicating that the force always attempts to restore the spring to zero displacement.

Hooke's Law for structural members is quite similar. It states

$$\sigma = E\epsilon \qquad \text{(Equation 2)}$$

where σ is stress, E is Young's Modulus, and ε is strain. Stress and Young's Modulus are given in units of force per unit area, and strain is unit-less. (Strain is calculated as displacement or elongation over original length. Length over length gives a simple numerical value.) By convention, members in compression have negative stress and strain, whereas members in tension have positive stress and strain.

Unfortunately, analysis of rocket fins and aircraft wings is not this simple. Aerodynamic surfaces must be analyzed as cantilevers in both bending and torsion. The torsional aspect is beyond the scope of this analysis, so concentration will be placed on bending loads.

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Bending Stresses in Beams

Stresses in structural members subjected to bending loads (referred to as beams) vary across the cross-section of beam. In doubly-symmetric (symmetric both vertically and horizontally) beams, the load varies linearly across the beam, with zero stress at the center of the beam. Applying Hooke's Law, this distribution is described by Equation 3.

$$\sigma = -\frac{My}{I} \qquad \text{(Equation 3)}$$

M is the moment load carried by the beam, y is the distance from the center of the beam, and I is the Area Moment of Inertia of the beam, which can be looked up in a table. In a singly-loaded cantilevered beam, such as those used in this report, the moment load is simply the distance from the point in question to the load multiplied by the load itself. This indicates that the maximum moment and stress will occur at the base of the beam.

Deflection in beams is a slightly more complex matter, and must be dealt with accordingly. The curvature of the beam, a measure of how sharply the beam is bent, is directly proportional to the load on the beam. This is described by the relationship

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI} \qquad \text{(Equation 4)}$$

where $\frac{d^2y}{dx^2}$ is the curvature of the beam. By integrating twice, the deflection of the beam over its length can be obtained. For a cantilevered beam with a single load, the equation resolves to

$$y = \frac{PL^3}{3EI} \qquad \text{(Equation 5)}$$

for the deflection at the tip of the beam, where P is the load applied and y is the deflection.

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Elasto-plastic Bending in Beams

So far, analysis has operated on the assumption that materials operate within the confines of Hooke's Law. However, if stressed to failure, a beam will stretch beyond the point where Hooke's Law is valid. This type of deformation is known as *plastic deformation*. Because of the linear nature of the stress distribution in a beam, the outermost portions of the beam will reach plastic deformation first. When this occurs, that portion of the beam can no longer support any more load, and the stress in that portion of the beam remains constant. This continues until the entire beam is in plastic deformation, and the beam fails. The point at which the beam fails is described by the relationship

$$M_P = Z_{xx}\sigma_y \qquad \text{(Equation 6)}$$

where M_p is the Fully Plastic Moment, Z_{xx} is the Plastic Section Modulus (looked up in a table), and σ_y is the Yield (or failure) Stress.

Analytical Procedure

Determining Young's Moduli

Before determining the breaking strength of the various materials, the Young's Modulus of each sample was determined. First, the area moment of inertia was determined for each sample from the following formula for rectangular sections

$$I_{xx} = \frac{bh^3}{12} \qquad \text{(Equation 7)}$$

where b is the width of the beam and h is the height of the beam. Subsequently, Equation 5 was solved for Young's Modulus, giving

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$$E = \frac{PL^3}{3Iy} \qquad \text{(Equation 8)}$$

Data values were entered into this equation for each loading condition and a Modulus for each condition was obtained. The values from each condition were pooled together to give an average value. These values and the data used to obtain them can be found in Table A-1 in the Appendix. The data is also presented graphically in Charts A-1 and A-3.

Determining Yield Strength

In the process of determining each sample's yield strength, the plastic section modulus for each sample was calculated. For a rectangular cross section, the plastic section modulus is:

$$Z_{xx} = \frac{bh^2}{4} \qquad \text{(Equation 9)}$$

Equation 6 was then solved for the yield strength to give

$$\frac{M_P}{Z_{xx}} = \sigma_y \qquad \text{(Equation 10)}$$

The data was subsequently put through this equation to determine the yield strength. The values are available in Table A-1 are presented graphically in Charts A-2 and A-4.

Practical Application: A Hypothetical Fin

All of this data means nothing without a practical application. For this purpose, a hypothetical fin is analyzed. Analysis starts with a small plywood fin because ply is available in only set thicknesses. For ease of analysis, this fin is rectangular in with a chord of 50mm and a

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semi-span of 100mm; only the thickness is varied to maintain equal breaking strength. The results of this analysis can be seen in Table 1.

The analysis in Table 1 shows that, while a plywood fin may seem like a good choice of fin, for the same strength, it is actually heavier than any of the balsa equivalents and twice as heavy as the equivalent contest balsa fin. Such plywood construction would only be necessary in a scale event, where the thickness of the fin is also important.

Material	Thickness (mm)	Density (kg/m^3)	Weight (g)	Yield Strength (MPa)	Plastic Section Modulus (m^3)	Fully Plastic Moment (N*m)	Breaking Load (g)
1/32" Ply	0.80	765	3.06	90.49	8.00E-09	7.24E-01	737.9152
Contest Balsa	2.92	96	1.41	6.78	1.07E-07	7.24E-01	737.9152
Light Balsa	2.00	144	1.44	14.52	4.98E-08	7.24E-01	737.9152
Medium Balsa	1.61	193	1.55	22.27	3.25E-08	7.24E-01	737.9152
Heavy Balsa	1.39	241	1.67	30.02	2.41E-08	7.24E-01	737.9152

Table 1: Balsa vs. Ply

This analysis was repeated in Table 2, using .020" G10 Waferglass as the starting material. The contrast between these two materials was even starker. Balsa fins that were more than 80% lighter than their waferglass counterparts maintained the same strength requirements.

Material	Thickness (mm)	Density (kg/m^3)	Weight (g)	Yield Strength (MPa)	Plastic Section Modulus (m^3)	Fully Plastic Moment (N*m)	Breaking Load (g)
.020" G10	0.51	1064	2.70	24.55	3.23E-09	7.92E-02	80.71104
Contest Balsa	0.97	96	0.47	6.78	1.17E-08	7.92E-02	80.71104
Light Balsa	0.66	144	0.48	14.52	5.45E-09	7.92E-02	80.71104
Medium Balsa	0.53	193	0.51	22.27	3.56E-09	7.92E-02	80.71104
Heavy Balsa	0.46	241	0.55	30.02	2.64E-09	7.92E-02	80.71104

Table 2: Balsa vs. G10 Waferglass

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Conclusions

Though popular for their strength, this study clearly shows that balsa is the lightest building material for its strength. Combined with its low price and relative availability as compared to many other materials, Balsa should and will continue to be the modeler's choice material for years to come.

Further Reading:

NACA Technical Report 685, "Mechanism of Flutter"

NACA Technical Note 4197, "Summary of Flutter Experiments…"

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Appendix: Raw Data, Analysis, and Charts

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Table A-1: Raw Data

From "A Scientific Study of Rocket Fin Materials" by Alyssa Stenberg. Used with Permission.

Material	Manufacturer	Weight (gm)	Thickness (mm)	0g/start pt. (mm)	25g (mm)	50g (mm)	100g (mm)	200g (mm)	400g (mm)	> 45°/broke
1/8" Balsa - Light		0.56	2.32	(0.72)	(1.74)	(3.07)	(6.14)	(11.69)	(35.00)	250
1/8" Balsa - Light		0.87	2.92	1.07	0.52	(1.26)	(2.27)	(4.28)	(8.85)	500
1/8" Balsa - Med		1.08	2.92	1.16	1.04	0.79	(1.29)	(2.04)	(4.54)	860
1/8" Balsa - Med		1.34	2.38	(1.17)	(1.38)	(1.66)	(2.47)	(3.38)	(5.38)	1050
1/8" Balsa - Med/Heavy		1.54	2.43	(1.09)	(1.26)	(1.49)	(2.30)	(3.28)	(5.12)	1425
1/8" Balsa - Med/Heavy		1.54	3.23	1.07	0.99	0.75	0.46	(1.51)	(2.70)	1560
1/16" Balsa - Med		0.97	1.67	(0.90)	(1.06)	(2.86)	(4.95)	(7.81)	(11.27)	620
1/16" Balsa - Med		1.08	1.72	(1.05)	(1.73)	(2.84)	(4.58)	(7.16)	(11.23)	745
1/16" Balsa - Heavy		1.46	1.80	(0.49)	(0.98)	(1.62)	(2.32)	(4.38)	(7.07)	1360
1/16" Balsa - Heavy		1.46	1.80	(0.49)	(0.98)	(1.62)	(2.32)	(4.38)	(7.07)	1360
1/32" Balsa - Light		0.37	1.05	0.00	(9.89)	(18.94)	(35.00)			65
1/32" Balsa - Light		0.43	1.06	(0.50)	(6.38)	(12.07)	(20.96)			165
1/32" Balsa - Light		0.49	0.90	0.32	(5.24)	(10.39)	(22.09)			160
1/32" Balsa - Med		0.72	1.00	0.03	(1.73)	(6.93)	(12.41)	(23.99)	(35.00)	300
1/32" Balsa - Med		0.95	1.05	(1.02)	(4.14)	(6.86)	(11.26)	(18.69)	(35.69)	450
3/32" Balsa - Light		0.67	2.39	(0.45)	(1.60)	(3.33)	(5.55)	(11.17)		255
3/32" Balsa - Light		0.79	2.44	(0.50)	(1.92)	(4.12)	(7.27)	(11.84)		385
3/32" Balsa - Med		1.95	2.47	(0.36)	(0.69)	(1.05)	(1.87)	(2.97)	(4.31)	2035
3/32" Balsa - Med		1.95	2.42	(0.48)	(0.86)	(1.20)	(1.96)	(2.81)	(4.31)	2075
1/16" Aircraft Plywood		4.16	1.65	(0.62)	(0.92)	(1.20)	(1.66)	(2.67)	(4.27)	2720
1/16" Aircraft Plywood		4.34	1.65	(0.54)	(0.86)	(1.07)	(1.74)	(2.68)	(4.09)	2720
1/32" Aircraft Plywood		2.66	0.90	0.14	(0.84)	(2.27)	(4.76)	(8.70)	(14.56)	1075
1/32" Aircraft Plywood		2.71	0.98	0.25	(0.60)	(1.99)	(4.42)	(8.41)	(14.31)	1110
1/64" Birch Aircraft Plywood	Midwest	1.43	0.57	(0.13)	(9.17)	(16.13)	(26.32)			170
1/64" Birch Aircraft Plywood	Midwest	1.48	0.48	(1.28)	(8.61)	(16.26)	(25.07)			130
3/64" Balsa plywood (3 ply)	Specialty balsa	0.70	1.59	2.25	(0.34)	(7.31)	(24.69)			100
3/64" Balsa plywood (3 ply)	Specialty balsa	0.85	1.74	(0.33)	(3.87)	(7.85)	(15.05)			140
1/32" Birch plywood	Midwest	2.37	0.80	0.25	(1.13)	(3.37)	(6.82)	(11.44)	(18.09)	1085
1/32" Birch plywood	Midwest	2.41	0.86	0.78	(0.45)	(2.93)	(6.66)	(10.94)	(18.06)	1105
1/16" Balsa plywood (2 ply, thick C	homemade	1.77	1.67	(0.03)	(1.94)	(2.85)	(4.19)	(6.81)	(11.89)	685
1/16" Balsa plywood (2 ply, thick C	homemade	1.13	1.74	(0.67)	(2.68)	(4.75)	(7.95)	(13.83)	(28.57)	400
1/32" Basswood	Midwest	1.75	0.99	(0.85)	(2.27)	(3.99)	(5.81)	(8.98)	(14.63)	1185
1/32" Basswood	Midwest	1.90	1.03	(0.79)	(2.18)	(3.64)	(5.46)	(8.33)	(13.45)	1210
Carbon plate 0.030"	CST	4.40	0.80	(0.18)	(1.68)	(3.04)	(5.06)	(8.84)	(16.93)	1675
Carbon fiber board	CST	9.04	1.75	(0.26)	(0.37)	(0.41)	(0.51)	(0.65)	(1.13)	2720
Styrene 0.030"	green Scale Mc	3.41	0.77	(2.11)	(17.46)	(29.87)				65
Lexan 0.030"	Team Cobra	3.94	0.90	(2.34)	(11.68)	(18.94)	(29.56)			150
G10-006		1.69	0.29	(0.66)						25
G10-020		4.12	1.00	(2.64)	(5.17)	(8.58)	(14.94)	(24.90)		360
G10-046		9.49	1.25	(0.48)	(0.54)	(1.38)	(1.91)	(3.10)	(5.30)	2720

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Table A-2: Data Analysis

Material	Thickness (m)		Plastic Section Modulus (m^3)	Maximum Moment at Failure (N*m)	Yield Stress (Mpa)
1/8" Balsa - Light	0.00232		5.13E-08	0.162	3.17
1/8" Balsa - Light	0.00292		8.12E-08	0.325	4.00
1/8" Balsa - Med	0.00292		8.12E-08	0.559	6.88
1/8" Balsa - Med	0.00238		5.40E-08	0.682	12.64
1/8" Balsa - Med/Heavy	0.00243		5.62E-08	0.925	16.45
1/8" Balsa - Med/Heavy	0.00323		9.94E-08	1.013	10.19
1/16" Balsa - Med	0.00167		2.66E-08	0.403	15.16
1/16" Balsa - Med	0.00172		2.82E-08	0.484	17.17
1/16" Balsa - Heavy	0.00180		3.09E-08	0.883	28.62
1/16" Balsa - Heavy	0.00180		3.09E-08	0.883	28.62
1/32" Balsa - Light	0.00105		1.05E-08	0.042	4.02
1/32" Balsa - Light	0.00106		1.07E-08	0.107	10.01
1/32" Balsa - Light	0.00090		7.72E-09	0.104	13.47
1/32" Balsa - Med	0.00100		9.53E-09	0.195	20.45
1/32" Balsa - Med	0.00105		1.05E-08	0.292	27.83
3/32" Balsa - Light	0.00239		5.44E-08	0.166	3.04
3/32" Balsa - Light	0.00244		5.67E-08	0.250	4.41
3/32" Balsa - Med	0.00247		5.81E-08	1.322	22.74
3/32" Balsa - Med	0.00242		5.58E-08	1.348	24.16
1/16" Aircraft Plywood	0.00165		2.59E-08	1.766	68.12
1/16" Aircraft Plywood	0.00165		2.59E-08	1.766	68.12
1/32" Aircraft Plywood	0.00090		7.72E-09	0.698	90.49
1/32" Aircraft Plywood	0.00098		9.15E-09	0.721	78.80
1/64" Birch Aircraft Plywood	0.00057		3.09E-09	0.110	35.67
1/64" Birch Aircraft Plywood	0.00048		2.19E-09	0.084	38.47
3/64" Balsa plywood (3 ply)	0.00159		2.41E-08	0.065	2.70
3/64" Balsa plywood (3 ply)	0.00174		2.88E-08	0.091	3.15
1/32" Birch plywood	0.00080		6.10E-09	0.705	115.59
1/32" Birch plywood	0.00086		7.04E-09	0.718	101.87
1/16" Balsa plywood (2 ply, thic	0.00167		2.66E-08	0.445	16.75
1/16" Balsa plywood (2 ply, thic	0.00174		2.88E-08	0.260	9.01
1/32" Basswood	0.00099		9.34E-09	0.770	82.43
1/32" Basswood	0.00103		1.01E-08	0.786	77.76
Carbon plate 0.030"	0.00080		6.10E-09	1.088	178.44
Carbon fiber board	0.00175		2.92E-08	1.766	60.56
Styrene 0.030"	0.00077		5.65E-09	0.042	7.47
Lexan 0.030"	0.00090		7.72E-09	0.097	12.63
G10-006	0.00029		8.01E-10	0.016	20.27
G10-020	0.00100		9.53E-09	0.234	24.55
G10-046	0.00125		1.49E-08	1.766	118.69

Chart A-1: Young's Modulus vs. Density for Balsa

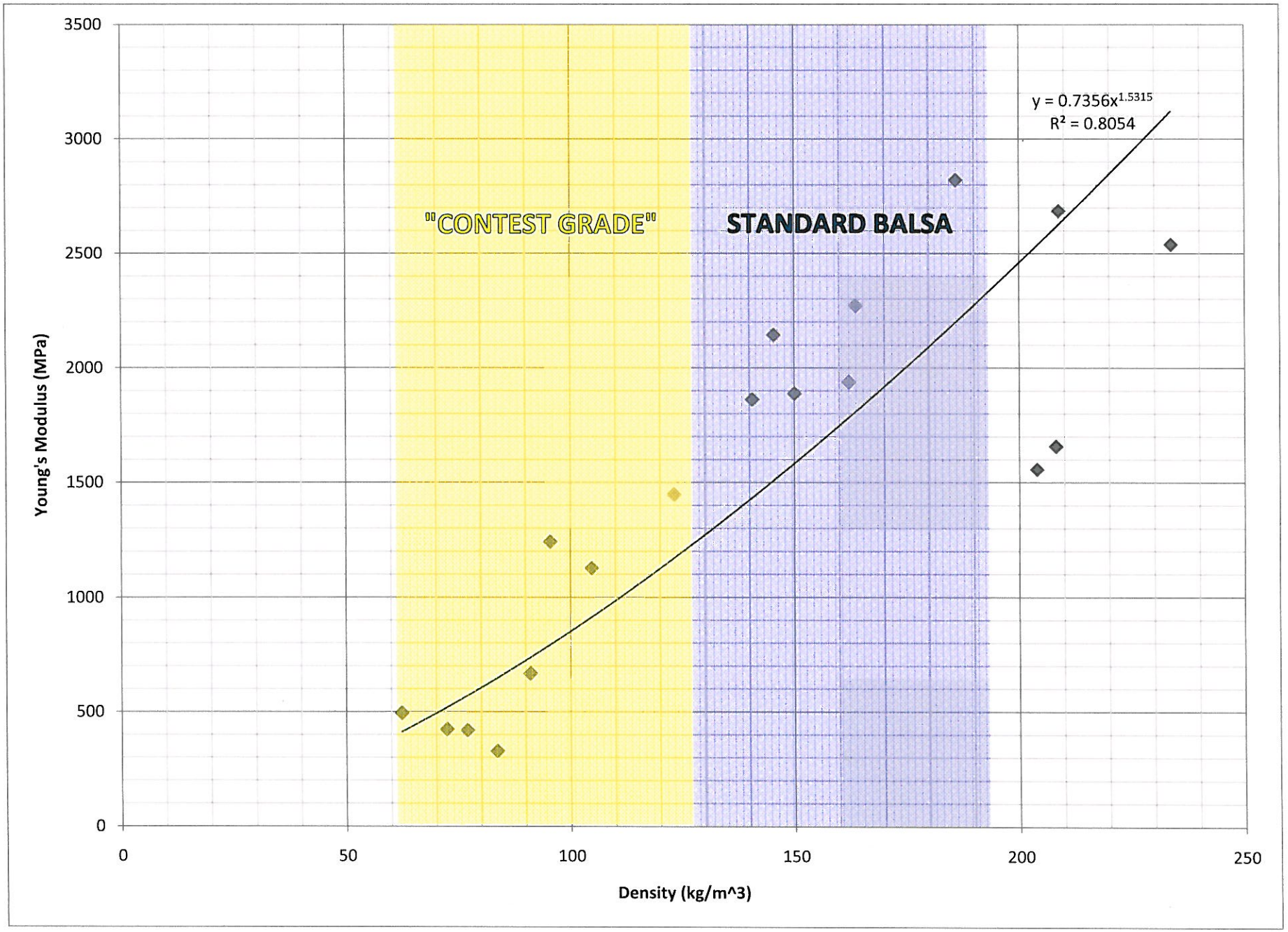

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Chart A-2: Yield Strength vs. Density for Balsa

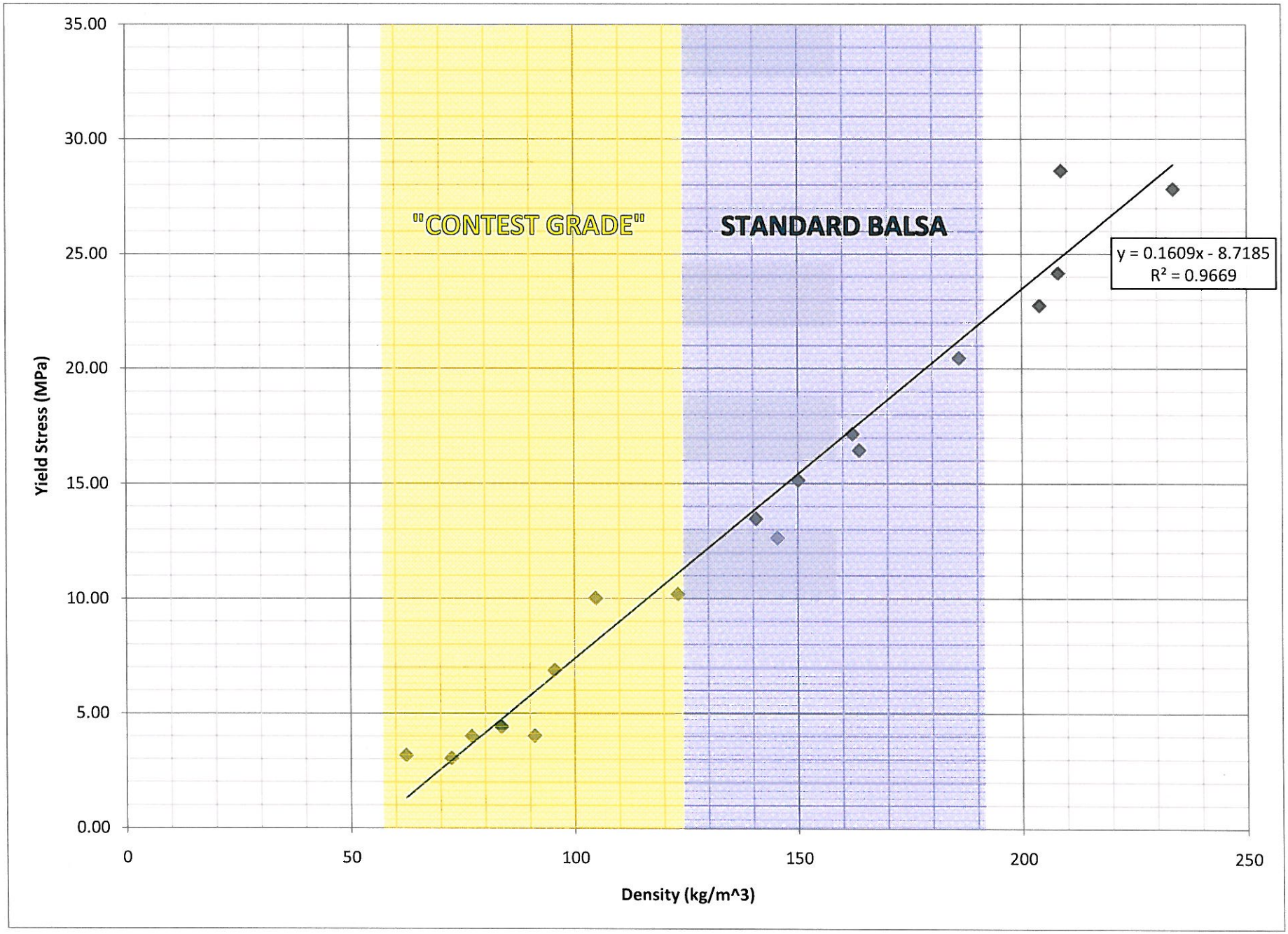

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Chart A-3: Young's Modulus vs. Density for All Samples

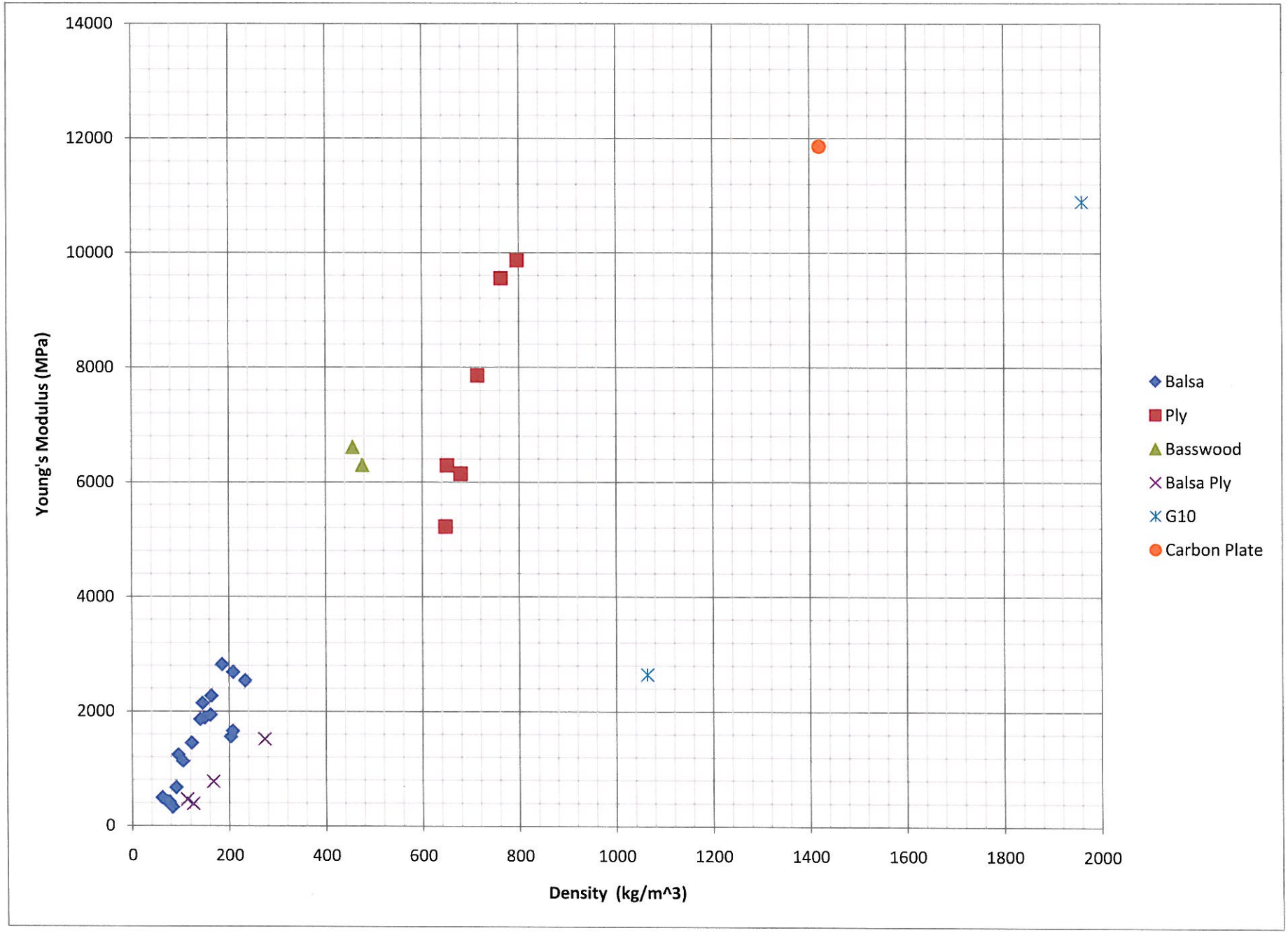

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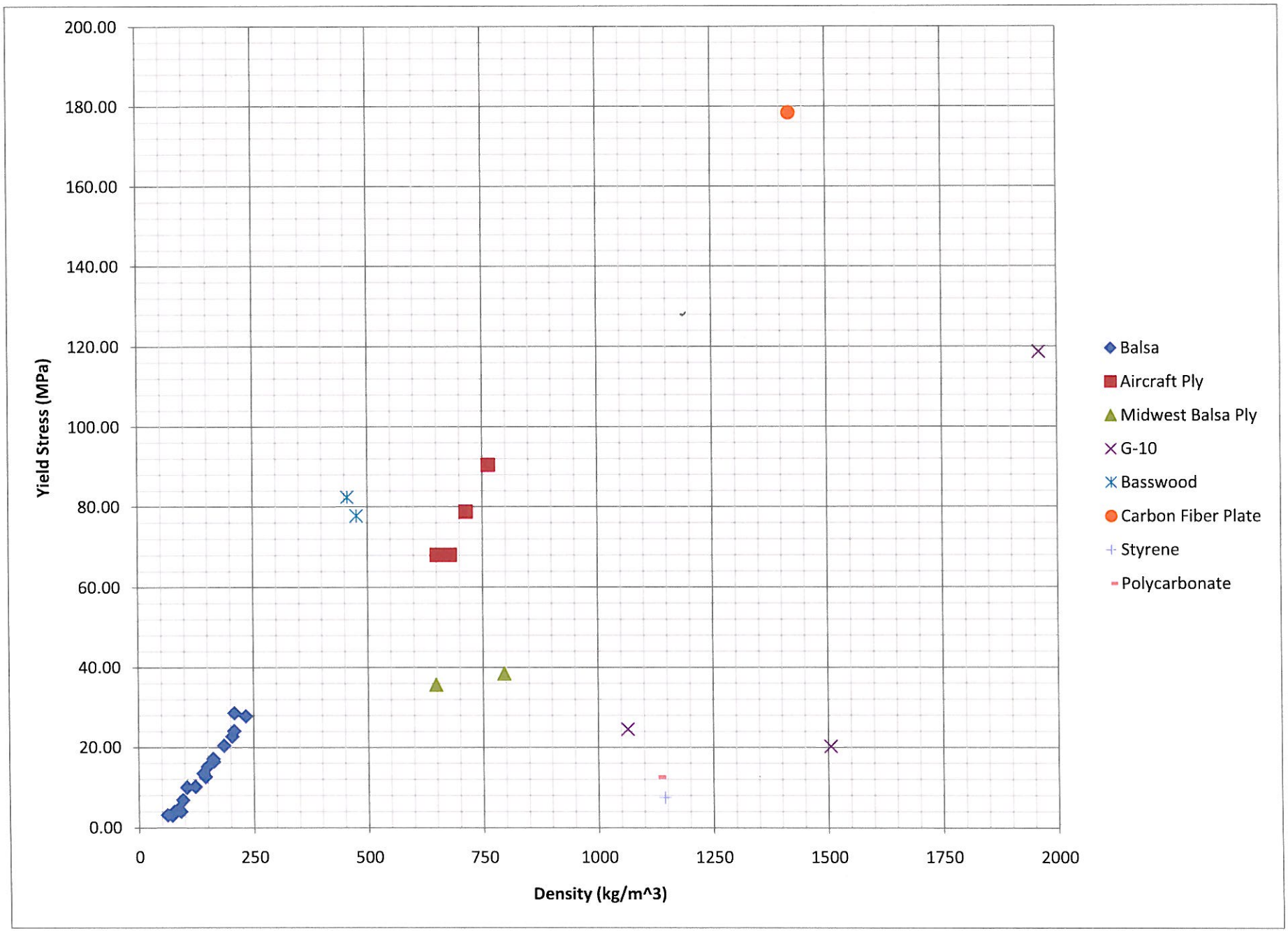
Chart A-4: Yield Stress vs. Density for All Samples



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