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PREDICTING COMPRESSIVE STRENGTH - A TOOL FOR MORTAR MIX DESIGNERS

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Abstract

In North America, mortar mix designers often optimise material combinations to meet the property specification requirements of ASTM C270. To meet the specified mortar type designation, designers must balance water retention, air content and aggregate ratio with compressive strength. Strength designations are based on results at the end of a 28 day period. In order to make adjustments in material components prior to the end of the 28 day period, many mix designers determine strength at an earlier age and extrapolate the early age data to the 28 day strength. This paper compiles cement-lime mortar compressive strength determinations at 7, 14 and 28 days for the purpose of offering the designer a predictive compressive strength graphing tool to better optimise and adjust materials prior to the end of the 28 day waiting period.

Key Words

Cement-Lime Mortar, Compressive Strength.

1 Introduction

In North America, most cement-lime masonry mortar is specified under the requirements of ASTM C270 (C270), Standard Specification for Mortar for Unit Masonry (ASTM 2000). C270 requires cement-lime masonry mortar to meet either proportion specification or property specification requirements for a designated mortar type (i.e. Type M; Type S; Type N; Type O). Proportion and property mortars must be made from constituent materials (e.g. cement, lime, aggregate and water) conforming to the material requirements specified in C270. Except for water, each constituent material has its own ASTM specification (e.g. Lime-C5, C207, C206; Cement-C150, C595,C1157; Aggregate-C144,C404). If all the constituent materials submitted to the project meet their individual ASTM standards and if the water is suitable (potable and non-deleterious to the mortar or metal in the wall), a proportion specification mortar will not require any special laboratory testing to determine conformance to C270.

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On the other hand, C270 property specification mortars require laboratory testing using the constituent materials of the project to show conformance to the requirements of the C270 property specification. Property specification mortars have minimum physical property requirements for average compressive strength, water retention, air content and aggregate ratio according to the mortar type designations listed in ASTM C270 Table 2 (Table 1).

Table 1. C270 Cement-Lime Property Specification Requirements[A]

Mortar	Type	Average Compressive Strength at 28 days, min, MPa [psi]	Water Retention Min, %	Air Content Max, %[B]	Aggregate Ratio (Measured in Damp, Loose Conditions)
Cement-Lime	M	17.2 [2500]	¼	12	Not less than 2¼ and not more than 3½ times the sum of the separate volumes of cementitious materials.
	S	12.4 [1800]	Over ¼ to ½	12	
	N	5.2 [750]	Over ½ to 1¼	14[C]	
	O	2.4 [350]	Over 1¼ to 2½	14[C]	

[A] Laboratory prepared mortar only.
[B] Air content of non air-entrained cement-lime mortar is generally less than 8%.
[C] When structural reinforcement is incorporated in cement-lime mortar, the maximum air content shall be 12%

There are a number of reasons for optimising property specification masonry mortars, however, the success or failure of a C270 property specification mortar is contingent upon the 28 day compressive strength.
The main goal of this paper is to provide mortar mix designers a graphical analysis tool for predicting cement-lime laboratory masonry mortar 28 day compressive strength based on 7 day testing results. This allows the masonry designer to make adjustments to the amounts of constituent materials before the end of the required 28 day curing period and significantly shortens the amount of time needed to complete a mortar design and optimisation project.

2 Study Materials, Testing Methods and Lab Apparatus

This study compares compressive strength results at 7, 14 and 28 days for 241 individual cement-lime mortars made from 31 different types of cement, 7 different types of Type S hydrated lime and 51 different local sands or Standard (Ottawa) sand. Study data is compiled from cement-lime-aggregate testing materials sent to Chemical Lime Company over a period of 7 years. The mortar materials are not individually characterised by any particular region of the United States, but can be considered randomly representative of the type of materials any national level mortar development laboratory might be expected to receive for development, optimisation and/or testing. The study includes without distinction proprietary mix designs, standard mix designs, and pre-blended sanded mix designs with the only requirement being that the design mortar be a combination of cement, lime and aggregate without any laboratory added admixtures. Cement and lime in the study met individual material specifications as outlined in C270, except that no known slag cements were used.

Testing protocols used by the laboratory are standard to the industry as referenced by the requirements of ASTM C270 and where necessary, within the specific reference standard of any individual constituent material. Mixing water added to the designs was filtered and deionised. Individual compressive strength results represent the average of 3 cubes for each age determination. Testing was conducted in Henderson Nevada by two laboratory technicians certified as Concrete Masonry Testing Technicians as recognized by the National Concrete Masonry Association. All laboratory equipment and/or apparatus utilized in the study (e.g. flow table, water retention apparatus, 50.8mm brass cube molds, etc.) were calibrated per the manufacturer's instructions, calibration schedule and requirements outlined in ASTM C1093, Accreditation of Testing Agencies for Unit Masonry (ASTM 1995). The compressive strength testing apparatus used in this study is a Tinius Olsen Super L Hydraulic Universal Testing Machine with Model 290 display system, model 496 controller and a pressure transducer weighing system.

2 Results

Sample summary statistics for compressive strength at 7, 14 and 28 days are given in Table 2 (Box, et al, 1976).

Table 2. Sample Summary Statistics: 7, 14 and 28 Day Compressive Strength

Sample Summary (one variable)	7 Day (MPa)	14 Day (MPa)	28 Day (MPa)	7 Day (psi)	14 Day (psi)	28 Day (psi)
Mean	12.77	15.48	18.33	1852.29	2245.39	2657.86
Variance	35.72	47.86	59.49	751392.41	1006689.21	1251391.00
Std. Dev.	5.98	6.92	7.71	866.83	1003.34	1118.66
Skewness	1.35	1.19	0.97	1.35	1.19	0.97
Kurtosis	5.31	4.61	3.91	5.31	4.61	3.91
Median	11.99	14.25	16.86	1739.20	2067.10	2445.80
Mean Abs. Dev.	4.44	5.21	5.96	643.93	756.31	864.14
Minimum	2.19	2.69	3.12	317.70	389.50	453.20
Maximum	35.63	40.46	43.73	5168.20	5868.40	6342.90
Range	33.44	37.78	40.61	4850.50	5478.90	5889.70
Count (N)	241.00	241.00	241.00	241.00	241.00	241.00
Sum	3077.95	3731.16	4416.55	446402.96	541139.42	640544.38
1st Quartile	8.47	10.49	12.85	1227.85	1521.60	1863.80
3rd Quartile	15.20	18.44	22.35	2203.85	2675.10	3241.90
Interquartile Range	6.73	7.95	9.50	976.00	1153.50	1378.10

Scatterplots of 14 day compressive strength versus 7 day compressive strength and 28 day compressive strength versus 7 day compressive strength are given in Figure 1 and Figure 2.

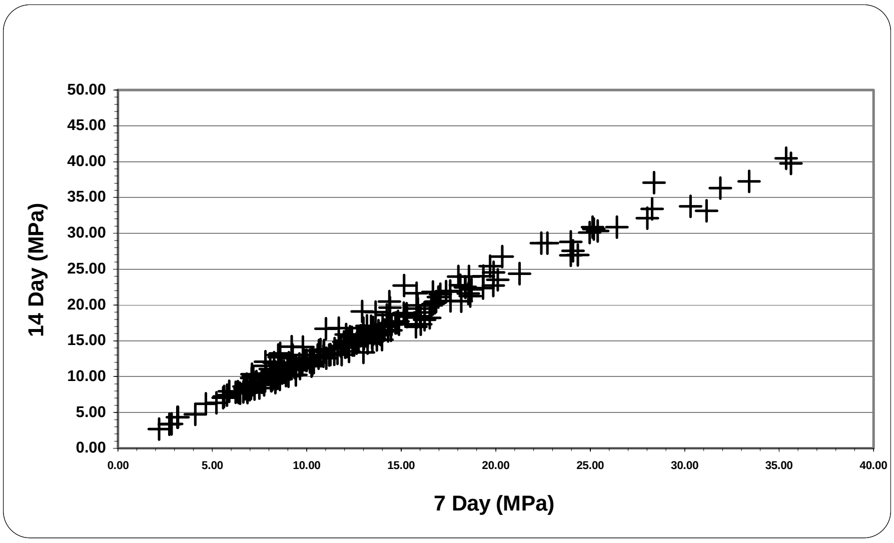

Figure 1. Scatterplot of 14 Day Versus 7 Day Compressive Strength.

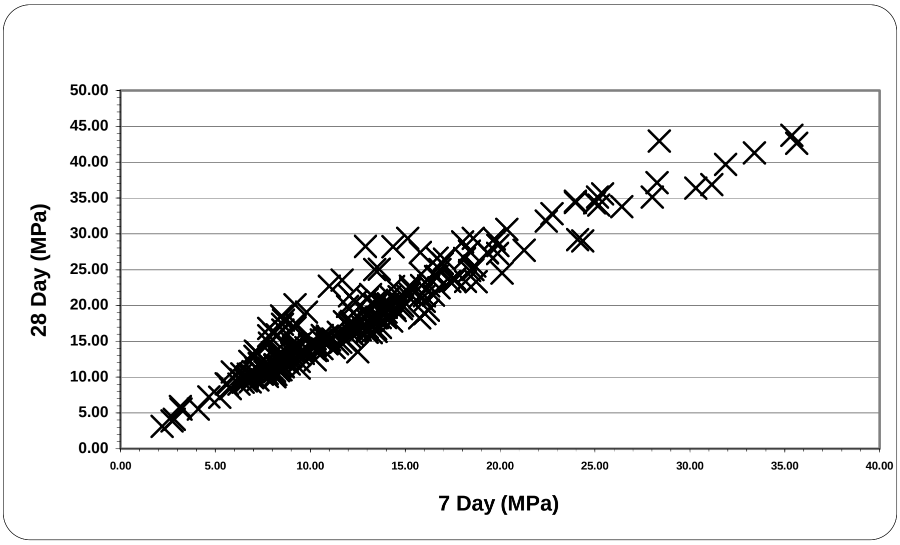

Figure 2. Scatterplot of 28 Day Versus 7 Day Compressive Strength.

4 Discussion

Scatterplots and the statistical summary show that the variance of the data increases over time. This increase in variance is most likely due to the standardized curing regime in 100% RH and the differing developmental rates of strength due to compositional differences.

Data density in the range of 6.00 to 20.00 MPa as indicated in both scatterplots and t is attributed to laboratory bias. The authors primarily design mortars for markets in the seismically active western United States. In this region of the USA, most building codes require reinforced unit masonry structures to be constructed using only C270 Type S mortar. Additionally, in other regions of the country, the authors are most are frequently asked to design and optimise C270 Type S mortar. This bias for Type S mortar does not mean that other Type designations aren't made or designed for optimisation, it only means that the amount of data in ranges higher and lower than about 6.00 to 20.00 MPa is not as numerous.

Regardless of regional bias, the wide variety of materials used to generate the data set shown in this study is very much a "real world" sampling of what any national level North American mortar development laboratory would expect to use in any given day-to-day work experience. (The thought that best describes this concept might be: "You never know what will show up at the laboratory door".) The presence of several mild to extreme outliers relative to the bias (see discussion regarding scatterplot of fit versus residuals later in this paper), therefore offer more than just some interesting statistical significance, they help in visually showing a designer the acceptance of an alternative hypothesis that the mortar thus tested is just too strong.

5 ANOVA and Regression Results

Results of analysis of variance (ANOVA) and simple linear regression are presented in Table 3.

Table 3. ANOVA and Regression Summary

Summary	Multiple R	R-Square	Adjusted R-Square	StErr of Estimate	Durbin Watson
14 Vs. 7 Day Strength (MPa)	0.9869	0.9739	0.9738	1.12017057	1.2566
28 Vs. 7 Day Strength (MPa)	0.9551	0.9122	0.9118	2.29072749	1.1222
14 Vs. 7 Day Strength (psi)	0.9869	0.9739	0.9738	162.461287	1.2566
28 Vs. 7 Day Strength (psi)	0.9551	0.9122	0.9118	332.230238	1.1222

ANOVA Table	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Ratio	P-Value
14 Vs. 7 Day (MPa) Explained	1	11186.2759	11186.276	8914.9151	< 0.0001
28 Vs. 7 Day (MPa) Unexplained	239	299.892924	1.2547821		
14 Vs. 7 Day (MPa) Explained	1	13024.0423	13024.042	2481.9838	< 0.0001
28 Vs. 7 Day (MPa) Unexplained	239	1254.13635	5.2474324		
14 Vs. 7 Day [psi] Explained	1	235297323	235297323	8914.9151	< 0.0001
28 Vs. 7 Day [psi] Unexplained	239	6308087.06	26393.67		
14 Vs. 7 Day [psi] Explained	1	273953754	273953754	2481.9838	< 0.0001
28 Vs. 7 Day [psi] Unexplained	239	26380086.4	110376.93		

Regression Table	Coefficient	Standard Error	t-Value	p-Value	Lower Limit	Upper Limit
Constant	0.8933714	0.17052785	5.2389	< 0.0001	0.557441895	1.229301
14 Vs. 7 Day Strength (MPa)	1.1422718	0.01209792	94.4188	< 0.0001	1.118439662	1.166104
Constant	2.5845286	0.3487262	7.4113	< 0.0001	1.897559148	3.271498
28 Vs. 7 Day Strength (MPa)	1.232536	0.02474002	49.8195	< 0.0001	1.183799627	1.281272
Constant	129.56801	24.7321027	5.2388594	< 0.0001	80.84726534	178.2888
14 Vs. 7 Day Strength [psi]	1.1422718	0.01209792	94.418828	< 0.0001	1.118439662	1.166104
Constant	374.84099	50.576679	7.4113	< 0.0001	275.2079983	474.474
28 Vs. 7 Day Strength [psi]	1.232536	0.02474002	49.8195	< 0.0001	1.183799627	1.281272

The scatterplots previously presented suggest the use of linear regression to study the relationship of compressive strength developed over time. A standardised residual plot indicates that the model does not significantly violate model assumptions; but that a conservative estimate of the population range is indicated because of outliers introduced against the bias of most mortars being designed as Type S (Figure 3). This need for conservatism in developing an estimate for the population is indicated by some large residuals and the influence of some excessively “strong” mortars.

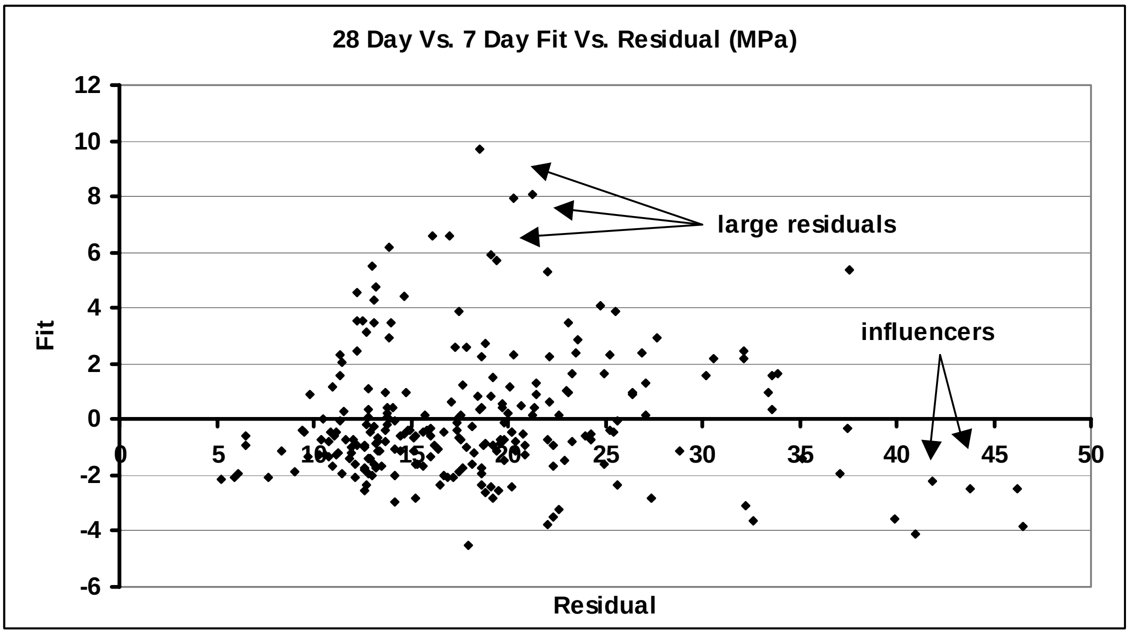

Figure 3. Graph of Fit Vs. Residuals Showing Need For Conservatism In Model.

Based on the result of model analysis, line equations outlined in Table 4 were used to develop a graphical analysis tool be used by the mortar mix designer for the purpose of estimating 28 day compressive strength when 7 day compressive strength is known. The model does not disregard outliers shown in the original data because these types of results can be expected to occur when a large variety of materials are utilized in mortar development projects. The conservatism is developed by the addition or subtraction of the estimated error (an estimate of the prediction error when using the equations developed by the regression; shown in the column labelled "StErr of Estimate" in the summary section of Table 2) above and below the confidence intervals of the population line instead of addition and subtraction of estimated error above and below the estimated population line itself. The model is established for 7 day compressive strength values in the range of 2.19 to 35.63 MPa [317.7 to 5168.2 psi]. Extrapolation to point values of mortars showing strengths outside this range is not supported. Line equations are presented for both SI (MPa) and English units [psi] (Table 4).

Table 4. Regression Equations for Building Predictive Graph(s) in MPa and psi.

Name of Line	7 Day Value of (x) (MPa)	Linear Equation (MPa)	28 Day Value of (y) (MPa)
Population Estimate Line (min.x,y)	2.19	(y)=2.5845286+1.232536(x)	5.28
Population Estimate Line (max.x,y)	35.63	(y)=2.5845286+1.232536(x)	46.50
Lower Confidence Limit Line (95%) (min. x,y)	2.19	(y)=1.897559148+1.183799627(x)	4.49
Lower Confidence Limit Line (95%) (max. x,y)	35.63	(y)=1.897559148+1.183799627(x)	44.08
Upper Confidence Limit Line (95%) (min. x,y)	2.19	(y)=3.271498+1.281272(x)	6.08
Upper Confidence Limit Line (95%) (max. x,y)	35.63	(y)=3.271498+1.281272(x)	48.92
Lower Range Line (min. x,y)	2.19	(y)=1.897559148+1.183799627(x)-2.2907275	2.20
Lower Range Line (max. x,y)	35.63	(y)=1.897559148+1.183799627(x)-2.2907275	41.79
Upper Range Line (min. x,y)	2.19	(y)=3.271498+1.281272(x)+2.2907275	8.37
Upper Range Line (max. x,y)	35.63	(y)=3.271498+1.281272(x)+2.2907275	51.21

Name of Line	7 Day Value of (x) [psi]	Linear Equation [psi]	28 Day Value of (y) [psi]
Population Estimate Line (min.x,y)	317.7	(y)=374.84099+1.232536(x)	766.4
Population Estimate Line (max.x,y)	5168.2	(y)=374.84099+1.232536(x)	6744.8
Lower Confidence Limit Line (95%) (min. x,y)	317.7	(y)=275.2079983+1.183799627(x)	651.3
Lower Confidence Limit Line (95%) (max. x,y)	5168.2	(y)=275.2079983+1.183799627(x)	6393.3
Upper Confidence Limit Line (95%) (min. x,y)	317.7	(y)=474.474+1.1281272(x)	832.9
Upper Confidence Limit Line (95%) (max. x,y)	5168.2	(y)=474.474+1.1281272(x)	7096.3
Lower Range Line (min. x,y)	317.7	(y)=275.2079983+1.183799627(x)-332.2	319.1
Lower Range Line (max. x,y)	5168.2	(y)=275.2079983+1.183799627(x)-332.2	6061.1
Upper Range Line (min. x,y)	317.7	(y)=474.474+1.1281272(x)+332.2	1165.1
Upper Range Line (max. x,y)	5168.2	(y)=474.474+1.1281272(x)+332.2	7428.5

The following graphs present the estimated population line, confidence intervals of the estimated population line and upper and lower ranges of expected values of 28 day compressive strength when 7 day compressive strength is known. Examples of how to use the graph for a design mortar of 12.4 [1800] psi is illustrated for both MPa and psi analysis (Figures 4 and 5).

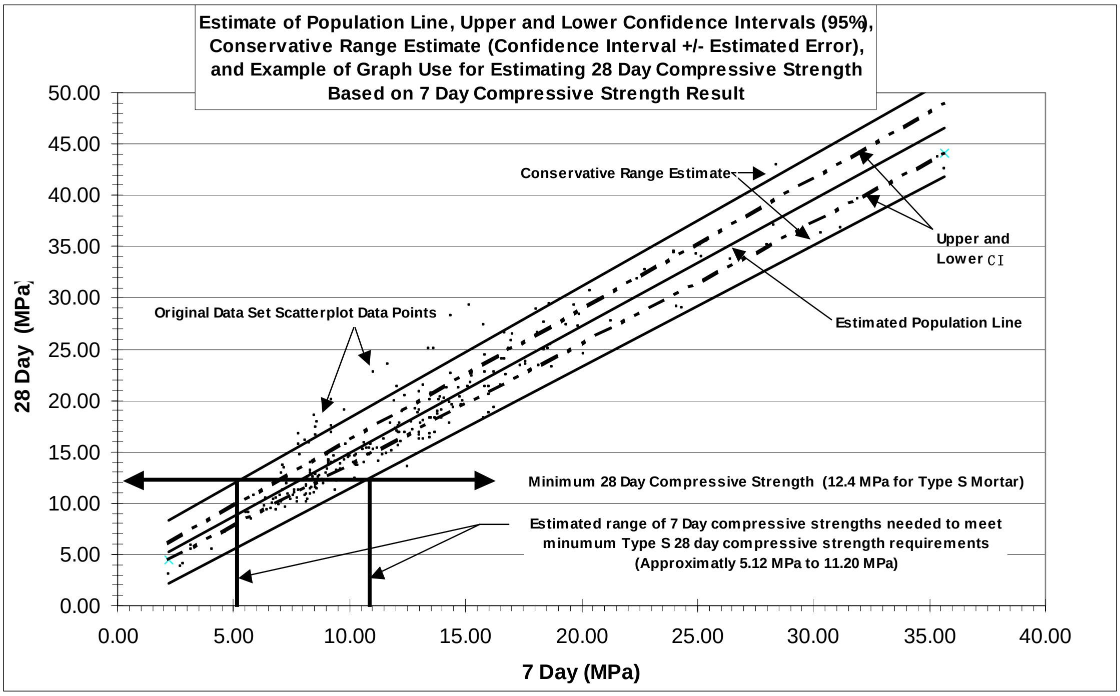

Figure 4. Predictive Graphing Tool (MPa).

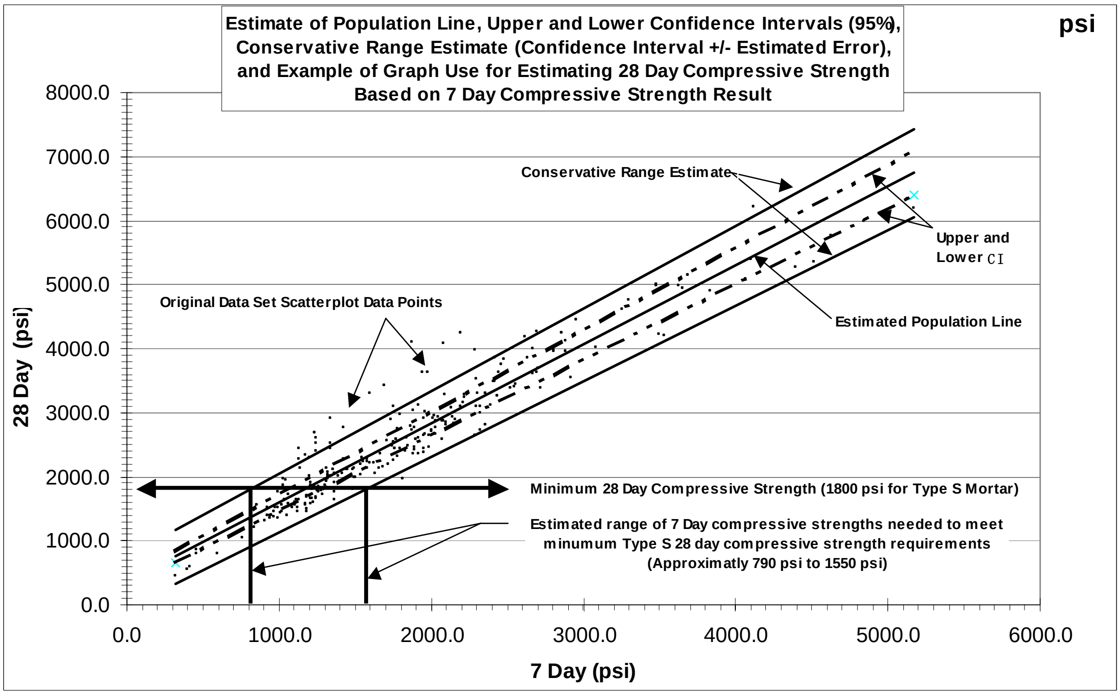

Figure 5. Predictive Graphing Tool [psi].

6 Conclusion

Strength is not and should not be the only factor in the design and optimisation of a masonry mortar. However, mortars designed under the property specification requirements of C270 are required to meet minimum compressive strengths for the mortar type designation of the design and optimisation project. The graphing tool presented in this paper offers the mortar designer a tool to determine if the range of compressive strength as determined at 7 days is acceptable for the design project at 28 days.

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