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Structural Lightweight Grout Mixture Design

Hannah Jean Polanco

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Structural Lightweight Grout Mixture Design

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This research focused on designing a grout mixture using lightweight aggregate that achieves the minimum 28-day compressive strength required for normal-weight grout, 2000 psi. This research specifically studied the effects of aggregate proportion, slump, and aggregate soaking on the compressive strength of the mixture. The variable ranges investigated were 3-4.75 parts aggregate to cement volumetrically, 8-11 in. slump, and 0 and 2 cycles of soaking. The statistical model developed to analyze the significance of variable effects included a three-way interaction between the explanatory variables.

All three explanatory variables had a statistically significant effect on the grout compressive strength, but the effect of soaking was minimal and decreased as aggregate proportion decreased. This research also showed that lightweight grout, when prepared using aggregate proportion and slumps within the ranges suggested in American Society for Testing and Materials C476, reaches the required minimum 28-day compressive strength with a factor of safety of at least 2.7.

Key words: Expanded shale, grout, lightweight aggregate, lightweight grout, lightweight masonry, masonry, Utelite

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1 INTRODUCTION

Lightweight aggregate, including expanded shale and expanded clay, has been in standardized use since 1953, when American Society for Testing and Materials (ASTM) C-330 (Standard Specification for Lightweight Aggregates for Structural Concrete) was first approved. Lightweight aggregate has many benefits that have been proven extensively through its use in lightweight concrete, especially in regards to lightweight concrete masonry units (CMUs) (Sousa 2014), but researchers have yet to explore uses for this technology in other fields, such as lightweight grout, for which there is no standard. Researchers hypothesize that the benefits of lightweight concrete can be applied to lightweight grout as well, but, until a mixture design is developed, this theory cannot be tested.

1.1 Lightweight Aggregate

There are numerous types of lightweight aggregate, but the most common is probably expanded clay, shale, or slate. These aggregates are manufactured by crushing raw material and heating the material to 1830 to 2190°F in a kiln. Small quantities of organic matter combust and rapidly form gas within the crushed materials, causing the particles to bloat. The expansion is allowed through partial melting of the material, and the resulting product is a porous, low density, highly absorptive aggregate (Mindess 2003). Lightweight aggregate can be approximately 20% lighter than normal-weight aggregate, effectively reducing the overall weight of an entire structure (Tanner 2014).

Lightweight concrete has been used in structures and pavements for decades, becoming even more widely used in recent years. However, the use of lightweight aggregate is less common in masonry, especially in grout. This is likely due to the limited research that shows lightweight aggregate to have lower compressive strength and increased cost relative to normal-weight aggregate (Sousa 2014, Tanner 2014). There has been extensive research in the field of lightweight concrete, but research specifically targeting lightweight grout is sparse.

Lightweight aggregates provide several benefits, including increasing the fire resistance of a structure by improving insulation (Al-Jabri 2005, Bastos 2005, Sousa 2014) and lightening dead loads from the structure itself—effectively lowering the overall cost of foundation construction. Furthermore, concrete with lightweight aggregate has been shown to gain strength comparable to that with normal-weight aggregate (Haque 2004). In pavements, presoaking lightweight aggregates has been shown to provide a degree of internal curing, reducing concrete shrinkage and cracking (Bentur 2001, Guthrie 2013). All of these benefits potentially apply to grout as well as concrete in structures and pavements. Currently, however, there are no standards for lightweight aggregate use in grout. Lightweight grout needs to be standardized to allow for its widespread use to take advantage of these beneficial properties.

The objective of this research was to determine a repeatable mixture design enabling standardized industrial use of lightweight grout while achieving the required minimum grout compressive strength. A statistical analysis was performed to determine the statistical significance of the effects of multiple variables on lightweight grout compressive strength. By establishing a lightweight grout mixture design framework, this research provides groundwork for future research into the field of lightweight grout.

1.2 Outline

This research explored the potential for standardizing lightweight grout by establishing a repeatable process and mixture design that will reliably result in a grout that can retain the standards of normal-weight grout, specifically focusing on compressive strength requirements. The testing process was designed to reflect the mixing process on an industrial level. Three variables were tested to determine their influence on compressive strength as well as their interaction with each other. These variables included aggregate-to-cement ratio, slump, and aggregate soaking time.

Chapter 2 contains background information and relevant literature. Chapter 3 presents the ranges of variables and the mixing and testing procedures. The effects of these variables on the lightweight grout compressive strength were determined in an analysis of variance, the results of which are shown in Chapter 4. In Chapter 5, the results are described, and their significance is explained. A summary of the results and their impact on the field of lightweight grout is contained in Chapter 6.

2 LITERATURE REVIEW

The benefits of using lightweight aggregate could prove to be useful in a field like masonry. Lightweight aggregates are already being utilized in CMUs, but grout can account for large volume of a structure, affecting the entire design.

Perhaps the main reason lightweight aggregate is used less often than normal-weight aggregate is that lightweight aggregates produce materials with lower tensile and compressive strengths. In the American Concrete Institute (ACI) Building Code, a modification factor, λ, is used in design to compensate for the lower tensile strength of lightweight materials (ACI Committee 318 2011). This research is intended to be groundwork for more extensive future research, so it does not explore the tensile strength of lightweight grout, focusing instead on the compressive strength requirements and possible mixture designs that could achieve this minimum compressive strength requirement.

2.1 Insulative Properties

Research has shown that lightweight aggregate can introduce air voids in cementitious materials. Because the thermal conductivity of air is significantly lower than that of concrete or grout, a decrease in the thermal conductivity and a corresponding increase in the fire resistance of cementitious materials can be achieved (Al-Jabri 2005, Bastos 2005, Sousa 2014).

Lightweight concrete can be up to six times more effective for increasing thermal resistance than normal-weight concrete (Chandra 2002). Lightweight concrete has been used in ship construction to improve insulation and has even been used on its own as insulating fill placed in CMU cavities (Chandra 2002).

The voids in lightweight aggregate also improve acoustic insulation. The pores in the lightweight aggregate absorb sound, decreasing acoustic transmission and making structures more soundproof (Kim 2010).

2.2 Pre-Wetting Benefits

There have also been investigations into the possibility of internal curing due to the high absorption capability of lightweight aggregate (Cusson 2008, Lo 1999). Research has proven that pre-wetting of lightweight aggregate can increase the strength of concrete either through shrinkage cracking reduction or strengthening of the aggregate-cement bond at the interfacial zone, somewhat compensating for the generally lower strength of lightweight aggregates relative to normal-weight aggregates (Lo 2007, Cusson 2008). For example, autogenous shrinkage of lightweight concrete can be reduced when using pre-wetted aggregates due to the moisture retained in the aggregate pores being released as internal water was lost to self-desiccation of the cement paste (Kohno 1999).

Other research has shown that, not only does pre-wetting lightweight aggregate affect the strength of the concrete, but also the amount of pre-wetting (measured as time of consistent wetting) can have an effect (Lo 1999, Lo 2004). One research paper looking specifically at expanded clay aggregate pinpointed 30 minutes of consistent wetting as the ideal pre-wetting time in regards to strength (Lo 2004).

2.3 Non-Structural Lightweight Grouts

There are a few examples of investigations of nonstructural lightweight grout, such as “pumpable cement grout,” which used an aqueous foam to achieve the desired lightweight attributes. However, the results of testing indicated an average 28-day compressive strength of 580 psi, well below the structural requirement of 2000 psi (Stephens 1989). A similar foamed grout has been developed for coal fire prevention, focusing on the insulative properties of the grout instead of its structural properties (Colaizzi 2004).

A lightweight grout intended solely for soundproofing was developed in 1996. That grout was also not intended for structural use but demonstrates one of the many benefits of lightweight grout (Anderson 1996). Lightweight grouts—mostly foam-based grouts—are existing and in use, but research on the properties of structural lightweight grout prepared using lightweight aggregate is severely lacking.

2.4 Other Benefits

Lightweight aggregate can be more expensive to manufacture (Chandra 2002), but, since it is a lighter aggregate option, the lower cost of transport and cost of construction can offset the higher manufacturing cost, especially if there is a manufacturing plant in the vicinity (Sousa 2014); therefore, lightweight aggregate may be an economically viable option for the masonry industry. The overall cost of construction can also decrease since lighter structures can be built with decreased reinforcement and element size. In addition, footings and foundations can be smaller, also cutting costs. These types of benefits have been proven many times over when using lightweight concrete, and they could be easily applied to masonry.

Researchers have speculated that the compressive strength of lightweight concrete can be as high as that of normal-weight concrete. However, the compressive strength of a concrete using lightweight aggregate depends heavily on the quality of the aggregate being used (Lo 1999).

Since the beneficial properties of lightweight aggregate are influenced by aggregate pore volume (Kim 2010), the aggregate gradation affects the properties of lightweight concrete and lightweight grout. The aggregate gradation of lightweight concrete generally includes larger aggregate sizes than that of lightweight grout. Thus, the benefits obtained by using lightweight aggregate in grout may differ from those obtained when lightweight aggregate is used in concrete.

2.5 Summary

The use of lightweight aggregate in structures can improve their thermal and acoustic insulation properties, and research has shown that pre-wetting the lightweight aggregate can prevent autogenous shrinkage and improve compressive strength through internal curing. Many types of non-structural lightweight grout have been developed, but none use lightweight aggregate or reach the required minimum grout compressive strength of 2000 psi. The strength of lightweight concrete can be comparable to that of normal-weight concrete. Overall, the benefits of using lightweight aggregate are not being applied in the field of masonry, specifically grout, because there is no ASTM standard specifying the use of structural lightweight grout.

3 RESEARCH PROCEDURE

To investigate the effects of different variables on lightweight grout mixtures, a matrix of experiments was developed as a framework for the statistical analysis to be performed. The main results include average maximum compressive strength and mode of failure. Other material attributes such as unit weights, cement contents, and water-cement ratios are included in Appendix A.

3.1 Variables

The grout mixture design was simplified to lightweight aggregate, portland cement Type I/II, and water, excluding any admixtures or pozzolans. The variables in the experiment were aggregate-to-cement ratio, slump, and aggregate soaking time. Each variable range was determined by using the material range for normal-weight grout as specified in ASTM C476 (Standard Specification for Grout for Masonry) as a baseline and adjusting those ranges after preliminary tests were performed.

Aggregate-to-cement ratio, or aggregate proportion, was chosen as a variable because aggregate directly influences the design of grout since it is the main variable considered in grout mixture design. Slump was chosen because it is a common measurement of concrete and grout workability and reflects the water content of the mixture. Soaking was chosen because pre-wetting influences the compressive strength of lightweight concrete; thus, it was hypothesized that it will also influence the compressive strength of the lightweight grout. Other variables such as cement content, water-cement ratio, and unit weight were considered but were ultimately excluded from the final analysis.

3.1.1 Aggregate Proportion

Not all types of lightweight aggregates have the same mechanical properties, and the results of the research presented herein may therefore not be applicable to all types of lightweight aggregates. The lightweight aggregate used for this research was expanded shale, or Utelite crushed fines, which complies with the fine aggregate gradation requirements of ASTM C330, the standard used for lightweight concrete applications. The expanded shale had an absorption of 19%, determined by the absorption test as specified in ASTM C128 (Standard Test method for Density, Relative Density, and Absorption of Fine Aggregate).

The standard aggregate proportion for fine normal-weight grout is 2.25 to 3 times the volume of cement (ASTM C476). These values are extremely conservative; normal-weight grout made using proportions at the top of the recommended range reached compressive strengths with safety factors of approximately 3.0 (Tanner 2014). To obtain grout strengths closer to the minimum grout strength of 2000 psi, the range used in this experiment was increased above the ASTM recommended range of 2.25 to 3.

Research shows that the use of lightweight instead of normal-weight aggregate results in weaker concrete (ACI Committee 318 2011, Sousa 2014); lightweight grout may be weaker than normal-weight grout as well. However, preliminary tests performed to determine design ranges for this experiment showed that even the maximum recommended aggregate proportion, 3 parts aggregate to 1 part cement by volume, resulted in lightweight grout compressive strengths well above the minimum. To have a range of samples that would most likely approach the minimum required compressive strength of 2000 psi (ASTM C476), the range of aggregate proportions for the experiment was changed from 2.25-3 to 3-4.75. The aggregate proportions used in this experiment were 3, 3.875, and 4.75 times the volume of cement. In the analyses presented herein, these aggregate proportions are referred to as low, medium, and high aggregate proportions, respectively.

3.1.2 Slump

The range of the slump required for normal-weight grout (ASTM C476) is 8 to 11 in., which is high enough for the grout to be easily poured and compacted into CMU cells. Since grout slump is difficult to target, a margin of error of 0.5 in. was deemed acceptable, changing the set of three slump target values to three non-overlapping slump target ranges. To span the normal-weight grout slump requirements, the three values chosen as the center of the three ranges were 8.25, 9.5, and 10.75 in. In the analysis, these slumps are referred to as low, medium, and high slumps, respectively.

3.1.3 Aggregate Soaking

The microstructure of lightweight aggregates allows for better bond between the aggregate and cement paste than that of normal-weight aggregate; thus, the overall strength of the sample increases by using lightweight aggregate (Lo 2004). Pre-wetting the aggregate has been shown to also improve the bond between aggregate and cement paste at the interfacial zone through self-curing (Lo 2007).

Shrinkage is a common problem with any cement-based mixture—such as grout. In addition, CMUs are highly absorptive. Consequently, much of the water in the grout mixture is absorbed by the CMUs during construction and curing, which causes additional grout shrinkage. In lightweight concretes—especially in pavement applications—pre-wetting the lightweight aggregates has been shown to induce internal curing, which reduces concrete shrinkage cracking (Bentur 2001, Cusson 2008, Guthrie 2007). Thus, the researchers hypothesize that pre-wetting can benefit lightweight grout not only by inducing internal curing but also by reducing or even preventing the separation between the grout and the walls of the CMU cells. Shrinkage was not analyzed in this research, but aggregate pre-wetting was considered.

Research has been conducted on internal curing using lightweight aggregates (Bentur 2001, Cusson 2008, Guthrie 2007), but full saturation would require the aggregate to undergo a long period of pre-wetting, which may not be economically feasible on an industrial scale. Instead of long-term pre-wetting, an alternative procedure was used to bring the aggregate to a moistened condition. In this procedure, a predetermined amount of water equal to approximately twice the aggregate absorption was added to the weighed aggregate, and two cycles of mixing and stationary soaking were then applied. Each cycle consisted of 3 minutes of mixing the water and aggregate followed by 3 minutes of stationary soaking in a concrete mixer. Both cycles were included to enable even absorption of the water by the aggregate. To examine the effects of pre-wetting the lightweight aggregate, an alternate set of mixtures was made without following the aforementioned pre-wetting procedure. In the analysis presented herein, these procedures are referred to as high and low soaking, respectively.

3.2 Preliminary Tests

Preliminary tests were performed to familiarize the researcher with the grout mixing and testing processes as well as to establish the variable ranges discussed in Section 3.1. Specifically, aggregate proportions above the range recommended in ASTM C476 were established as 3 to 4.75 parts aggregate to 1 part cement by volume. Additionally, estimates for the additional water needed to achieve certain slumps were established for simplification of future mixture designs. Preliminary pre-wetting tests were also conducted to determine the amount of water used to condition the lightweight aggregate. Although these preliminary tests followed established procedures, they were performed in a trial-and-error manner and were therefore not included in the final analysis.

Four mixtures were designed and used during preliminary testing: A, B, C, and D. The attributes of these preliminary mixtures are presented in Table 3-1.

Table 3-1. Preliminary Test Results

Mixture	Aggregate Proportion	Slump (in.)	Soaking Cycles	Compressive Strength (psi)
A	2.625	9.5	2	5153
B	1.875	10	2	5958
C	1.875	9.5	5	7287
D	3.000	10.5	2	5938

The aggregate proportion was changed because, as shown in Table 3-1, the ASTM recommended aggregate proportions produced grouts with very high compressive strengths. The range of aggregate proportions selected for the final experiment was 3-4.75.

As shown in Table 3-1, the use of 5 soaking cycles resulted in a high average compressive strength, but the coefficient of variance was significantly higher than that when 2 or

0 soaking cycles were used. To avoid the larger coefficient of variance, 2 cycles were selected as the "high" soaking for the final grout mixtures. These preliminary tests demonstrate the possible value of future research into the optimization of expanded shale aggregate soaking time.

3.3 Testing Matrix

For this thesis, six samples were manufactured for each mixture. There were three variables: aggregate proportion, slump, and soaking time. There were three ranges for the aggregate proportion, three ranges for grout slump, and two soaking times. The combination of these variables and ranges resulted in 18 mixture designs and a total of 108 specimens.

3.4 Specimen Mixing

Each mixture was designed according to its assigned aggregate proportion. The aggregate underwent conditioning, as applicable, as described previously. During preliminary tests, the water was not absorbed fast enough by the aggregate to achieve a sufficiently moistened condition during the 12 minutes of mixing time allotted for soaking if the exact amount of water for 100% saturation was added into the mixer. Based on engineering judgment, a decision was made to use twice the amount of water required for full saturation during the soaking process. Observations during the preliminary tests confirmed that the modification led to improved wetting of the aggregates and adequate aggregate absorption for the purposes of this experiment. The water used for conditioning the aggregate was not enough to fully hydrate the cement or achieve the desired slump, so additional water was added later in the process.

The order in which the mixtures were manufactured was randomized to account for minor variations in environmental conditions. For record-keeping purposes, they were each labeled with three letters signifying first aggregate proportion, then slump, and then soaking method. For example, the sample with high aggregate proportion, medium slump, and no (low) soaking would be labeled HML. Each of the six specimens was also assigned a number for record-keeping purposes. More details on the grout mixture design process are presented in Appendix B.

During production of the mixtures, tools were pre-wetted. The aggregate was added to the concrete mixer first and the conditioning water—twice the water required to achieve 100% saturation—was added second. If the design specified soaking, then the aforementioned soaking protocol was followed, and, if not, the concrete mixer was turned on for approximately 10-15 seconds to distribute the water. The portland cement was then added incrementally into the mixer, and additional water was added as needed to achieve the target slump. A slump test was performed according to ASTM C143 (Standard Test Method for Slump of Hydraulic-Cement Concrete), and the value was recorded. The grout used for the slump test was returned to the mixer, and the mixer was turned on for another 1-2 minutes before the mixture was transported to the specimen mold.

Following the mixing, the grout was placed in a bucket, moved to the area where the specimen mold was set up, and poured into the mold. The molds were constructed as specified by ASTM C1019 (Standard Test Method for Sampling and Testing Grout) and, as shown in Figure 3-1, included four CMU faces for each of the six specimens with a permeable lining on the blocks—paper towels for this research—to allow for absorption of water by the CMU as it would take place in actual masonry construction. The lining also allowed simple removal of the specimens from the mold since the grout did not directly bond to the CMUs. A square cut of nonabsorbent plastic was placed at the bottom of each mold to ensure a smooth bottom face and to systematize the dimensions of the specimens. All six specimens were cast at the same time, and the same CMUs were used as molds for all specimens. The specimens were removed from the mold after 24-48 hours, labelled, and placed in a fog room until the day of testing. The CMUs were allowed to air-dry for at least 36 hours between grout placements.

Figure 3-1. Grout Mold Diagram

3.5 Specimen Testing

The specimens were measured according to ASTM C1019 and capped with gypsum according to ASTM C1552 (Standard Practice for Capping Concrete Masonry Units, Related Units and Masonry Prisms for Compression Testing). Compressive strength tests were performed at 14 and 28 days, and the strength results and break types were recorded. Tests were performed at two times so the compressive strengths could be compared and a relationship could be determined, as discussed further in Section 4.2. Testing at 14 days also provided a means of anticipating 28-day strengths and determining whether changes in the experimentation were needed. Specimens labeled 1, 3, and 5 were tested at 14 days, and specimens labeled 2, 4, and 6 were tested at 28 days. The compressive strengths of specimens tested at 14 days were converted to 28-day strengths for the statistical analysis performed in this research.

3.6 Summary

The three variables used in this experiment include aggregate proportion, slump, and soaking cycles. The aggregate proportion categories for this experiment are 3 (low), 3.875 (medium), and 4.75 (high). The slump targets for this experiment are 8.25 (low), 9.5 (medium), and 10.75 (high). The soaking cycles are either no (low) soaking, or high soaking. Specimen mixing and testing were done following general ASTM procedures.

4 RESULTS

The results of this research include the maximum compressive strengths, back-calculated predictor ratios, and modes of failure. These results were analyzed to determine if there are significant trends in any of the variables tested. The data were analyzed using the statistical analysis software JMP Pro 13 (JMP 2015).

The variables—aggregate proportion, slump, and soaking—were all used as categorical variables in the statistical analysis due to the nature of the testing matrix. The final model was developed by applying a logarithmic transformation to the compressive strength response variable and considering a three-way interaction among the three categorical explanatory variables.

As mentioned in Section 3.1, other variables were considered during preliminary testing but were excluded from the final analysis for various reasons. Although cement content influences the compressive strength of cementitious materials, for the range investigated cement content did not have a statistically significant influence on the compressive strength. Unit weight was determined to be less useful to have as an input in the statistical model since it is a measured quantity that depends on other design variables like aggregate proportion. Water-cement ratio was considered as well, but as a continuous variable it caused interference in the model in a way slump did not as a categorical variable, and the two variables provided similar information.

4.1 Raw Results

Aggregate proportion, slump target, and amount of soaking are shown in the 3-letter identifier for each mixture design, but actual recorded slumps are given in Section 4.1.1. Compressive strengths are shown and discussed in Section 4.1.2. Further details on the material properties of each specimen are given in Appendix A.

4.1.1 Slump

Slump target values were 8.25, 9.5, and 10.75 in. with a margin of error of ±0.5 in. The measured slump for each mixture is given in Table 4-1. All recorded values are within ±0.5 in. of the target slump.

Table 4-1. Experimental Grout Slumps (in.)

Aggregate	High Soak			Low Soak		
	Slump					
	High	Medium	Low	High	Medium	Low
High	10.50	10.00	8.00	10.50	9.00	7.75
Medium	10.50	9.25	8.00	10.50	8.25	8.00
Low	10.50	9.50	8.75	10.25	9.75	8.50

4.1.2 Compressive Strengths

All compressive strengths from this experiment were above the 2000 psi minimum required by ASTM. Table 4-2 presents the average compressive strength results; six specimens were tested for each mixture. Detailed individual results are provided in Appendix A.

Table 4-2. Average Experimental Grout Compressive Strengths (psi)

Aggregate	High Soak			Low Soak		
	Slump					
	High	Medium	Low	High	Medium	Low
High	2978	3012	3475	2475	2743	3308
Medium	4301	5182	5701	3871	4707	5252
Low	6014	6435	7110	6547	6469	6554

The lowest average compressive strength in this experiment was 2475 psi for the HHL mixture, shown in Table 4-2. The lowest average compressive strength for the lowest considered aggregate proportion (mixture LHH), which was the highest aggregate proportion recommended by ASTM C476, was 6014 psi. The LLH mixture achieved the required compressive strength of normal-weight grout with a safety factor of 3.0 (the absolute minimum compressive strength of a single specimen recorded in this experiment at the low aggregate proportion was 5429 psi as shown in Table A-1 in Appendix A, which still provided a safety factor of 2.7).

4.2 28-Day Compressive Strength Estimations

There are no compressive strength prediction equations for grout, lightweight or otherwise. The relationship between the compressive strengths of samples tested at 14 days and the corresponding strengths of samples tested at 28 days was analyzed to back-calculate a ratio that could be used to estimate 28-day compressive strength from a given 14-day compressive strength. The back-calculated ratios are presented in Table 4-3, and a graphical representation of the values presented in Table 4-3 is shown in Figure 4-1. The overall average ratio between the 14-day and 28-day compressive strengths was 0.85.

Table 4-3. 14-Day to 28-Day Compressive Strength Ratios

Aggregate	High Soak			Low Soak		
	Slump					
	High	Medium	Low	High	Medium	Low
High	0.84	0.79	0.85	0.85	0.78	0.81
Medium	0.82	0.88	0.88	0.88	0.86	0.81
Low	0.87	0.90	0.89	0.86	0.82	0.88

There is a mild trend of a general increase in the ratio as the aggregate proportion decreases. Also, as a general rule, the ratio appears to be smaller at the low soak level compared to the high soak level, with exceptions at high and medium aggregate proportion and high slump. The data presented herein demonstrates the possibility of further research into developing a model to predict the 28-day compressive strength of lightweight grout from that of 14-day or even 7-day strengths.

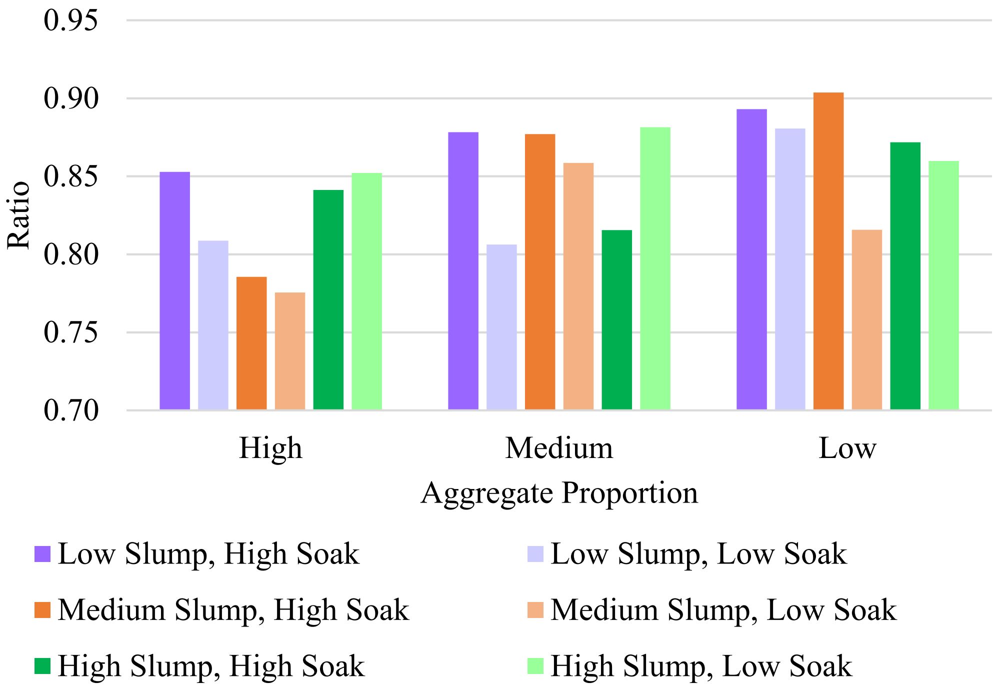

Figure 4-1. Predictor Ratios

A model for predicting the compressive strength of concrete was used to calculate the ratio between the strengths at 14 and 28 days, and that result was compared to the value calculated above. ACI Committee 209 (ACI 2001) recommends the relationship presented in Equation 4-1 to predict the compressive strength for moist-cured concrete made with Type I portland cement at any age given the 28-day compressive strength:

$$f_{cmt} = \left[\frac{t}{a+bt}\right] f_{cm28} \qquad (4\text{-}1)$$

where t is the sample age in days, a is 4.0 for Type I portland cement and moist-cured concrete, b is 0.85 for Type 1 portland cement and moist-cured concrete, f_{cm28} is the compressive strength of the sample at 28 days, and f_{cmt} is the compressive strength of the sample at age t. From Equation 4-1, for a sample age of 14 days, the ratio between f_{cmt} and f_{cm28} is 0.88. The calculated value was slightly higher than the back-calculated ratio of 0.85. This small discrepancy is likely due to the significantly higher water content of grout compared to concrete.

To determine if using the 0.85 ratio estimate was accurate enough to be used in the statistical analyses, a Tukey-Kramer test was performed to establish if there was a statistically significant difference between the means of the compressive strength estimated from the 14-day tests ($f_{cm14}/0.85$) and the means of the 28-day tests (f_{cm28}) from the same mixture. The result of that test indicated that there is not sufficient evidence to show that a statistically significant difference exists, effectively confirming the appropriateness of using the 0.85 ratio estimate. The direct output of the Tukey-Kramer test is presented in Appendix C.

4.3 Statistical Analysis

The following subsections detail the statistical analysis, including the inferences that were made from the results of this research and the process of developing a final model.

4.3.1 Inferences

The order of testing was randomized, which allows for cause and effect inferences. Results from this study can be applied to grout using portland cement Type I/II, Utelite crushed fines as the lightweight aggregate, and potable water.

4.3.2 Model Development

All explanatory variables were treated as categorical variables because the testing matrix was set up with three levels of aggregate proportion, three slump targets, and two methods of soaking. There were not enough levels of each variable for them to be considered continuous.

Various models that included main effects, two-way interactions, and a three-way interaction were considered. The calculated *p*-values for most of the terms were less than or equal to 0.05 (or a significance level of 5%), which is the arbitrary threshold used herein to indicate the statistical significance of the results. The terms that were statistically significant were included in the final model as shown in Table 4-4. Although the two-way interaction between soaking and slump was not statistically significant— the *p*-value was 0.5831—it was included in the statistical analysis since the three-way interaction including these two variables was statistically significant.

Table 4-4. Effects Test

Variable/Interaction	*p*-Value
Soaking Cycles	<0.0001
Aggregate Proportion	<0.0001
Slump Target	<0.0001
Soaking Cycles*Aggregate Proportion	<0.0001
Soaking Cycles*Slump Target	0.5831
Aggregate Proportion*Slump Target	<0.0001
Aggregate Proportion*Slump Target*Soaking Cycles	<0.0001

The three-way interaction limits the number of quantifiable or graphical results, but this rich model was required to accommodate the interactions between all three variables. Appendix C shows more details of the results of the statistical analysis.

During model development, the response variable, grout compressive strength, needed to be logarithmically transformed. The response variable was transformed using the natural logarithm for this experiment. Additionally, an outlier was identified in the residual plot, as shown in the bottom left region of Figure 4-2, and confirmed with laboratory notes. Records showed that this particular sample—specimen 5 of mixture HML—had poor compaction and did have a significantly lower compressive strength than other specimens of that mixture. The residual plot excluding the outlier is shown in Figure 4-3, which is the residual plot for the model used in the final analysis. The final model had an R^2 value of 0.98.

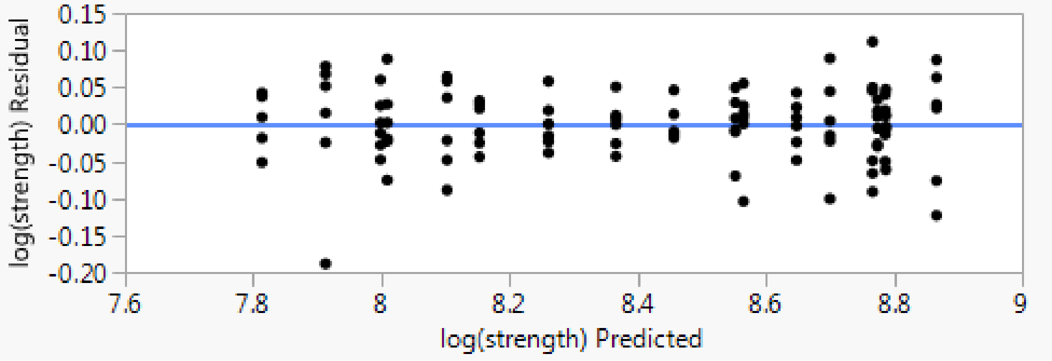

Figure 4-2. Transformed Residual Plot with Outlier

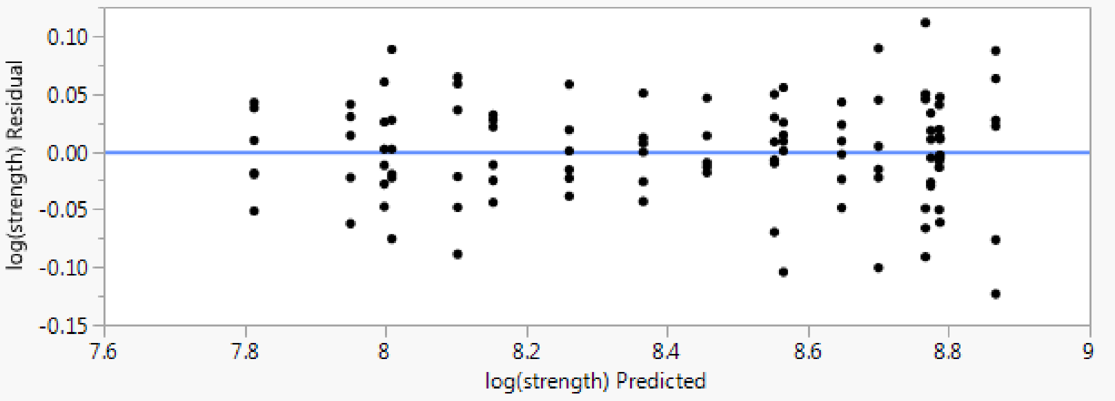

Figure 4-3. Final Residual Plot

4.4 Statistical Analysis Results

Several aspects of the three-way interaction model were analyzed, including the individual variables or main effects, two-way interaction trends, and three-way interaction.

4.4.1 Main Effects

As shown in Table 4-4 from Section 4.3.2, the *p*-values of all three explanatory variables are <0.0001, meaning that each main effect is statistically significant. However, as shown in Figure 4-4, not every main effect seems to have a practically important effect on the response variable.

There is a statistically significant difference in compressive strengths between levels of aggregate proportion. The difference in compressive strengths between levels of slump are, however, less prominent, and the difference in compressive strengths between levels of soaking is so subtle that it does not have a practically important effect on compressive strength.

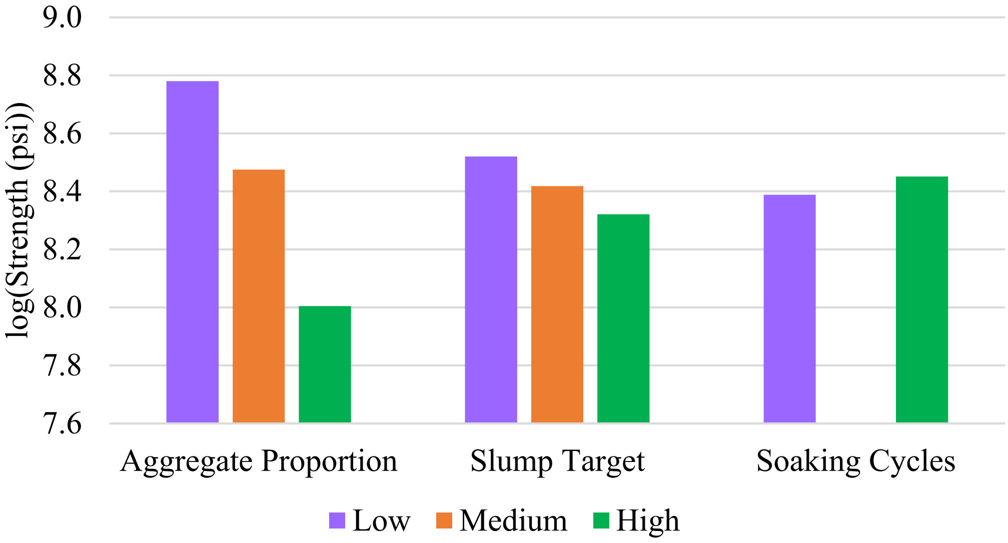

Figure 4-4. Main Effect Least Squares Means

4.4.2 Two-Way Interaction Trends

The researchers hypothesized that a lower aggregate proportion and a lower slump would both increase the compressive strength of the grout samples. As shown in Figures 4-4 and 4-5, these hypotheses were correct, but a much richer model—including a three-way interaction—was required to fully describe the interaction between the explanatory variables.

As demonstrated by the least squares means of the main effects shown in Figure 4-4, aggregate proportion had the largest effect while soaking had the smallest effect on the compressive strength. This is further supported by the results presented in Figures 4-5, 4-6, and 4-7. For example, in Figure 4-5, the compressive strength difference between aggregate proportion levels is more than that between the three levels of slump shown in Figure 4-6 and even more substantial than that of the two levels of soaking shown in Figure 4-7.

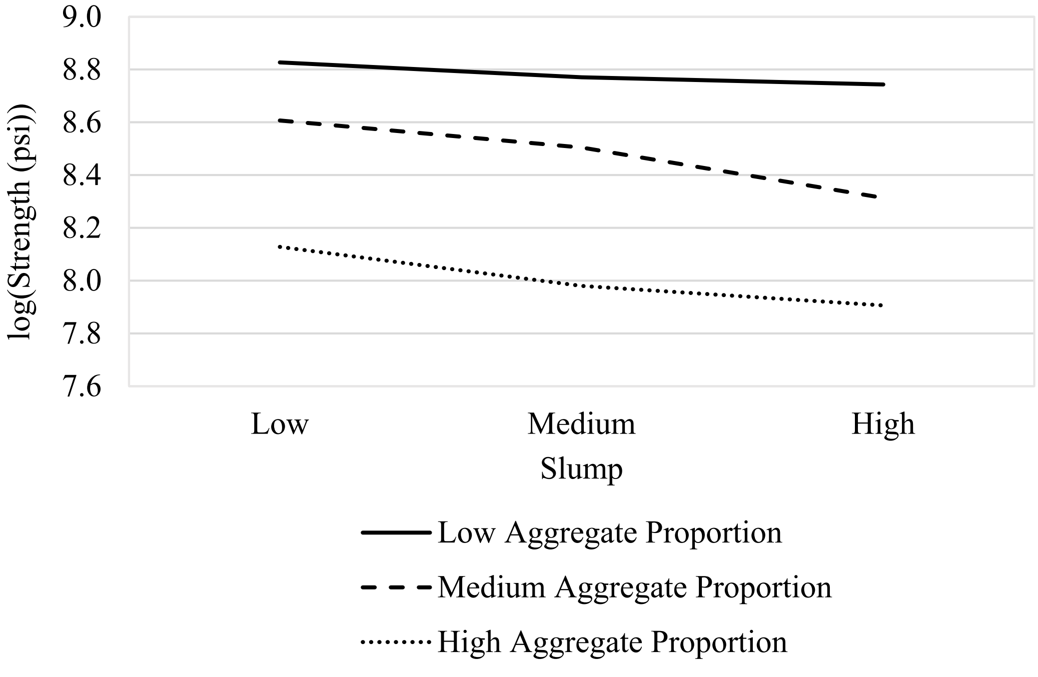

Figure 4-5. Two-Way Interaction between Slump and Aggregate Proportion

Figure 4-6 also shows that, as the aggregate proportion decreases, the compressive strength difference between slump levels decreases and the compressive strength values begin to converge. The observed tendency indicates that, with a lower aggregate proportion, the slump of a lightweight grout mixture has less of an effect on the compressive strength of the mixture.

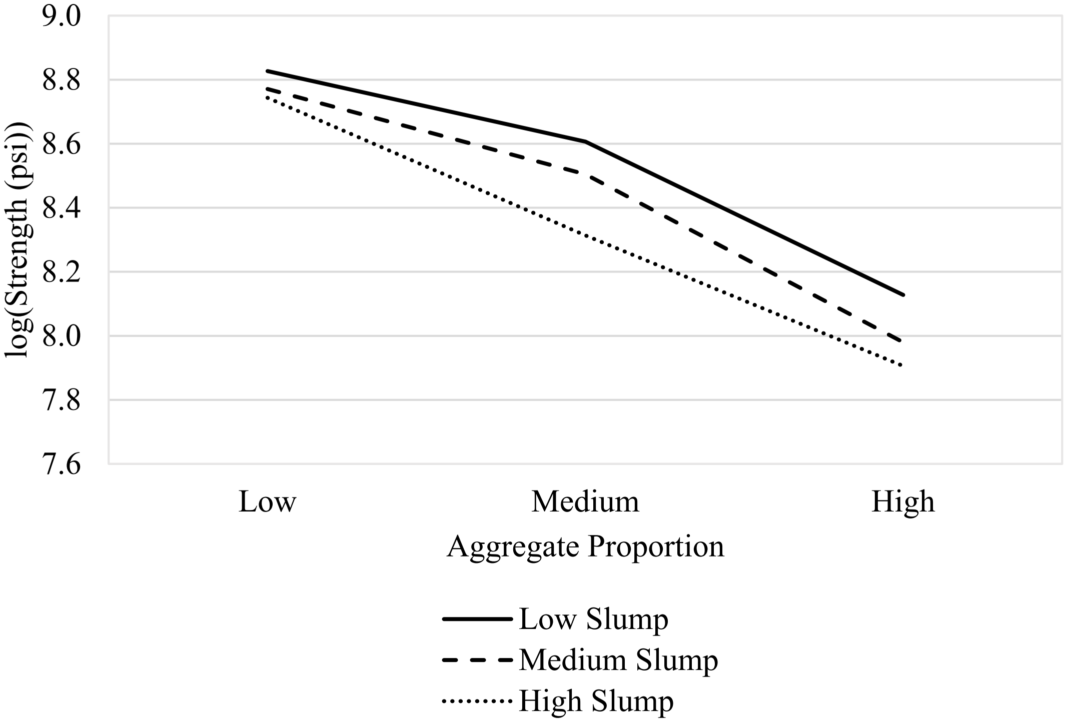

Figure 4-6. Two-Way Interaction between Aggregate Proportion and Slump

Similarly, as shown in Figure 4-7, as the aggregate proportion decreases, the effect of soaking on the compressive strength of the mixture decreases as well, with the two levels of soaking converging at the low aggregate proportion. The other two-way interaction plots are shown in Appendix C.

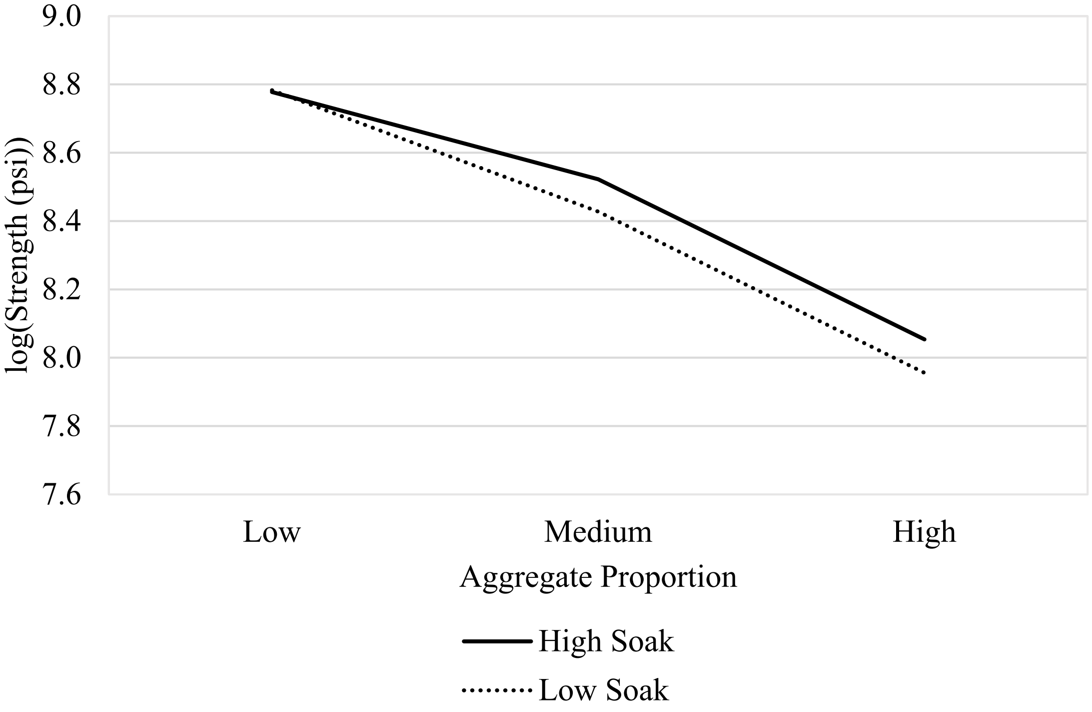

Figure 4-7. Two-Way Interaction between Aggregate Proportion and Soaking

4.4.3 Three-Way Interaction

A three-way interaction is essentially a two-way interaction being affected by a third variable. The interaction between aggregate proportion and slump at low and high soaking are shown in Figures 4-8 and 4-9. The three-way interactions shown are very similar to the two-way interaction shown in Figure 4-6 because they include the same interaction between aggregate proportion and slump; the difference is that the three-way interaction includes soaking level.

The main difference between the low and high soaking levels, shown in Figures 4-8 and 4-9, respectively, is that the slumps converge at the low aggregate proportion for the mixtures with a high soak level. This indicates that soaking the lightweight aggregate allows slump to retain its effect on compressive strength even as the aggregate proportion changes. In other words, at low aggregate proportion and with soaked aggregate, slump does not affect the compressive strength of the mixture. This observed relationship demonstrates the need for a three-way interaction in the model.

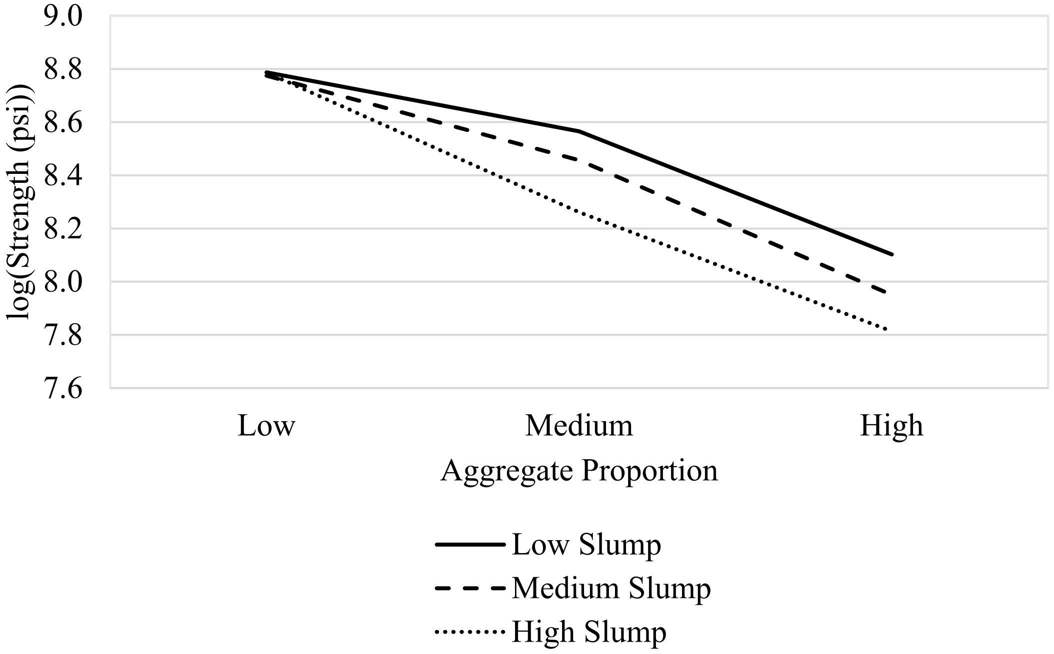

Figure 4-8. Three-Way Interaction between Aggregate Proportion and Slump for Low Soak

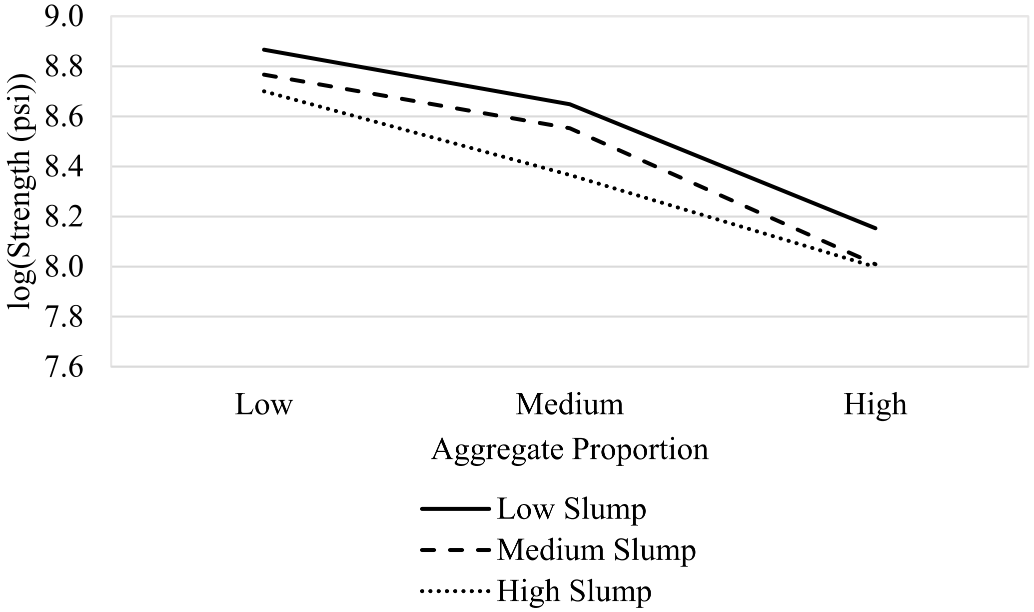

Figure 4-9. Three-Way Interaction between Aggregate Proportion and Slump for High Soak

Evidence provided by the other graphical representations of the least squares means of the three-way interaction support the aforementioned observations. All least squares means are given in Appendix C.

In addition to the basic graphical depiction of the three-way interaction least squares means shown in Figures 4-8 and 4-9, a Tukey-Kramer test was performed on the three-way interaction. The results are shown in Table 4-5. These results demonstrate where there are significant differences between sample means. When two mixtures share a letter (assigned in order of least squares means), they are not statistically significantly different from each other.

Table 4-5. Tukey-Kramer Test

Mixture												Log(Strength (psi))
LLH	A											8.866
LLL	A	B										8.787
LHL	A	B										8.786
LML	A	B										8.774
LMH		B										8.767
LHH		B	C									8.700
MLH			C	D								8.648
MLL				D								8.565
MMH				D	E							8.552
MML					E	F						8.456
MHH						F						8.366
MHL							G					8.261
HLH								H				8.153
HLL								H	I			8.103
HMH									I	J		8.009
HHH										J		7.998
HML										J		7.950
HHL											K	7.814

To better depict the tabular data shown in Table 4-5, shaded shapes were overlaid onto a graphical representation of the raw data to illustrate which mixtures did not have evidence to show that they were statistically significantly different from each other. The overlaid raw data are shown in Figures 4-10 through 4-15, each figure representing a letter from Table 4-5.

Letters C, F, and I were excluded because more than one variable was different between the mixtures in these categories and the comparisons were deemed irrelevant. Letters G and K were also excluded because only one mixture is under each of these two categories as they were statistically significantly different from all other mixtures in this experiment.

According to the results shown in Figures 4-10 and 4-11, there is no evidence to show that there is a statistically significant difference in compressive strengths between the three slump levels at the low aggregate proportion. Figures 4-10 and 4-11 also demonstrate that soaking has little effect on compressive strength at the low aggregate proportion.

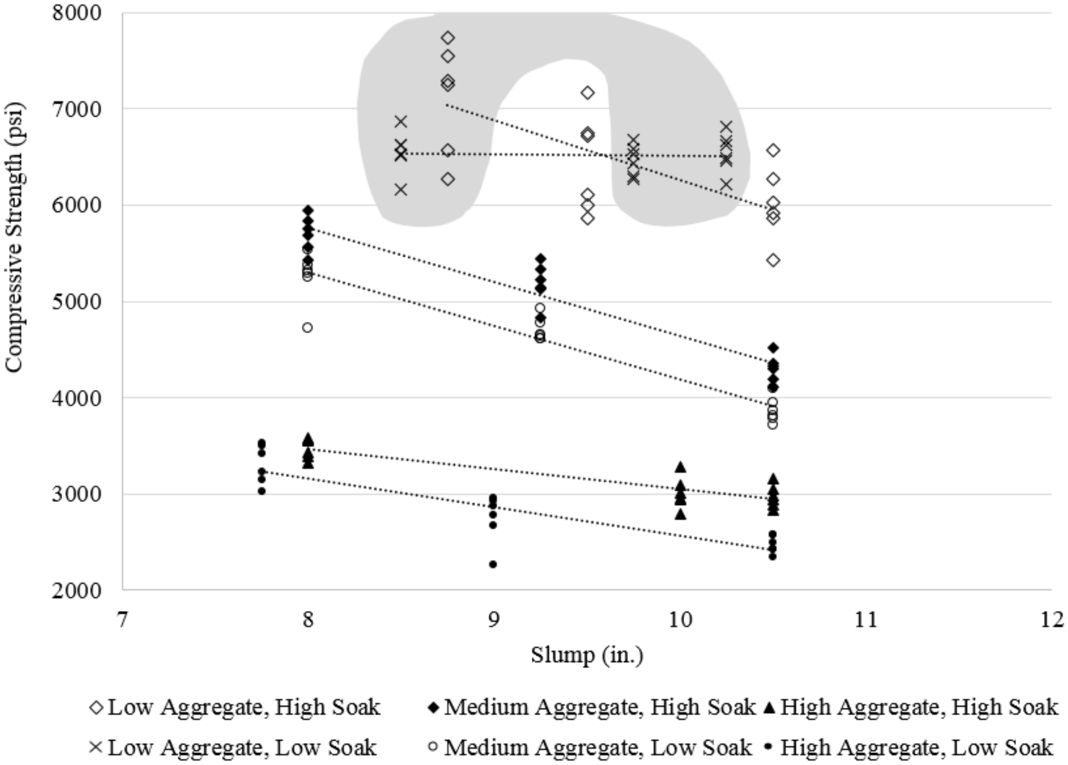

Figure 4-10. Tukey-Kramer Results, Letter A

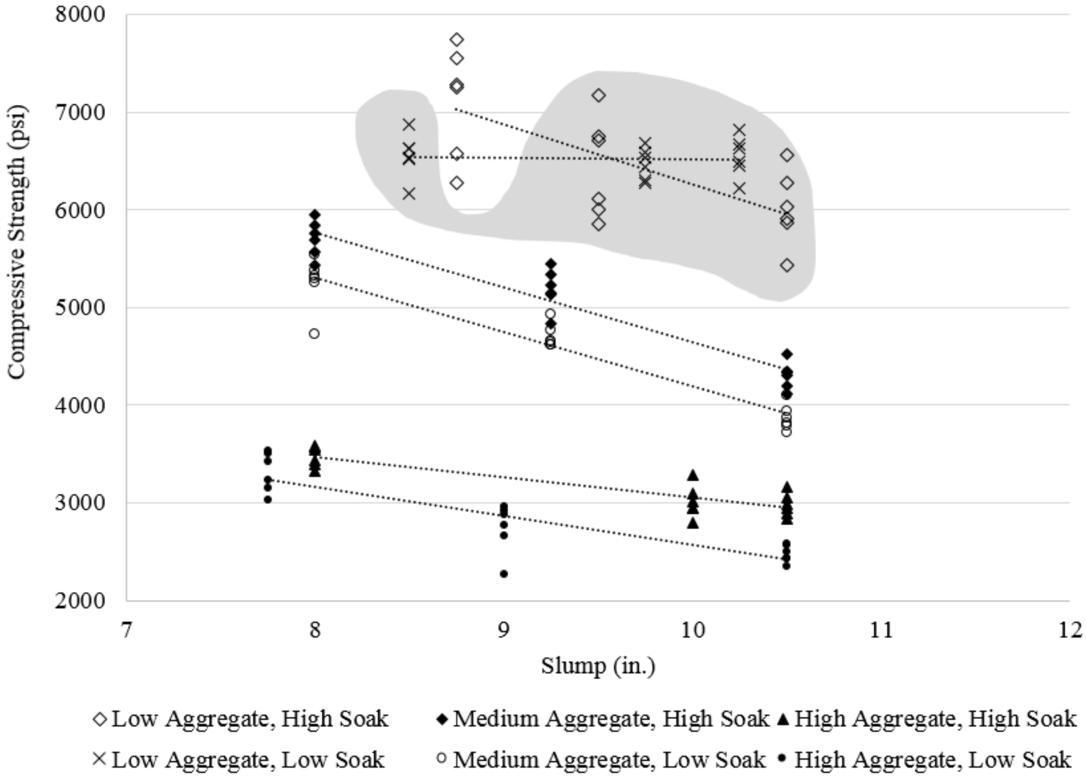

Figure 4-11. Tukey-Kramer Results, Letter B

Figure 4-12 shows there is not sufficient evidence to say that slump and soaking affect the compressive strength at the medium aggregate proportion. Figure 4-13 demonstrates that soaking makes no statistically significant difference at the medium aggregate proportion and medium slump. The mixtures at the high slump for the medium aggregate proportion are significantly affected by soaking. Figures 4-12 and 4-13 also show that slump has a statistically significant effect on compressive strength of the medium aggregate mixtures when the mixture was unsoaked. Slump also has a statistically significant effect when the slumps were high. Figures 4-14 and 4-15 show that mixtures with the high aggregate proportion are unaffected by soaking at the low and medium slumps.

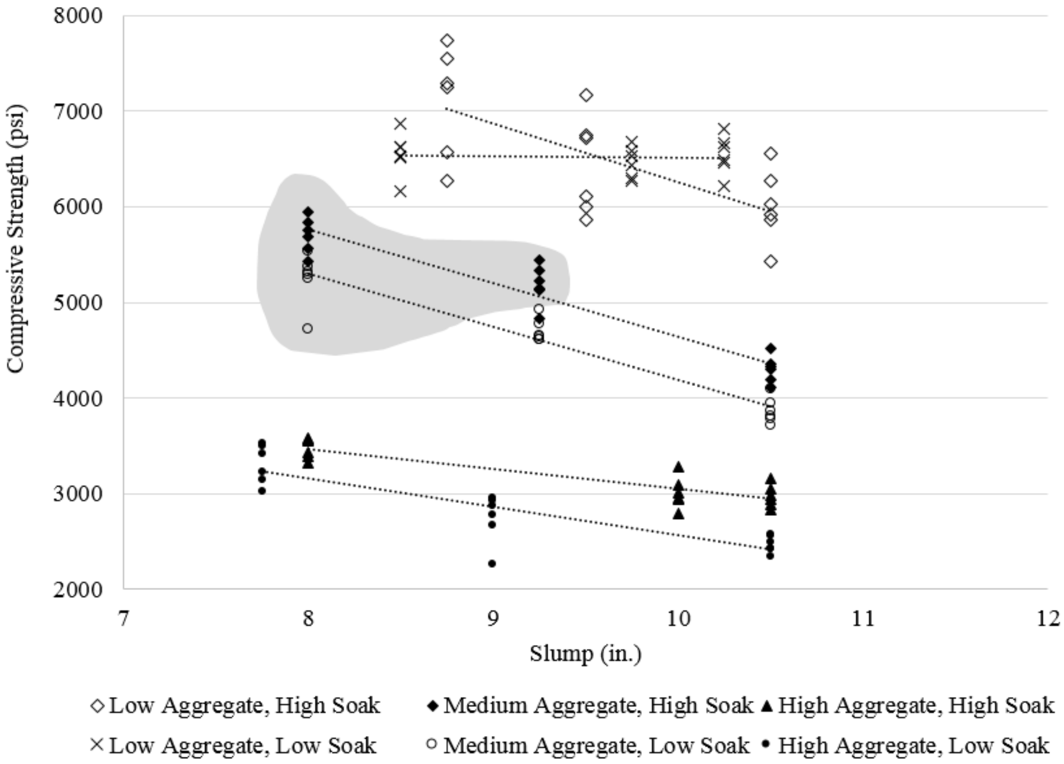

Figure 4-12. Tukey-Kramer Results, Letter D

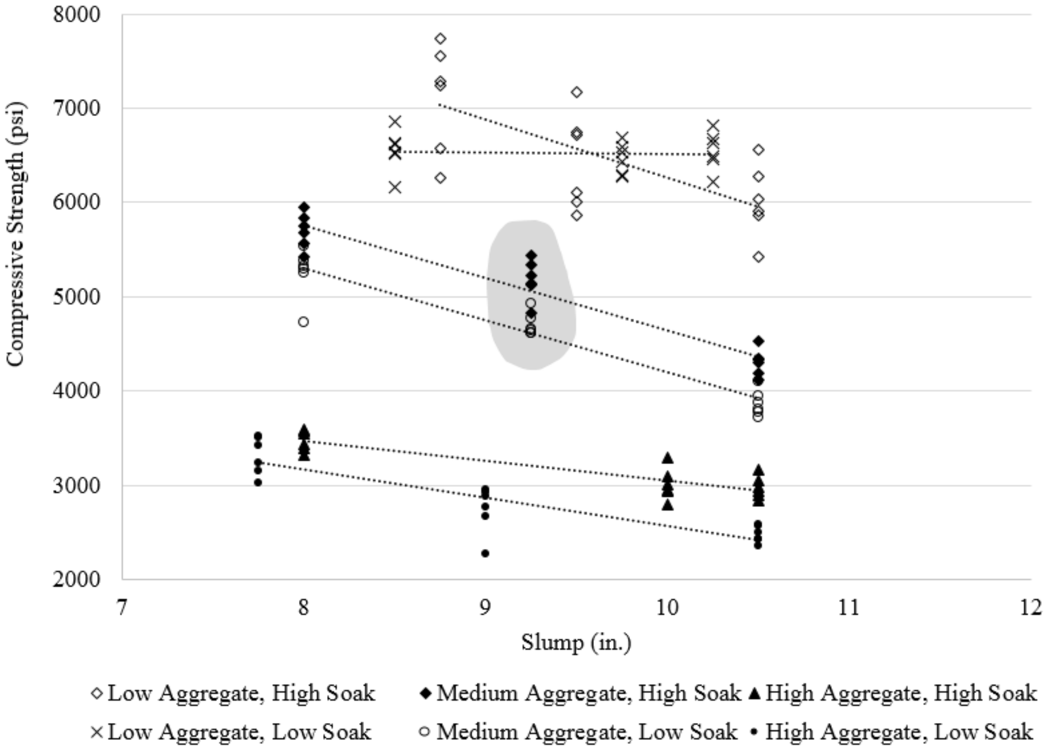

Figure 4-13. Tukey-Kramer Results, Letter E

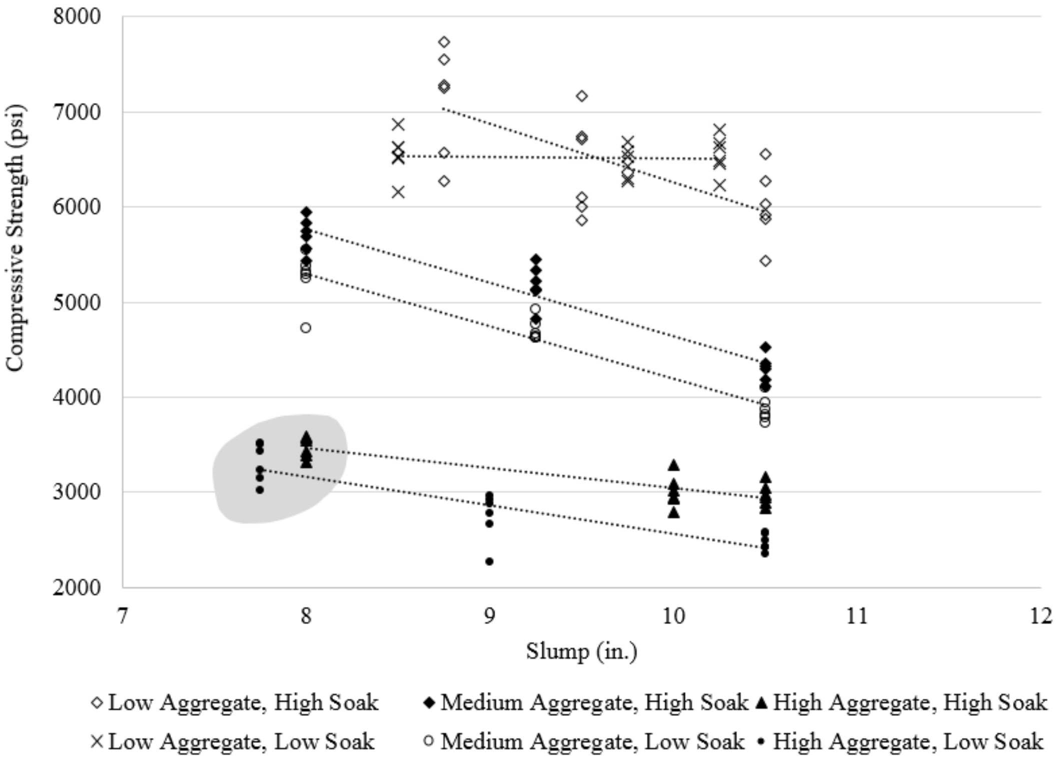

Figure 4-14. Tukey-Kramer Results, Letter H

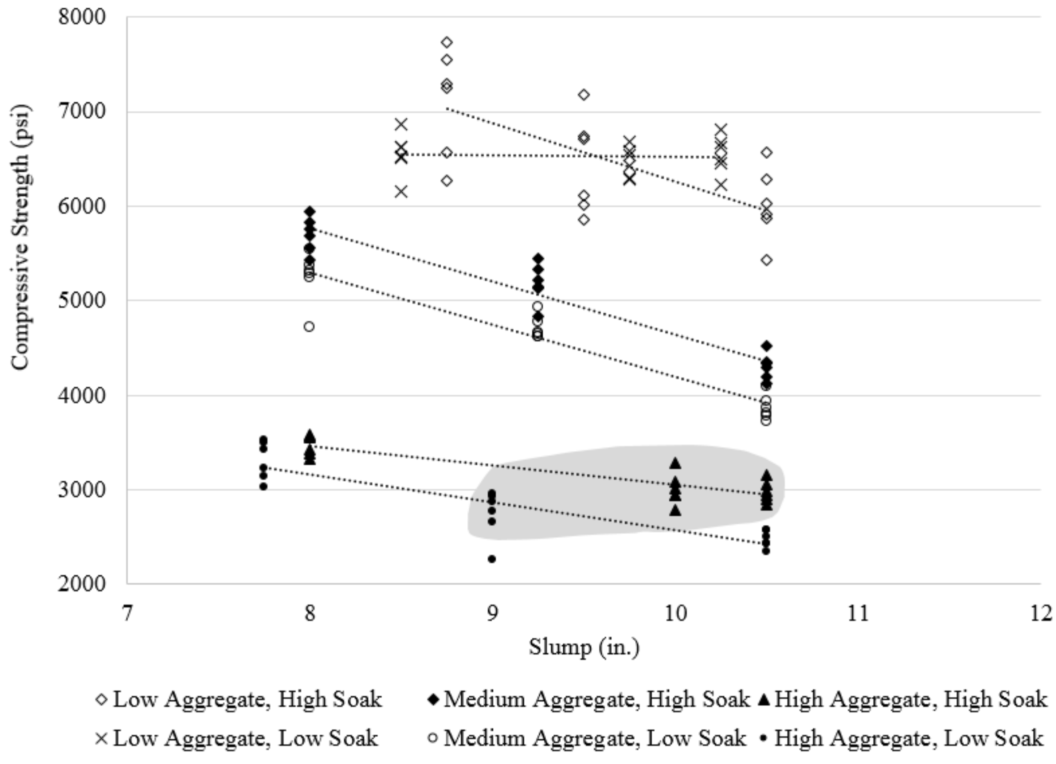

Figure 4-15. Tukey-Kramer Results, Letter J

Overall, soaking only makes a statistically significant difference for the highest slump and the medium or high aggregate proportions. Slump only makes a significant difference at the medium and high aggregate proportions when the mixture is unsoaked. In regards to aggregate proportion, there is always a statistically significant difference between mean compressive strengths of samples with different aggregate proportions when other variables remain unchanged.

4.5 Failure Modes

Failure modes are generally analyzed with concrete cylinder samples and masonry prisms, but there is no reference chart for grout sample failure modes. Instead, as an estimate, the masonry prism failure mode diagram from the ASTM C1314 standard (Standard Test Method for Compressive Strength of Masonry Prisms), shown in Figure 4-16, was used to determine if there were any discernable patterns in failure mode.

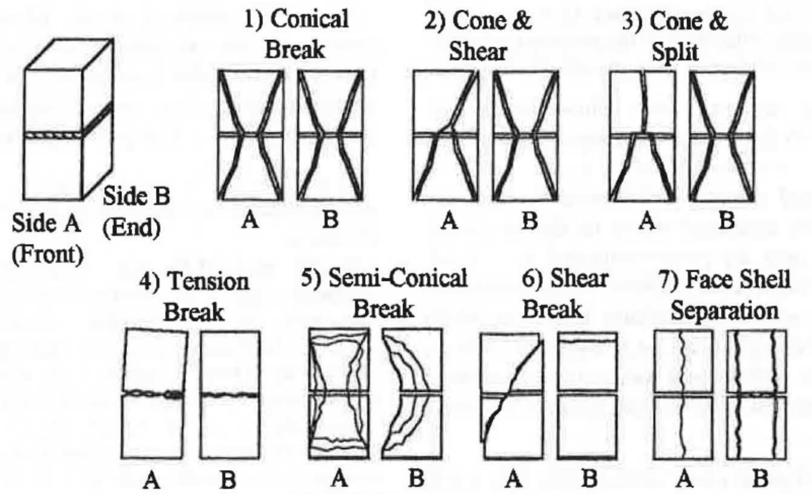

Figure 4-16. Masonry Prism Failure Modes

Mixtures and their corresponding failure modes were sorted by aggregate proportion level, slump level, and soaking level as shown in Tables 4-6, 4-7, and 4-8, respectively. Table 4-6 shows that there are more conical (1) breaks at the high aggregate proportion and more cone and shear (2) breaks at the low aggregate proportion. During testing, very sudden breaks occurred in mixtures with the low aggregate proportion, and more gradual breaks occurred in mixtures with the high aggregate proportion. The occurrences of other types of breaks are not common enough to identify any substantial patterns in Tables 4-6, 4-7, and 4-8.

Table 4-6. Experimental Grout Failure Modes, Aggregate Comparison

Aggregate Proportion	Mixture/Specimen	1	2	3	4	5	6
High	HHH	2	2	1	6	1	2
	HHL	1	6	1	1	1	2
	HMH	1	6	2	1	1	1
	HML	2	6	1	6	2	1
	HLH	1	2	2	1	6	1
	HLL	2	1	1	2	1	1
Medium	MHH	1	1	6	2	1	1
	MHL	2	2	1	2	1	6
	MMH	2	6	1	1	1	6
	MML	6	2	6	2	6	2
	MLH	2	2	2	6	6	2
	MLL	2	1	6	2	6	1
Low	LHH	1	7	3	2	3	6
	LHL	2	2	2	2	2	2
	LMH	2	1	2	6	6	1
	LML	2	2	2	2	6	1
	LLH	2	1	1	2	2	2
	LLL	2	2	2	2	2	2

Table 4-7 shows that there are relatively similar amounts of conical (1) breaks and cone and shear (2) breaks at the high and medium slump levels. At the low slump level, there are more cone and shear (2) breaks. As shown in Table 4-8, there are more cone and shear (2) breaks at the low level of soaking. Pictures of the typical modes of failure are presented in Appendix D.

Table 4-7. Experimental Grout Failure Modes, Slump Comparison

Slump	Mixture/Specimen	1	2	3	4	5	6
High	HHH	2	2	1	6	1	2
	HHL	1	6	1	1	1	2
	MHH	1	1	6	2	1	1
	MHL	2	2	1	2	1	6
	LHH	1	7	3	2	3	6
	LHL	2	2	2	2	2	2
Medium	HMH	1	6	2	1	1	1
	HML	2	6	1	6	2	1
	MMH	2	6	1	1	1	6
	MML	6	2	6	2	6	2
	LMH	2	1	2	6	6	1
	LML	2	2	2	2	6	1
Low	HLH	1	2	2	1	6	1
	HLL	2	1	1	2	1	1
	MLH	2	2	2	6	6	2
	MLL	2	1	3	2	6	1
	LLH	2	1	1	2	2	2
	LLL	2	2	2	2	2	2

Table 4-8. Experimental Grout Failure Modes, Soak Comparison

Soak	Mixture/Specimen	1	2	3	4	5	6
High	HHH	2	2	1	6	1	2
	HMH	1	6	2	1	1	1
	HLH	1	2	2	1	6	1
	MHH	1	1	6	2	1	1
	MMH	2	6	1	1	1	6
	MLH	2	2	2	6	6	2
	LHH	1	7	3	2	3	6
	LMH	2	1	2	6	6	1
	LLH	2	1	1	2	2	2
Low	HHL	1	6	1	1	1	2
	HML	2	6	1	6	2	1
	HLL	2	1	1	2	1	1
	MHL	2	2	1	2	1	6
	MML	6	2	6	2	6	2
	MLL	2	1	3	2	6	1
	LHL	2	2	2	2	2	2
	LML	2	2	2	2	6	1
	LLL	2	2	2	2	2	2

4.6 Summary

The grout compressive strength response variable was logarithmically transformed, and the final statistical model accounted for a three-way interaction between the three explanatory variables. Trends indicate that the effects of soaking and slump on the grout compressive strength decrease as the aggregate proportion decreases. In addition, specimens experienced cone and shear (2) breaks more at the low slump, low aggregate proportion, and low soaking level.

5 INTERPRETATION OF RESULTS

First and foremost, every measured compressive strength result from this experiment program was above the required 2000 psi minimum. Such results demonstrate that lightweight grout indeed reaches a compressive strength comparable to that of normal-weight grout. The highest aggregate proportion considered by ASTM C476 provides an average safety factor of 3.0 for normal-weight grout (Tanner 2014) and, as described herein, for lightweight grout as well. The higher aggregate proportions used in this experimental program could be adopted into an ASTM standard, but the factor of safety would be lower than that obtained from the mixtures with lower aggregate proportions.

The measured slumps never reached a value higher than 10.50 in., which limits the slump domain to which these results are applicable to 7.75 to 10.50 in. instead of the standard 8 to 11 in. To verify that 11 in. slump mixtures still accomplish the necessary compressive strength, further research is required.

All variables examined in this research have a statistically significant effect on grout compressive strength. However, statistical significance is not the same as practical importance. Two-way and three-way interaction analyses show that soaking has less of an effect on the grout compressive strength for lower aggregate proportions. Since the lowest aggregate proportion of this experiment, which was 3 parts aggregate to 1 part cement, is the highest proportion in the recommended range of ASTM C476, there is not sufficient evidence to state that the addition of soaking cycles affect the grout compressive strength when using aggregate proportions within the advised range. There are other pre-wetting options or longer pre-wetting times that could still be industrially feasible. There are also other potential benefits of pre-wetting lightweight aggregate such as aggregate-cement bond improvement, tensile strength gain, and shrinkage prevention, but these facets were not explored in this experiment. Future research should investigate other pre-wetting options and/or pre-wetting times.

All results of this analysis show that slump and aggregate proportion make a statistically significant—and likely practically important—difference in the grout compressive strength of the sample, which corroborates the fact that aggregate proportion and water content influence the compressive strength of a sample (Mindess 2003).

The results of the failure mode analysis show that cone and shear (2) breaks occurred most often in mixtures with low aggregate proportion, low slump, or low soaking. These results could possibly be explained by the fact that all of these levels of variables are correlated with lower water contents. In other words, a mixture with the low aggregate proportion contains less of the highly-absorptive lightweight aggregate, which in turn means a lower water content; a mixture with the low slump level requires less water to achieve the target slump, and less water is needed to saturate the aggregate for a mixture with the low soaking level. Most likely, the lower water contents of these variable levels create a more brittle mixture and increase the likelihood of the specimens to experience the cone and shear (2) failure mode.

The results obtained herein are intended to provide a starting point for future research such as determining the tensile strength of lightweight grout, determining the development length of reinforcement embedded in lightweight grout, and standardizing a lightweight grout mixture design procedure.

6 CONCLUSION

The purpose of this research was to determine a repeatable mixture design enabling the use of lightweight grout while obtaining the required minimum grout compressive strength. The results indicate that the standard for mixing normal-weight grout (ASTM C476) is also adequate for mixing lightweight grout.

The most important conclusion of this research is that the compressive strength of lightweight aggregate more than reaches the minimum required strength of 2000 psi when analyzing samples within the suggested aggregate proportion and slump ranges.

In this experiment, soaking the aggregate before mixing had a statistically significant effect on the compressive strength of a sample, but that effect decreased as the aggregate proportion decreased. When used within the aggregate proportion and slump ranges suggested by ASTM, there is insufficient evidence to show that soaking will have a perceivable effect on the compressive strength of a sample.

A model was developed using a three-way interaction between the following three categorical explanatory variables: aggregate proportion, slump, and soaking. The response variable was the logarithmically transformed compressive strength. The model was used to show that the main effects and interactions of all three variables have a statistically significant effect on the compressive strength of a lightweight grout mixture.

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APPENDIX A. MATERIAL PROPERTIES

Table A-1 shows the various material properties of all specimens tested; the mixtures are displayed in order of testing. W/C ratio is the water-cement ratio. The unit weight is measured in weight of grout over volume of grout and cement content is measured in weight of cement over volume of grout.

Table A-1. Material Properties

Mixture	Specimen	Aggregate Proportion	Slump Target (in.)	Slump (in.)	Soaking Cycles	Unit Weight (lb/ft^3)	Cement Content (lb/ft^3)	W/C Ratio	Comp. Strength (psi)
LHH	1	3	10.75	10.5	2	108.29	28.81	0.892	6278
LHH	2	3	10.75	10.5	2	108.25	28.81	0.892	5912
LHH	3	3	10.75	10.5	2	108.57	28.81	0.892	6563
LHH	4	3	10.75	10.5	2	108.74	28.81	0.892	6031
LHH	5	3	10.75	10.5	2	106.81	28.81	0.892	5429
LHH	6	3	10.75	10.5	2	107.63	28.81	0.892	5870
HMH	1	4.75	9.5	10	2	103.45	19.67	1.342	2940
HMH	2	4.75	9.5	10	2	103.34	19.67	1.342	3014
HMH	3	4.75	9.5	10	2	103.86	19.67	1.342	2790
HMH	4	4.75	9.5	10	2	104.82	19.67	1.342	3286
HMH	5	4.75	9.5	10	2	102.53	19.67	1.342	2950
HMH	6	4.75	9.5	10	2	104.37	19.67	1.342	3091
HLH	1	4.75	8.25	8	2	102.85	20.38	1.231	3549
HLH	2	4.75	8.25	8	2	103.81	20.38	1.231	3434
HLH	3	4.75	8.25	8	2	105.38	20.38	1.231	3570
HLH	4	4.75	8.25	8	2	103.85	20.38	1.231	3586
HLH	5	4.75	8.25	8	2	104.32	20.38	1.231	3324
HLH	6	4.75	8.25	8	2	102.83	20.38	1.231	3388

Table A-1. Continued

Mixture	Specimen	Aggregate Proportion	Slump Target (in.)	Slump (in.)	Soaking Cycles	Unit Weight (lb/ft^3)	Cement Content (lb/ft^3)	W/C Ratio	Comp. Strength (psi)
HML	1	4.75	9.5	9	0	101.72	20.22	1.255	2666
HML	2	4.75	9.5	9	0	102.89	20.22	1.255	2877
HML	3	4.75	9.5	9	0	101.03	20.22	1.255	2924
HML	4	4.75	9.5	9	0	103.68	20.22	1.255	2955
HML	5	4.75	9.5	9	0	102.41	20.22	1.255	2263
HML	6	4.75	9.5	9	0	104.88	20.22	1.255	2774
LHL	1	3	10.75	10.25	0	106.81	28.81	0.826	6455
LHL	2	3	10.75	10.25	0	107.81	28.81	0.826	6224
LHL	3	3	10.75	10.25	0	106.92	28.81	0.826	6671
LHL	4	3	10.75	10.25	0	107.57	28.81	0.826	6491
LHL	5	3	10.75	10.25	0	107.57	28.81	0.826	6628
LHL	6	3	10.75	10.25	0	108.18	28.81	0.826	6814
MLL	1	3.875	8.25	8	0	103.24	24.98	0.945	5322
MLL	2	3.875	8.25	8	0	105.14	24.98	0.945	5379
MLL	3	3.875	8.25	8	0	103.48	24.98	0.945	5293
MLL	4	3.875	8.25	8	0	106.51	24.98	0.945	5249
MLL	5	3.875	8.25	8	0	104.05	24.98	0.945	4726
MLL	6	3.875	8.25	8	0	105.80	24.98	0.945	5544
HHL	1	4.75	10.75	10.5	0	101.11	19.44	1.379	2426
HHL	2	4.75	10.75	10.5	0	103.12	19.44	1.379	2569
HHL	3	4.75	10.75	10.5	0	102.37	19.44	1.379	2429
HHL	4	4.75	10.75	10.5	0	104.46	19.44	1.379	2498
HHL	5	4.75	10.75	10.5	0	104.35	19.44	1.379	2581
HHL	6	4.75	10.75	10.5	0	103.71	19.44	1.379	2350
LML	1	3	9.5	9.75	0	106.28	29.81	0.819	6277
LML	2	3	9.5	9.75	0	107.74	29.81	0.819	6535
LML	3	3	9.5	9.75	0	105.66	29.81	0.819	6297
LML	4	3	9.5	9.75	0	107.66	29.81	0.819	6685
LML	5	3	9.5	9.75	0	106.29	29.81	0.819	6432
LML	6	3	9.5	9.75	0	108.12	29.81	0.819	6585
LLL	1	3	8.25	8.5	0	105.78	30.46	0.775	6628
LLL	2	3	8.25	8.5	0	107.12	30.46	0.775	6621
LLL	3	3	8.25	8.5	0	106.38	30.46	0.775	6866
LLL	4	3	8.25	8.5	0	106.61	30.46	0.775	6531
LLL	5	3	8.25	8.5	0	106.79	30.46	0.775	6516
LLL	6	3	8.25	8.5	0	106.99	30.46	0.775	6161

Table A-1. Continued

Mixture	Specimen	Aggregate Proportion	Slump Target (in.)	Slump (in.)	Soaking Cycles	Unit Weight (lb/ft^3)	Cement Content (lb/ft^3)	W/C Ratio	Comp. Strength (psi)
MML	1	3.875	9.5	9.25	0	104.32	24.38	1.007	4620
MML	2	3.875	9.5	9.25	0	106.65	24.38	1.007	4770
MML	3	3.875	9.5	9.25	0	105.25	24.38	1.007	4928
MML	4	3.875	9.5	9.25	0	106.45	24.38	1.007	4618
MML	5	3.875	9.5	9.25	0	106.27	24.38	1.007	4643
MML	6	3.875	9.5	9.25	0	105.34	24.38	1.007	4661
MMH	1	3.875	9.5	9.25	2	105.96	23.97	1.051	5222
MMH	2	3.875	9.5	9.25	2	105.88	23.97	1.051	5141
MMH	3	3.875	9.5	9.25	2	105.69	23.97	1.051	5126
MMH	4	3.875	9.5	9.25	2	106.40	23.97	1.051	5333
MMH	5	3.875	9.5	9.25	2	105.84	23.97	1.051	5442
MMH	6	3.875	9.5	9.25	2	106.35	23.97	1.051	4830
LMH	1	3	9.5	9.5	2	107.60	29.25	0.860	6715
LMH	2	3	9.5	9.5	2	108.12	29.25	0.860	5859
LMH	3	3	9.5	9.5	2	106.91	29.25	0.860	6006
LMH	4	3	9.5	9.5	2	108.65	29.25	0.860	6109
LMH	5	3	9.5	9.5	2	108.47	29.25	0.860	7174
LMH	6	3	9.5	9.5	2	108.58	29.25	0.860	6745
MHH	1	3.875	10.75	10.5	2	104.24	23.20	1.137	4189
MHH	2	3.875	10.75	10.5	2	104.44	23.20	1.137	4297
MHH	3	3.875	10.75	10.5	2	105.26	23.20	1.137	4330
MHH	4	3.875	10.75	10.5	2	105.68	23.20	1.137	4522
MHH	5	3.875	10.75	10.5	2	105.98	23.20	1.137	4118
MHH	6	3.875	10.75	10.5	2	105.28	23.20	1.137	4351
LLH	1	3	8.25	8.75	2	107.29	29.92	0.812	7736
LLH	2	3	8.25	8.75	2	107.35	29.92	0.812	7286
LLH	3	3	8.25	8.75	2	106.10	29.92	0.812	6569
LLH	4	3	8.25	8.75	2	107.62	29.92	0.812	6269
LLH	5	3	8.25	8.75	2	107.14	29.92	0.812	7552
LLH	6	3	8.25	8.75	2	107.38	29.92	0.812	7248
HLL	1	4.75	8.25	7.75	0	103.60	20.30	1.243	3424
HLL	2	4.75	8.25	7.75	0	104.44	20.30	1.243	3522
HLL	3	4.75	8.25	7.75	0	104.24	20.30	1.243	3232
HLL	4	4.75	8.25	7.75	0	104.05	20.30	1.243	3502
HLL	5	4.75	8.25	7.75	0	103.07	20.30	1.243	3022
HLL	6	4.75	8.25	7.75	0	104.44	20.30	1.243	3147

Table A-1. Continued

Mixture	Specimen	Aggregate Proportion	Slump Target (in.)	Slump (in.)	Soaking Cycles	Unit Weight (lb/ft^3)	Cement Content (lb/ft^3)	W/C Ratio	Comp. Strength (psi)
MHL	1	3.875	10.75	10.5	0	104.20	23.00	1.161	3781
MHL	2	3.875	10.75	10.5	0	105.03	23.00	1.161	3723
MHL	3	3.875	10.75	10.5	0	105.06	23.00	1.161	4101
MHL	4	3.875	10.75	10.5	0	105.03	23.00	1.161	3809
MHL	5	3.875	10.75	10.5	0	105.10	23.00	1.161	3943
MHL	6	3.875	10.75	10.5	0	105.39	23.00	1.161	3871
HHH	1	4.75	10.75	10.5	2	104.85	19.31	1.400	2941
HHH	2	4.75	10.75	10.5	2	104.61	19.31	1.400	2982
HHH	3	4.75	10.75	10.5	2	104.55	19.31	1.400	3053
HHH	4	4.75	10.75	10.5	2	104.67	19.31	1.400	3161
HHH	5	4.75	10.75	10.5	2	104.14	19.31	1.400	2894
HHH	6	4.75	10.75	10.5	2	103.07	19.31	1.400	2838
MLH	1	3.875	8.25	8	2	104.17	24.85	0.958	5947
MLH	2	3.875	8.25	8	2	104.60	24.85	0.958	5428
MLH	3	3.875	8.25	8	2	103.51	24.85	0.958	5751
MLH	4	3.875	8.25	8	2	104.70	24.85	0.958	5832
MLH	5	3.875	8.25	8	2	104.10	24.85	0.958	5686
MLH	6	3.875	8.25	8	2	105.15	24.85	0.958	5564

APPENDIX B. GROUT MIXTURE DESIGNS

Grout mixtures were designed according to the assigned aggregate proportion with a target volume of 0.65 ft^3. Water for soaking the aggregate—or adding to aggregate but not soaking—was twice the water required for aggregate saturation to maximize absorption during the soaking cycles. While cement was added, additional water was added as required to meet the slump target for that particular mixture. An example mixture for sample MLH with the actual slump recorded (target slump was 8.25 in.) is shown in Table B-1.

Table B-1. Example Mixture Design

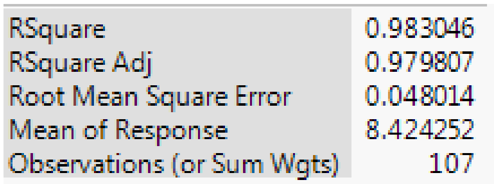
Test	MLH	Slump (in.)
Proportion	3.875	8
	Weight (lb)	Volume (ft^3)
Cement	16.8	0.086
Aggregate	38.1	0.332
Soak Water	14.5	0.232
Added Water	1.6	0.026
Total	71.0	0.676
Cement Content	24.9	lb cement/ft^3 grout

APPENDIX C. STATISTICAL ANALYSIS RESULTS

C.1 Statistical Analysis Software Output

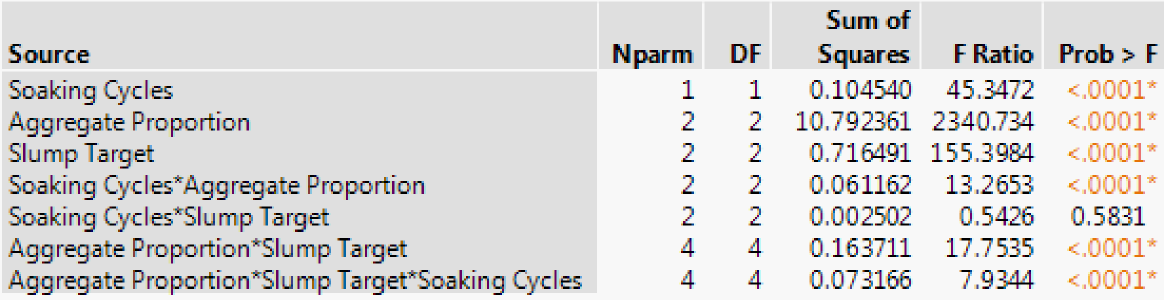
Tables C-1 and C-2 show the output of the final JMP statistical analysis. The R^2 value listed in Section 4.3.2 is shown in Table C-1. The *p*-values listed in Section 4.3.1 are shown in Table C-2.

Table C-1. Summary of Fit Output



RSquare	0.983046
RSquare Adj	0.979807
Root Mean Square Error	0.048014
Mean of Response	8.424252
Observations (or Sum Wgts)	107

Table C-2. Effect Test Output



Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Soaking Cycles	1	1	0.104540	45.3472	<.0001*
Aggregate Proportion	2	2	10.792361	2340.734	<.0001*
Slump Target	2	2	0.716491	155.3984	<.0001*
Soaking Cycles*Aggregate Proportion	2	2	0.061162	13.2653	<.0001*
Soaking Cycles*Slump Target	2	2	0.002502	0.5426	0.5831
Aggregate Proportion*Slump Target	4	4	0.163711	17.7535	<.0001*
Aggregate Proportion*Slump Target*Soaking Cycles	4	4	0.073166	7.9344	<.0001*

The least squares means used in Section 4.4 are shown in Table C-3. The left column describes the main effect or interaction, the center column indicates the variable level (for interactions the order of the levels corresponds to the order listed in the left column), and the right column presents the least squares mean of the main effect or interaction where the compressive strength has been logarithmically transformed.

Table C-3. Least Squares Mean Output

Variable/Interaction	Level	Least Squares Mean
Soaking Cycles	L	8.389
	H	8.451
Aggregate Proportion	L	8.780
	M	8.475
	H	8.005
Slump Target	L	8.520
	M	8.418
	H	8.321
Soaking Cycles*Aggregate Proportion	L*L	8.783
	L*M	8.428
	L*H	7.956
	H*L	8.778
	H*M	8.522
	H*H	8.053
Soaking Cycles*Slump Target	L*L	8.485
	L*M	8.394
	L*H	8.287
	H*L	8.556
	H*M	8.443
	H*H	8.355
Aggregate Proportion*Slump Target	L*L	8.827
	L*M	8.771
	L*H	8.743
	M*L	8.607
	M*M	8.504
	M*H	8.314
	H*L	8.128
	H*M	7.980
	H*H	7.906

Table C-3. Continued

Aggregate Proportion*Slump Target*Soaking Cycles	L*L*L	8.787
	L*L*H	8.866
	L*M*L	8.774
	L*M*H	8.767
	L*H*L	8.786
	L*H*H	8.700
	M*L*L	8.565
	M*L*H	8.648
	M*M*L	8.456
	M*M*H	8.552
	M*H*L	8.261
	M*H*H	8.366
	H*L*L	8.103
	H*L*H	8.153
	H*M*L	7.950
	H*M*H	8.009
	H*H*L	7.814
	H*H*H	7.998

C.2 Residual Plots

During model development, several models were explored, the residual plots of which are shown below in Figures C-1, C-2, C-3, and C-4. Figure C-1 shows the residual plot of the model before the response variable—compressive strength—was transformed logarithmically. This model includes the three categorical individual variables and their two-way interactions, but excludes the three-way interaction used in the final model. This model also includes the outlier which was eventually removed for the final model. There is a clear wave pattern that indicated there was some kind of interaction unaccounted for.

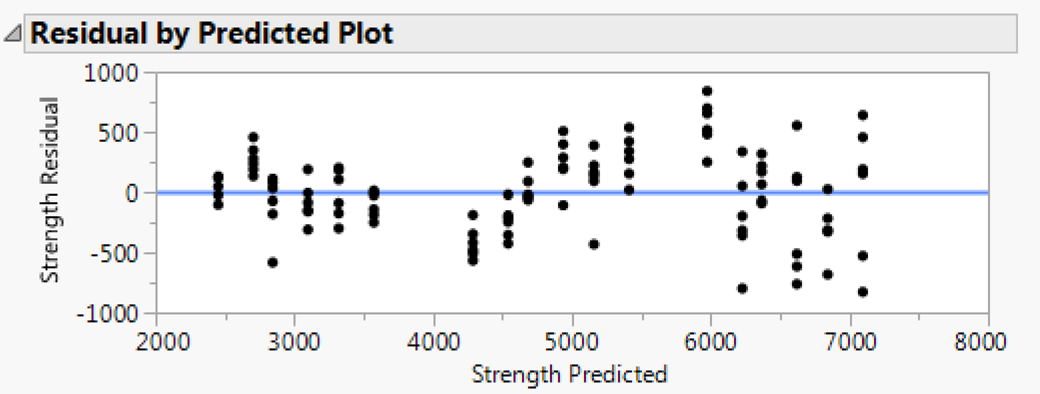


Figure C-1. Preliminary Model Residual Plot

Figure C-2 shows the residual plot of the model after the three-way interaction was accounted for. This model includes the outlier that was later removed, and the response variable was untransformed. Figure C-3 shows the residual plot of the model after the three-way interaction was accounted for and after the response variable was logarithmically transformed to minimize the variability in the residual plot.

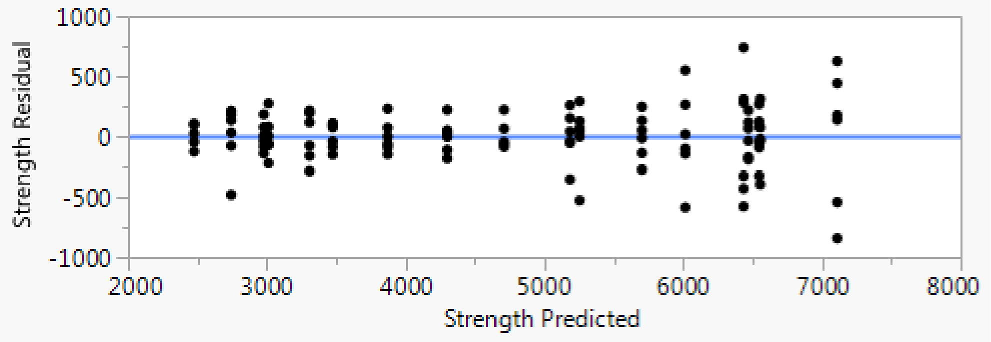


Figure C-2. Residual Plot with Three-way Interaction

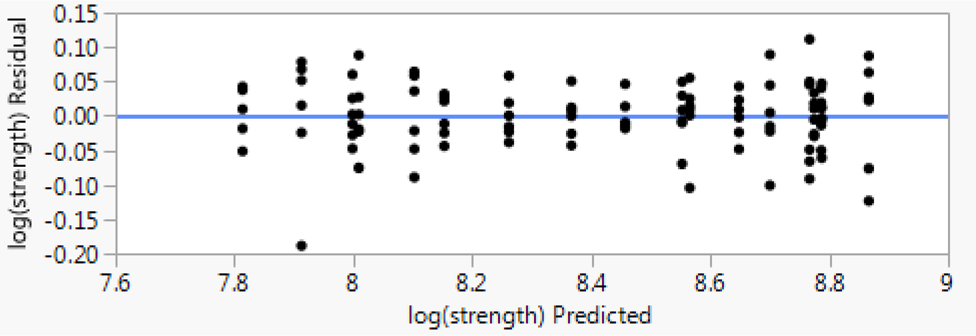


Figure C-3. Residual Plot with Transformed Response Variable

Figure C-4 show the residual plot of the final model. This includes the three-way interaction and the logarithmically transformed response variable and excludes the outlier.

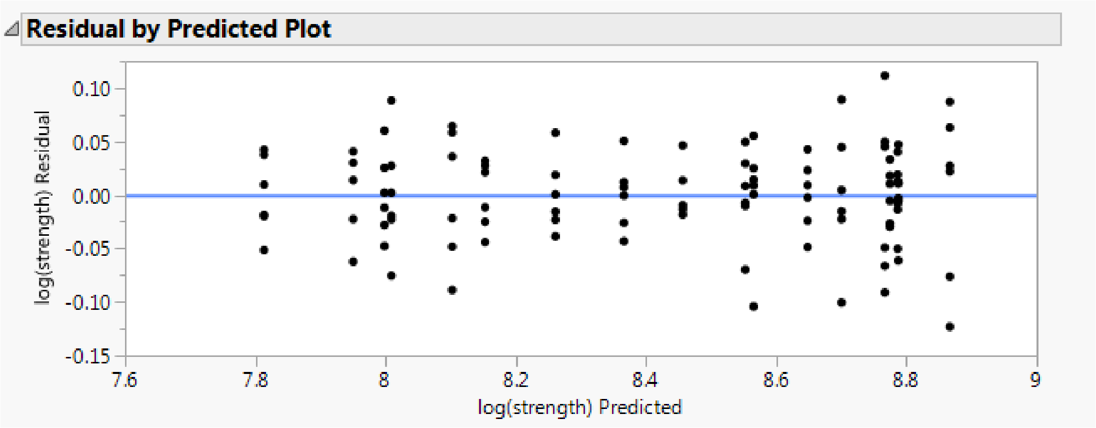


Figure C-4. Final Model Residual Plot

C.3 Two-Way Interactions

The remainder of the two-way interaction plots are shown in Figures C-5, C-6, and C-7. These figures support information given in Section 4.4.2.

Figures C-5 and C-6 demonstrate the only term in the final model that was not statistically significant (the *p*-value of the Soaking Cycles*Slump interaction was 0.5831 as shown in Table 4-4 in Section 4.3.2). These two figures show this lack of significance through the mild slopes and narrow spacing between variable levels.

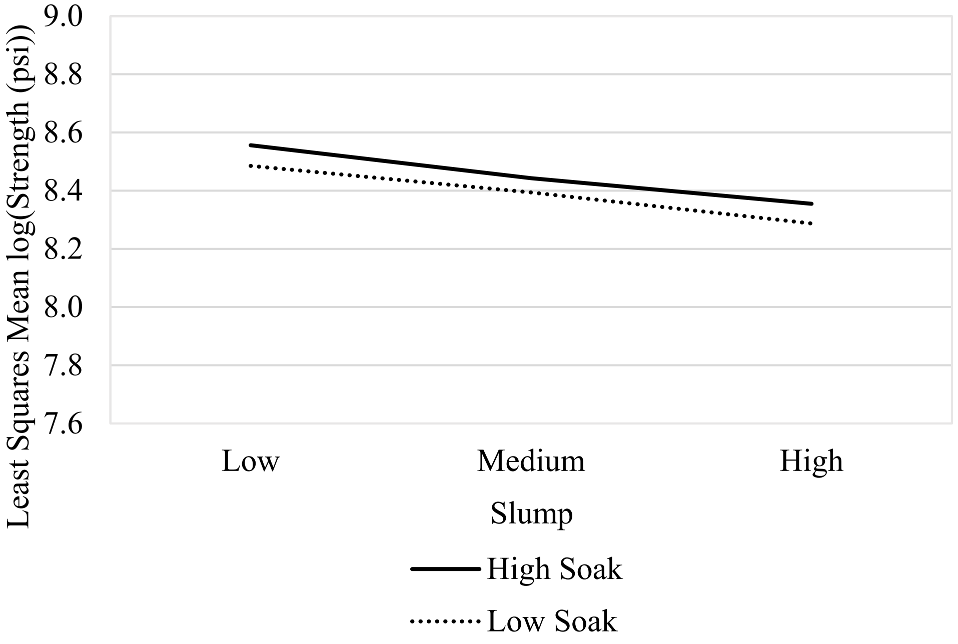


Figure C-5. Two-Way Interaction between Slump and Soaking

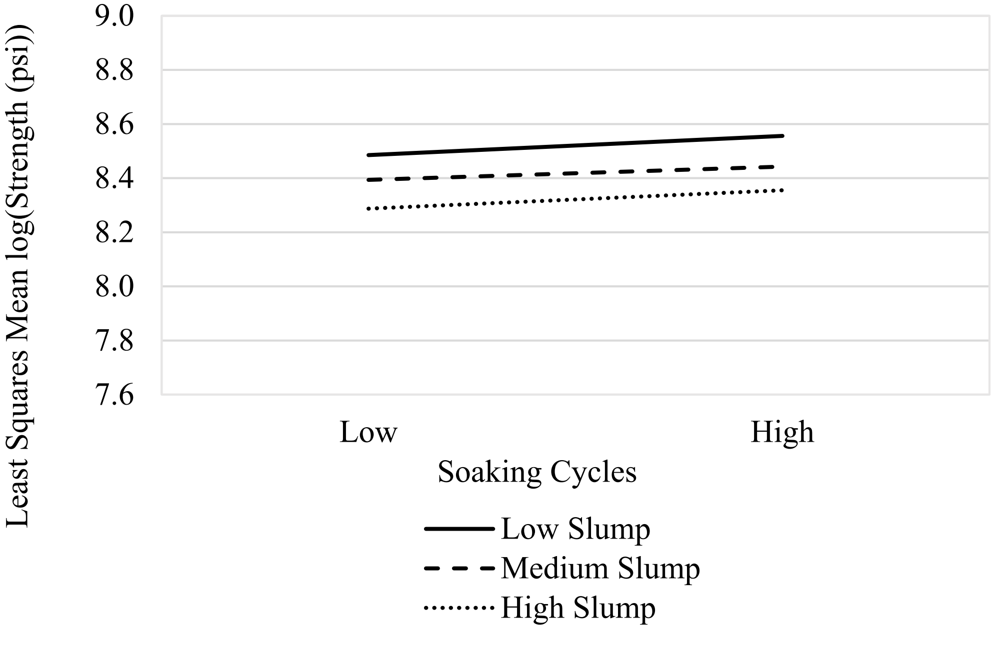


Figure C-6. Two-Way Interaction between Soaking and Slump

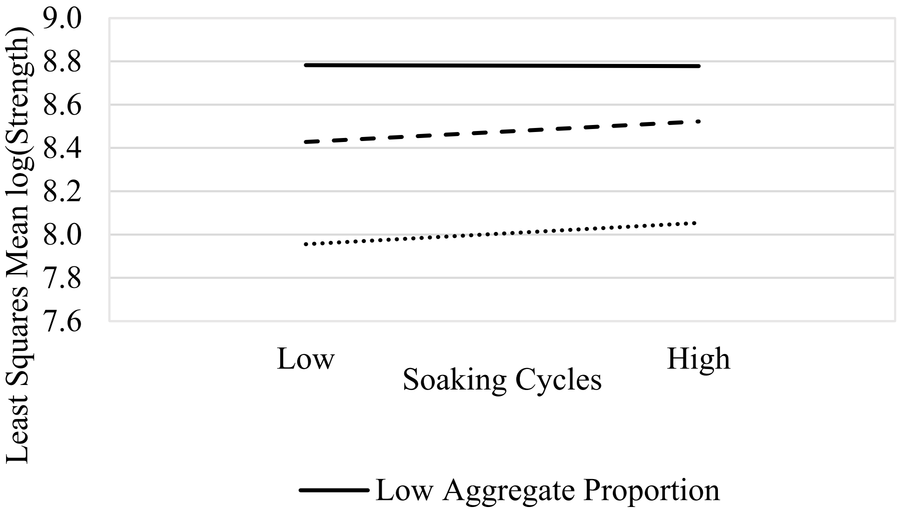
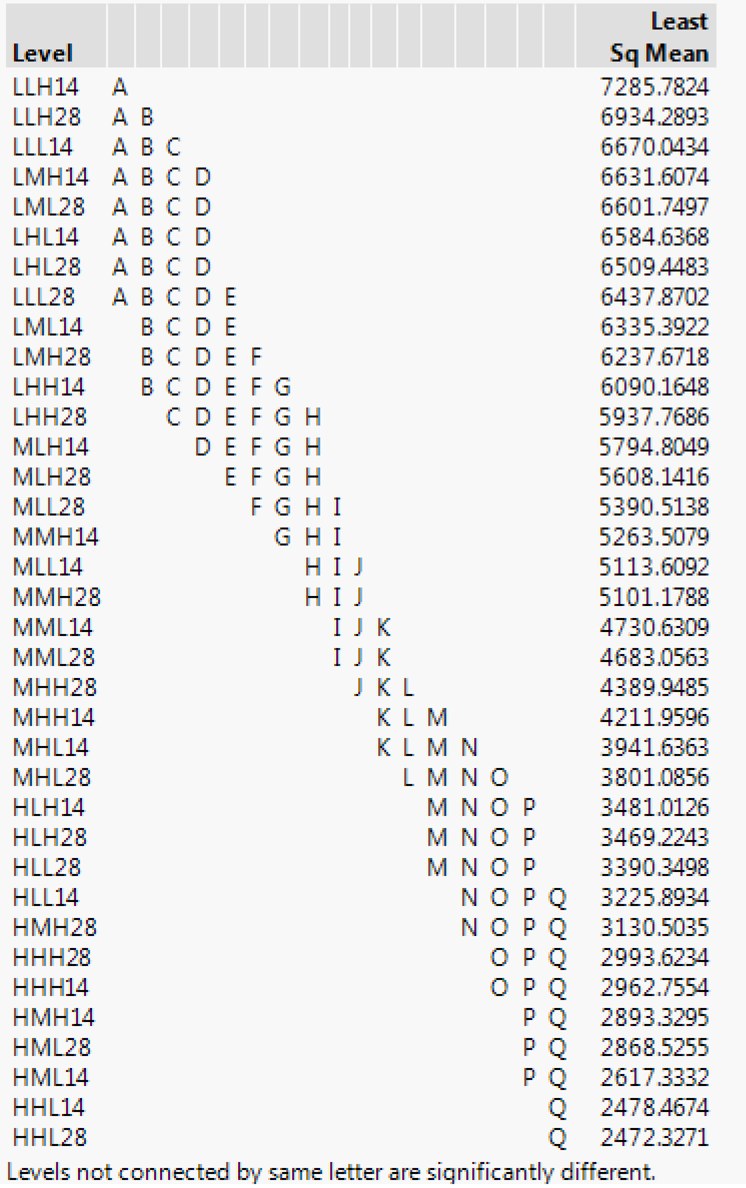


Figure C-7. Two-Way Interaction between Soaking and Aggregate Proportion

C.4 28-Day Compressive Strength Predictor Ratio

The three specimens tested at 14 days were divided by the factor of 0.85 to determine an estimated 28-day compressive strength. To verify that the ratio of 0.85 was appropriate to use in this experiment, an analysis was performed comparing the mean of the predicted 28-day strengths and the mean of the actual 28-day strengths for a given mixture. None of the predicted means were statistically significantly different from their corresponding 28-day strength means, thus confirming the appropriateness of the factor 0.85. The Tukey-Kramer test output is presented in Table C-4. The left column contains the mixture identifier and the test day (14 or 28). Those categories sharing a letter in the center columns (A through Q) are considered not statistically significantly different.

Table C-4. Tukey-Kramer Test for Predictor Ratio between 14-Day and 28-Day Strength



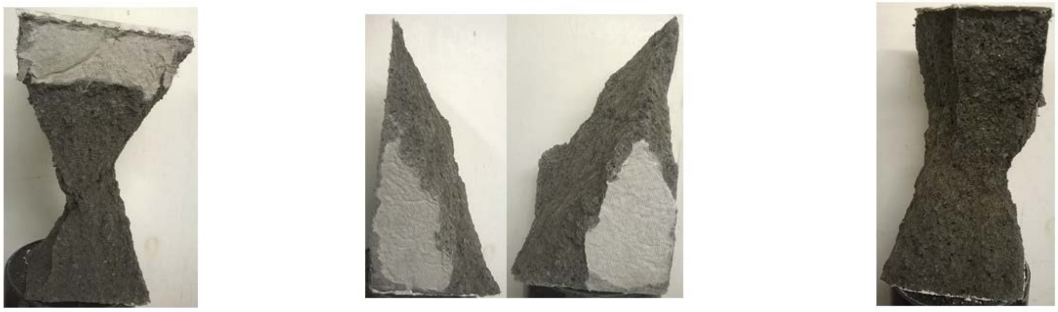
Level																		Least Sq Mean
LLH14	A																	7285.7824
LLH28	A	B																6934.2893
LLL14	A	B	C															6670.0434
LMH14	A	B	C	D														6631.6074
LML28	A	B	C	D														6601.7497
LHL14	A	B	C	D														6584.6368
LHL28	A	B	C	D														6509.4483
LLL28	A	B	C	D	E													6437.8702
LML14		B	C	D	E													6335.3922
LMH28		B	C	D	E	F												6237.6718
LHH14		B	C	D	E	F	G											6090.1648
LHH28			C	D	E	F	G	H										5937.7686
MLH14				D	E	F	G	H										5794.8049
MLH28					E	F	G	H										5608.1416
MLL28						F	G	H	I									5390.5138
MMH14							G	H	I									5263.5079
MLL14								H	I	J								5113.6092
MMH28								H	I	J								5101.1788
MML14									I	J	K							4730.6309
MML28									I	J	K							4683.0563
MHH28										J	K	L						4389.9485
MHH14											K	L	M					4211.9596
MHL14											K	L	M	N				3941.6363
MHL28												L	M	N	O			3801.0856
HLH14													M	N	O	P		3481.0126
HLH28													M	N	O	P		3469.2243
HLL28													M	N	O	P		3390.3498
HLL14														N	O	P	Q	3225.8934
HMH28														N	O	P	Q	3130.5035
HHH28															O	P	Q	2993.6234
HHH14															O	P	Q	2962.7554
HMH14																P	Q	2893.3295
HML28																P	Q	2868.5255
HML14																P	Q	2617.3332
HHL14																	Q	2478.4674
HHL28																	Q	2472.3271

Levels not connected by same letter are significantly different.

APPENDIX D. FAILURE MODES

Six specimens were prepared from each mixture design. One specimen from each mixture was taken to act as a representative for the mixture as shown in Figures D-1, D-2, and D-3. The labels in the figures show the identifying letters used for that mixture, and the failure mode most common in that mixture as depicted in the corresponding picture. Further details on failure modes are discussed in Section 4.5.

a) HHH; Cone/Shear b) HMH; Conical c) HLH; Conical



d) HHL; Conical e) HML; Shear f) HLL; Conical

Figure D-1. High Aggregate Failure Modes

a) MHH; Conical b) MMH; Conical c) MLH; Cone/Shear

d) MHL; Cone/Shear e) MML; Cone/Shear f) MLL; Shear

Figure D-2. Medium Aggregate Failure Modes

a) LHH; Cone/Split b) LMH; Shear c) LLH; Cone/Shear

d) LHL; Cone/Shear e) LML; Cone/Shear f) LLL; Shear

Figure D-3. Low Aggregate Failure Modes