MEEN 404 - 905
Experiment 3
Effects of the ratios of aggregate, sand, and water to cement on the compressive strength of cured concrete

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Group 6:	HARTZER, Jacob
	MICHELS, Colin
	MODI, Vishal
Lecture Instructor:	Dr. Waruna Kulatilaka
Studio Instructor:	Dr. Choongho Yu

Abstract

This experiment explored the effects of fine aggregate (sand) to cement ratio, coarse aggregate (marble chips) to cement ratio, and water to cement ratio on the compression strength of concrete for home use. Concrete is one of the most widely used materials in the world and is commonly used by homeowners for Do-It-Yourself projects such as garden walls and making pavers. It is important that the concrete made in these applications is strong, yet cost-effective. Therefore, this experiment sought to find the most cost-effective concrete recipe that also met a minimum compressive strength requirement of 13.79 MPa (2000 psi) for a concrete pad. A full-factorial experiment was conducted with the independent variables having the following levels: [1, 3, 5] for fine aggregate to cement ratio, [1, 3, 5] for coarse aggregate to cement ratio, and [0.3, 0.4, 0.5] for water to cement ratio. These samples were made and tested in compression. A generally negative trend was found both between the fine aggregate to cement ratio and the compressive strength as well as between the coarse aggregate to cement ratio and the compressive strength. A generally positive trend was found between the water to cement ratio and the compressive strength. The overall uncertainty in the compressive strength was determined to be $\pm 55.0\ kPa$ which relates to a 0.78% uncertainty of the measurement. With the given specifications, it was found that the optimal recipe was coarse aggregate to cement ratio equalling 3, fine aggregate to cement ratio equalling 1, and water to cement ratio equalling 0.5, which produces concrete at $0.55\frac{\$}{kg}$ while also being relatively easy to mix by hand. This can be used by homeowners to save money while ensuring the strength of their concrete.

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Glossary Table

$'aggregate'$:	In the scope of this experiment, will refer to marble chips
$ANOVA$:	Analysis of Variance
a/c :	See x_a
$°C$:	Degrees Celsius
C_a :	Cost per kilogram of aggregate in $\frac{\$}{kg}$
$C_{a,bag}$:	Cost per bag of aggregate in $\frac{\$}{bag}$
C_c :	Cost per kilogram of cement in $\frac{\$}{kg}$
$C_{c,bag}$:	Cost per bag of cement in $\frac{\$}{bag}$
C_s :	Cost per kilogram of sand in $\frac{\$}{kg}$
$C_{s,bag}$:	Cost per bag of sand in $\frac{\$}{bag}$
C_w :	Cost per kilogram of water in $\frac{\$}{kg}$
$C_{w,1000gal}$:	Cost per 1000 gallons of water in $\frac{\$}{1000gal}$
cm :	Centimeter
$'coarse\ aggregate'$:	See 'aggregate'
$'fine\ aggregate'$:	Sand
$FMEA$:	Failure Modes and Effects Analysis
g :	Grams
h :	height of the sample
kg :	Kilogram
kN :	Kilonewton
kPa :	Kilopascal
lbs :	Pounds
mm :	Millimeter
$m_{c,bag}$:	Mass of cement per bag in $\frac{kg}{bag}$
$m_{s,bag}$:	Mass of sand per bag in $\frac{kg}{bag}$

m_a : Mass of aggregate

m_c : Mass of cement

m_s : Mass of sand

m_w : Mass of water

ρ : Sample density in $\frac{g}{cm^3}$

MPa : MegaPascal

ρ_a : Density of aggregate in $\frac{g}{cm^3}$

ρ_c : Density of cement in $\frac{g}{cm^3}$

ρ_s : Density of sand in $\frac{g}{cm^3}$

ρ_w : Density of water in $\frac{kg}{1000\ gallon}$

pH : A measure of the hydrogen ion concentration of a solution (acidity)

π : The mathmatical constant pi

PMT : Provide means to

psi : Pounds per square inch

PVC : Polyvinyl chloride

r : Radius of the samples

s/c : See x_s

t : Time (in minutes)

$TxDOT$: Texas Department of Transportation

UTM : Universal Testing Machine

V : Volume in cm^3

$V_{a,bag}$: Volume of aggregate per bag in $\frac{ft^3}{bag}$

x_a : Ratio of aggregate by mass to cement by mass

x_s : Ratio of sand by mass to cement by mass

x_w : Ratio of water by mass to cement by mass

w/c : See x_c

1 Introduction & Objective

Concrete is the single most widely used material in the world [1]. Whether it's someone doing a personal project at home or professionals building a highway or skyscraper, they are likely to choose concrete as their main building material. A particular type of concrete used for pavement and other similar personal projects is structural lightweight concrete [2]. This concrete is suitable for home use for non-structural projects such as pavers and garden work and is characterized by having a compressive strength of 13.79 MPa (2000 psi) [3, 4].

With many homeowners executing their own projects, it is important for these individuals to understand the most cost-effective yet viable way to make concrete. If an individual was to make their own concrete, they would likely use a combination of fine aggregate (like sand), coarse aggregate (like larger rocks), cement, and water. These materials are readily available at a retailer such as Home Depot, at a relatively low cost [5, 6, 7]. Therefore, the objective of this experiment is to determine the weight percent of aggregate, sand, and water to cement that has the lowest price per kilogram but is also able to meet the standards of structural lightweight concrete.

2 Theory

Concrete is the term used for a composite material that is made from a filler and binder. This filler material is typically rocks, sand, or some combination of the two whereas the binder material is typically Portland cement and water, which serves as a glue. Cement is a powder made from combining limestone and clay in a kiln at $1450°C$. When water is added to cement, it begins to cure through a chemical process known as hydration [8].

Various studies have been done in the past by organizations such as the American Concrete Institution in order to determine how to maximize the compressive strength of concrete [9]. In order to predict the results of the compression tests, a literature review was conducted. In Figure 1, where f'_c represents the compressive strength at failure of concrete, there appears to be a bell-curve relationship between the sand to cement ratio (X_s) and compressive strength. Figure 2 shows the relationship between the water to cement ratio (X_w) and the compressive strength of concrete. A lower X_w will make stronger concrete. However, too low of a ratio can also lead to excessive shrinkage, cracking and curling [8]. Figure 3 shows a similar trend in compression strength versus X_w while also showing the somewhat positive linear trend of compression strength versus

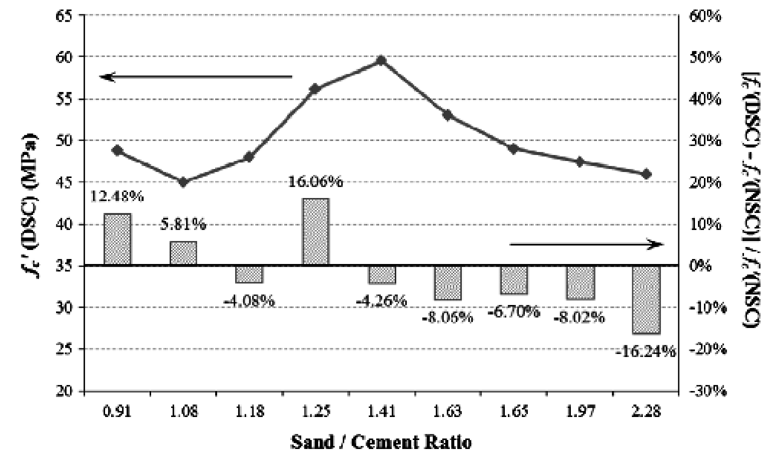

Figure 1: Compressive Strength as a Function of Sand to Cement Ratio [10]

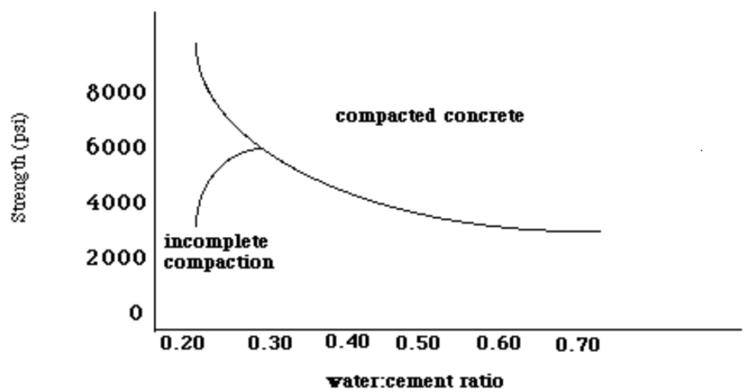

Figure 2: Compressive Strength as a Function of Water to Cement Ratio [8]

aggregate to cement ratio (X_a). Therefore, a positive linear trend of a lower magnitude than the relationship with X_w is expected.

From these individual plots, it is possible to construct an overall expected set of results for the experiment. This data is shown in Figure 4. Note that there is a linearly positive trend between aggregate content and compressive strength and an even larger yet negative trend between water content and compressive strength. Lastly, there is a bell curve relationship between sand content and compressive strength. These data ranges were chosen to represent recommended ratios from literature, and the compressive strength values were estimated from base cases and extrapolated from expected trends [8, 11, 12, 13].

The water to cement ratio, x_w, was calculated using Equation (1) below. Similarly, the sand ratio, x_s, and the aggregate ratio, x_a, were calculated using Equations (2) and (3) below.

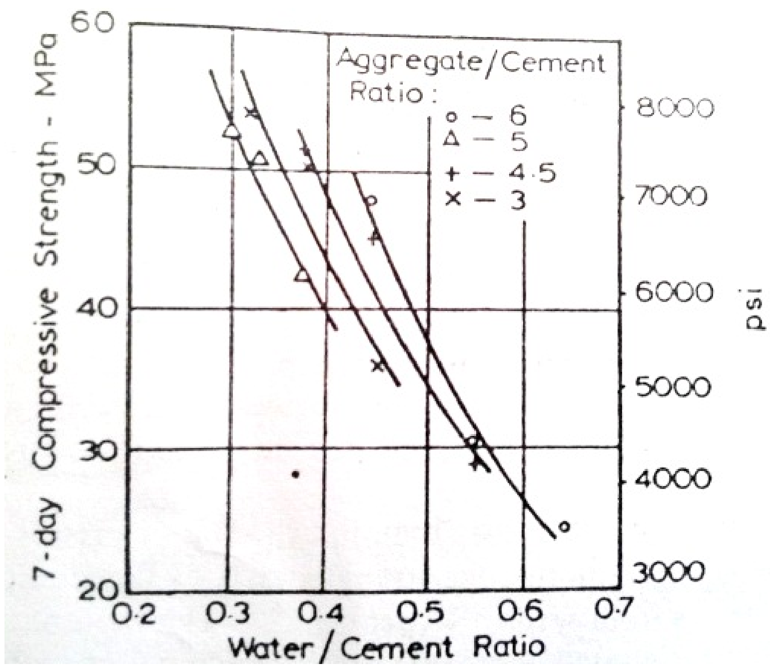

Figure 3: Compressive Strength as a Function of Water to Cement Ratio and Aggregate to Cement Ratio [11]

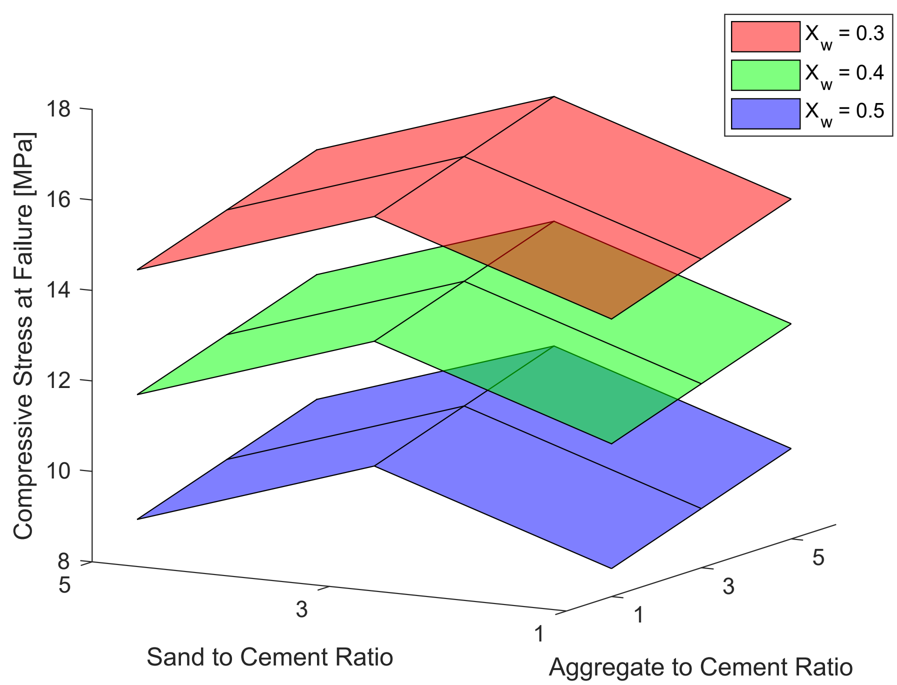

Figure 4: Predicted Data Trends

$$x_w = \frac{m_w}{m_c} \tag{1}$$

$$x_s = \frac{m_s}{m_c} \tag{2}$$

$$x_a = \frac{m_a}{m_c} \tag{3}$$

In order to calculate the mass of each ingredient, the total volume was first calculated using Equation (4). Assuming the density of Portland cement is 2.01 $\frac{g}{cm^2}$ [14], the density of gravel is approximately 2.65 $\frac{g}{cm^2}$ [15], and the density of dry sand is 1.65 $\frac{g}{cm^2}$ [16], Equations (5) to (8) can be used to calculate the masses.

$$V = \pi r^2 h \tag{4}$$

$$m_c = \frac{V}{(\frac{1}{\rho_c} + \frac{x_a}{\rho_a} + \frac{x_s}{\rho_s})} \tag{5}$$

$$m_a = \frac{V \cdot x_a}{(\frac{1}{\rho_c} + \frac{x_a}{\rho_a} + \frac{x_s}{\rho_s})} \tag{6}$$

$$m_a = \frac{V \cdot x_s}{(\frac{1}{\rho_c} + \frac{x_a}{\rho_a} + \frac{x_s}{\rho_s})} \tag{7}$$

$$m_w = m_c x_w \tag{8}$$

To find the cost per kilogram of each of the four components, Equations (9) to (12) were used. The price for each material can be found per bag for aggregate, cement, and sand via The Home Depot, and the price per 1000 gallons for water via the City of College Station. Bags of cement and sand are measured in kilograms while a bag of aggregate is measured in cubic feet [5, 6, 7].

$$C_a = \frac{C_{a,bag}}{V_{a,bag} \times \rho_a \times \frac{28316.8cm^3}{ft^3} \times \frac{1kg}{1000g}} \tag{9}$$

$$C_c = \frac{C_{c,bag}}{m_{c,bag}} \tag{10}$$

$$C_s = \frac{C_{s,bag}}{m_{s,bag}} \tag{11}$$

$$C_w = C_{w,1000gal} \times \rho_w \tag{12}$$

3 Experimental Apparatus

This experiment concerned the compression strength of concrete samples. Therefore, an Instron 5984 Universal Testing Machine (UTM) was selected to perform these compression tests. The machine was outfitted with the compression testing plates and a 150 kN load cell in order to perform axial compression tests. Figure 5 outlines a basic compression testing machine and Figure 6 shows the UTM setup with a sample before testing. This UTM was equipped with an on-board computer capable of collecting and plotting data in real time, as well as performing basic calculations. One such calculation is the force at break, which was used in this experiment to determine the maximum compression force and to stop the test.

The uncertainties of the instruments used in this experiment are shown in Table 2. These uncertainties were combined using the equations outlined in Appendix B to find the uncertainties in the independent variables and calculated stress. The uncertainties in X_a, X_s, and X_w were 4.96×10^{-4} , 5.12×10^{-4} , and 1.96×10^{-4} respectively which relates to respective percent uncertainties of 0.0165%, 0.0171%, and 0.0490%. The uncertainty in the compressive strength was determined to be $\pm 55.0\ kPa$ which relates to a 0.78% uncertainty.

Using the Failure Modes and Safety Analysis (FMEA), it was determined that a major possible issue would be equipment scheduling or failure. Therefore multiple suitable universal testing machines were found in order to reduce this risk. In regards to the sample creation, poor mixing could lead to inconsistent results. Therefore, tamping was applied to each sample to encourage

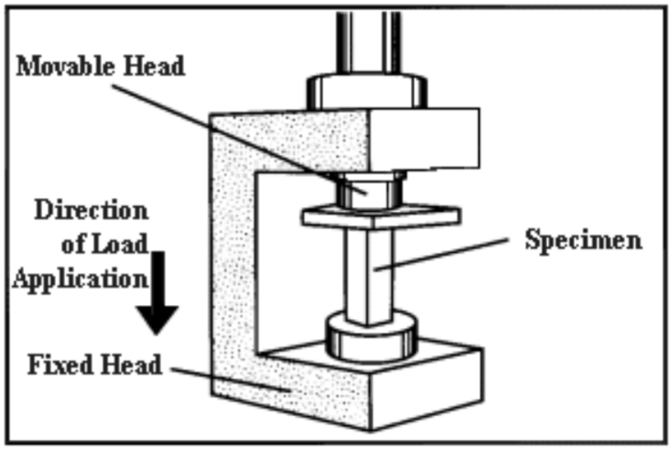

Figure 5: Compression Testing Apparatus

Figure 6: Experimental Setup with sample wrapped in paper

Table 2: Instrumentation Uncertainty

Instrument	**Range**	**Uncertainty**	**% Uncertainty**
Instron UTM [17]	0-150 kN	150 N to 0.5%	$\pm 0.5\%$
Scout Pro 4000g Balance [18]	0-4000g	0.1g	$\pm 0.1\%$
Brown and Sharpe 12” Caliper [19]	0-30.48 cm	2.54 e-3 cm	$\pm 0.05\%$

settling. Additionally, inconsistencies in the raw materials could have caused variability in the results, therefore the materials were checked for foreign material and defects before use. Hysteresis in the UTM could have also been an issue. Therefore, the team randomly assigned the testing order prior to experimentation. Safety was also a major focus during this experiment. The bags of raw materials used in creating these samples and the samples themselves were heavy, some weighing up to 90 lbs. As a result, the team made use of a cart to transport these objects between rooms so not to put stress on their bodies. Gloves were also used during this time to prevent injuries to hand due to pinch points and rough surfaces. In addition, cement is actually basic with a pH of around 12 [20]. To prevent chemical burns, the team made sure to wash their hands frequently and to mix the concrete in a well-ventilated area. The team also had to be careful when making the molds as a band saw was used to make all of the cuts. Safety glasses, long pants, and boots were worn to minimize the risk of using such a machine curing these cuts. To remove the samples from the molds, the team used a screwdriver to cut the tape and help pry the mold off. The team member made sure to keep their hands out of the direction of the screwdriver in case it slipped to as to prevent injuries to their hands. Finally, when testing, the team made use of a blast shield to protect themselves while operating the UTM to ensure no bits of concrete that fractured off of a sample while it was under load could hurt someone nearby.

4 Experimental Procedures

1. Create Molds
   - 1.1. Cut the PVC pipe into 200 mm lengths, and cut each mold along its length on one side such that it is still one piece but can be opened once the concrete is cured
   - 1.2. Tape the molds closed along the cut and tape one end of every mold closed so that concrete will not leak out the bottom
2. Create Samples
   - 2.1. Starting with sample one (of a randomly assigned order), weigh out the appropriate masses of aggregate, water, sand, and cement according to the sample's predetermined component ratios. These ratios can be found in Table 9 of Appendix D
   - 2.2. Add all of the measured components to a five gallon bucket and stir vigorously until the concrete is uniformly mixed
   - 2.3. Pour the concrete into its mold, tamp, and label
   - 2.4. If the mold is full and there is remaining concrete mix in the bucket, scrape it out as

thoroughly as possible and dispose of the excess

2.5. Repeat these steps for the next 26 samples

2.6. For the final sample that is made of Quikrete, weigh out 3120 grams of the dry mix and 240 grams of water. Mix these components together in the bucket until uniform and pour the concrete into mold 28

2.7. Let the samples cure in a well-ventilated room

2.8. Remove the samples from the molds, and transfer all sample labels

3. Test Samples

3.1. Transport the samples to the testing facility. Be sure to keep the samples safe so as to not break them during this process

3.2. Set up the universal testing machine (UTM) for a compression test. This includes setting up both the software of the machine and the physical testing apparatus. Set the strain rate to 1 inch per minute, and move the blast shield in place

3.3. Compress the samples in order and stop when either the machine reaches 120 kN or when there is a %40 drop in the compressive force from the max experienced force

3.4. Between each sample, remove any dust and concrete pieces from the UTM in order to ensure the samples are level and there is consistency between the tests

5 Results

The compression tests of all the samples were performed and the measured maximum compression stresses were plotted in Figure 7 against the values of aggregate to cement ratio, sand to cement ratio, and water to cement ratio. Note that the machine was limited to 14.8 MPa, and therefore some of the data points do not represent the true stress at failure. The maximum compression stresses were then plotted with respect to each of the three independent variables in Figures 8 to 10 with the errors of the independent and dependent variables shown. The relative error bars in each of the ratios, X_a, X_s, and X_w are so small that they appear to be simply vertical lines. The lines between the data points should only be used to identify data sets and does not imply a linear regression fit. Finally, using the measured diameters of the samples, the maximum compression stresses of each sample were calculated and those that exceed the required 13.79 MPa and their costs are summarized in Table 3.

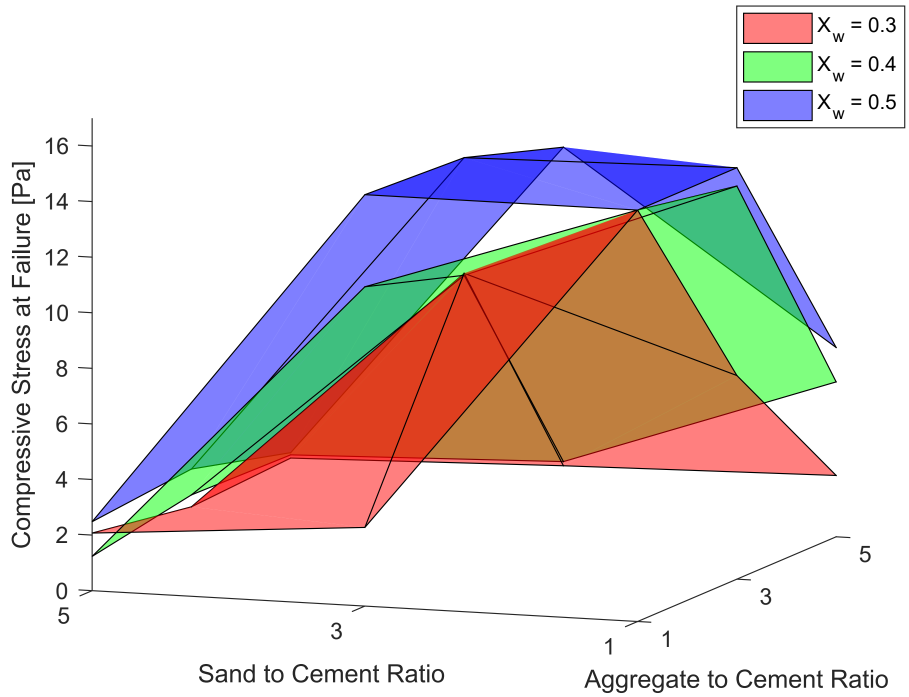

Figure 7: Compressive Strength as a Function of the Ratios of Aggregate, Sand, and Water to Cement

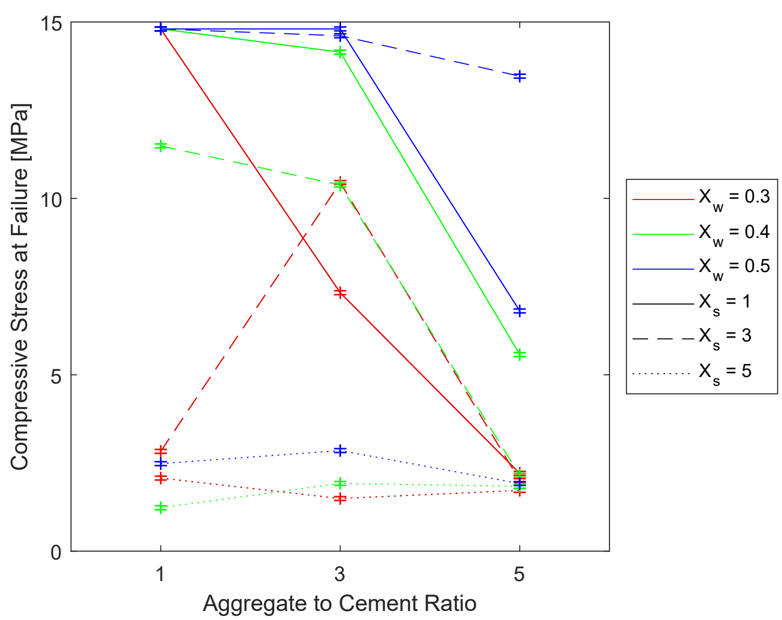

Figure 8: Compression Strength as a Function of Aggregate Ratio

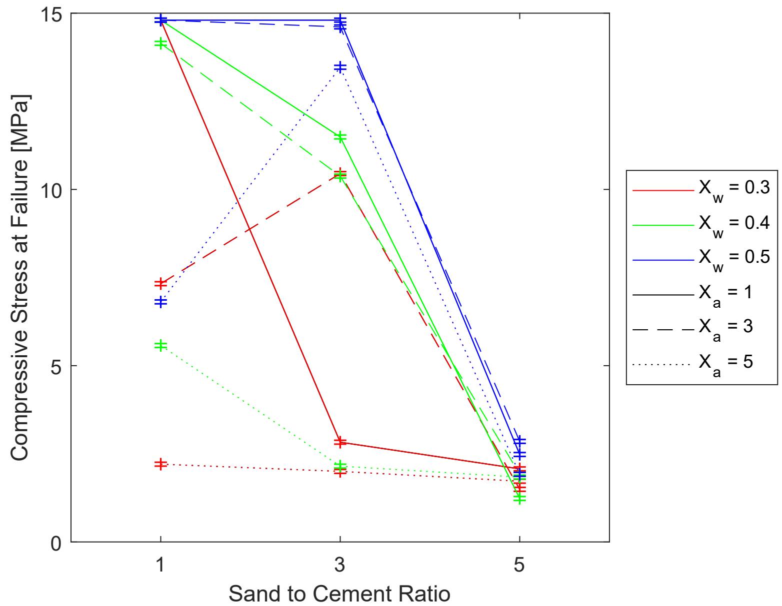

Figure 9: Compression Strength as a Function of Sand Ratio

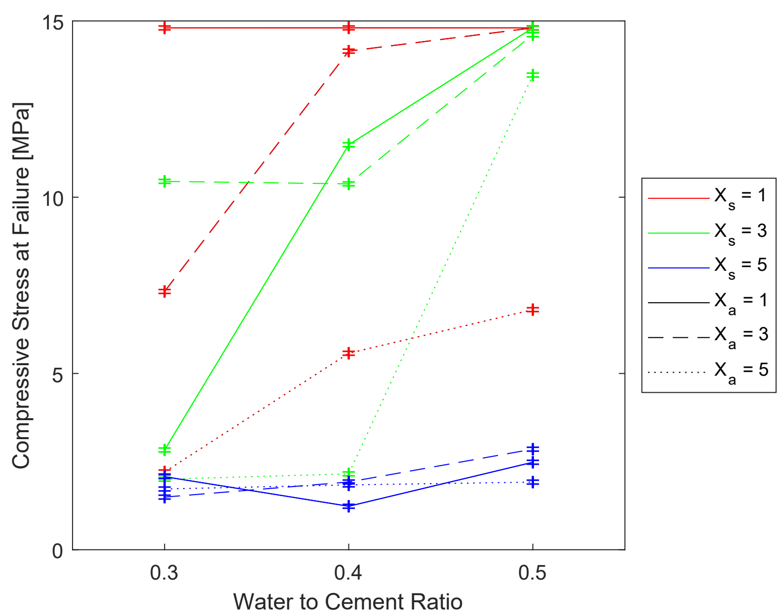

Figure 10: Compression Strength as a Function of Water Ratio

Table 3: Cost of the Samples that had a Compression Strength of $> 13.79\ MPa$

Sample	Cement Cost [$]	Aggregate Cost [$]	Sand Cost [$]	Water Cost [$]	Total Sample Cost [$]
1	0.252	0.160	0.186	0.0003	0.598
3	0.151	0.286	0.111	0.0002	0.549
5	0.116	0.219	0.256	0.0002	0.591
6	0.252	0.160	0.186	0.0003	0.598
17	0.252	0.160	0.186	0.0002	0.598
19	0.167	0.106	0.370	0.0002	0.643
26	0.151	0.286	0.111	0.0002	0.549

6 Discussion of Results

Only 7 of the tested 28 samples met the minimum 13.79 MPa requirement. Of these samples, 3 and 26 were the cheapest at approximately $0.55 per kg. Each of these samples has an aggregate ratio (x_a) of 3 and sand ratio (x_s) of 1. However, the water ratio (x_w) was different with sample 3 having an X_w of 0.4 and sample 26 having an X_w of 0.5. ANOVA was conducted on the data and it was determined that sand to cement ratio has the greatest impact on the force required to break the sample followed by the aggregate to cement ratio and then by the water to cement ratio. The critical F-value for each ratio individually is 5.14 which is less than the calculated F-values of 29.04 for x_s, 9.44 for x_a. and 7.25 for x_w. This indicates, with a 95% confidence, that all three ratios independently have an effect on strength. Using Minitab, interaction plots were created, shown in Figure 12 of Appendix C, which indicates an interaction exists between sand to cement ratio and aggregate to cement ratio. An F-value of 3.26 was calculated for the interaction of the aggregate ratio with the sand ratio which is actually lower than the critical value of 3.84 at a 95% confidence level. This indicates that there may be an interaction but it is not certain.

In regards to the predicted data, it was found that the actual data greatly diverged from what was expected. Therefore, the team conducted a review of relevant literature. First, the water to cement ratio had the opposite effect of what was expected. This implies that in the samples that were made, the water to cement ratio was actually in the inconsistent mixing regime that is characterized by sub-optimal strength [8]. In this region, increasing the water to cement ratio actually increases the strength due to better mixing. Next, increasing the aggregate to cement ratio also had the opposite effect of what was expected where increasing it would generally decrease the experienced maximum compression strength. After testing, this was thought to have been caused by the relatively large size of the aggregate with respect to the size of the sample. This caused great difficulty in mixing. Poor mixing generally decreases compression strength as shown by MAST [8]. Finally, increasing the sand to cement ratio generally decreased the compression strength instead of a bell-curve relationship. This is thought to have been due to the difference in ranges between the sources used to develop the final ranges and Figure 1 [8, 11, 12, 13]. As such, the bell-curve regime might have been only centered around a X_a value of 1.4 and what was experienced in this experiment was one end of the bell-curve.

As stated previously, the recipes and ratios used to create samples 3 and 26 are both valid options that a homeowner could use to construct a personal concrete pad that meets the minimum compressive strength standard at the cheapest price possible [3]. That being said, the team has unanimously agreed that the recipe used in sample 26 ($X_a = 3$, $X_s = 1$, and $X_w = 0.5$) be recommended to homeowners first and foremost. This is because this recipe had the highest water to concrete ratio and was thus the easiest to mix compared to the other two. While creating the samples, the team found that by adding more water to the mixture, it was less strenuous and less time consuming to mix all of the components together into one homogeneous mixture. It should also be said that sample 25, which had the same aggregate and sand ratios as sample 3 and 26, had a slightly lower water ratio of 0.3 than that of the other two samples. This sample on the other hand, only had a compressive strength of 7.33 MPa whereas samples 3 and 26 had strengths well above 14 MPa as seen in Table 5 in Appendix D. After conducting a literature review, this dramatic difference in strengths is due to the fact that not enough water was added to sample 25. This lack of water resulted in a crumbly mix of dry cement clumps coated in a wet cement shell. This is not ideal as the mixture is no longer homogeneous [21]. This sample did not cure properly as a result and thus did not create a strong bond which caused it to crumble under a low stress. Had the sample bonded well, the compressive strength would have been higher. On another note, having more water led to the samples having a smoother finish. This may be desirable to a homeowner as appearance may be taken into consideration when constructing a concrete pad, not just its compressive strength.

Another interesting point to make is that the sample made using the Quikcrete pre-made mix did not meet the minimum compressive strength standard of 13.79 MPa [3]. In fact, this sample only had a compressive strength of 4.276 MPa. After conducting a literature review, it was determined that this drastic difference is due to the fact that Quikcrete is not meant for constructing a concrete pad. It is intended to be used in quick curing applications such as setting a fence post which would not induce a large compressive stress on the concrete [22]. The creators of this product themselves have stated that this product was designed more so for fast curing and setting than for strength. As a result of this literate review, it now makes sense why the store bought brand does not meet the requirements in this experiment.

7 Summary

- 10 cm in diameter concrete samples were created using various aggregate to content ratios, sand to content ratios, and water to cement ratios
- Each sample was tested to determine the maximum compressive force it could withstand and then this value was compared to a 13.79 MPa (4000 psi) standard
- Seven samples met the minimum compressive strength requirement and the price per kilogram was calculated for each of these samples to determine the most cost-effective recipe
- The samples that maximized the x_s and x_a values were the cheapest
- The optimal recipe for the given specifications was determined to be $X_a = 3$, $X_s = 1$, and $X_w = 0.5$
- The sand ratio had the greatest influence on compressive strength but all three independent variables were found to be significant
- A slight interaction may exist between sand and aggregate ratios

8 Conclusions

- According to the trends in this data, increasing the aggregate to cement ratio from 1 to 5 generally decreases the concrete compressive strength
- According to the trends in this data, increasing the sand to cement ratio from 1 to 5 generally decreases the concrete compressive strength
- According to the trends in this data, increasing the water to cement ratio from 0.3 to 0.5 generally increases the concrete compressive strength
- There is a slight interaction between aggregate content and sand content
- Maximizing the sand and aggregate ratios, of the recipes that meet the minimum strength requirement, lead to the cheapest concrete

- Increasing the water to cement ratio creates a more uniform sample with a smoother surface
- Using the Quickrete recommended recipe does not create strong enough concrete under the given specifications
- The optimal recipe for the given specifications was determined to be $X_a = 3$, $X_s = 1$, and $X_w = 0.5$

9 Recommendations

The following are recommendations for improving the experiment:

- Increase the number of samples to test for interactions between all three variables
- Increase the range and number of levels of each of the independent variables to further explore their effects
- Consider using a fractional factorial experiment design to decrease the cost and time of the experiment
- Create smaller diameter samples to test for ultimate failure without maxing out the compression testing machine
- Ensure better uniformity of concrete when creating the samples by pressing the mixture tightly into the mold
- Use smaller aggregate with respect to the sample size to ensure better uniformity

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A FMEA

Table 4: Failure Modes and Effects Analysis

Item	Severity	Occurrence	Detection	RPN
Equipment failure or unavailability	8	7	3	168
Injury while lifting raw materials	8	3	3	72
Machine Hysteresis	6	1	8	48
Chemical burns from cement	8	5	1	40
Dangerous chips during testing	8	3	1	24
Poor Mixing	5	4	1	20
Sample defects and cracks	6	2	1	12
Inconsistent aggregate	4	2	1	8
Inconsistent cement	4	2	1	8
Inconsistent sand	4	2	1	8

B Uncertainty Analysis

$$x_a = \frac{m_a}{m_c}$$

$$\Delta x_a = \sqrt{\left(\frac{1}{m_c} \cdot \Delta m_a\right)^2 + \left(\frac{-m_a}{m_c^2} \cdot \Delta m_c\right)^2}$$

$$\Delta x_a = \sqrt{\left(\frac{1}{549.2g} \cdot 0.1g\right)^2 + \left(\frac{-1392.4g}{(549.2g)^2} \cdot 0.1g\right)^2}$$

$$\Delta x_a = 0.000496$$

$$x_s = \frac{m_s}{m_c}$$

$$\Delta x_s = \sqrt{\left(\frac{1}{m_c} \cdot \Delta m_s\right)^2 + \left(\frac{-m_s}{m_c^2} \cdot \Delta m_c\right)^2}$$

$$\Delta x_s = \sqrt{\left(\frac{1}{549.2g} \cdot 0.1g\right)^2 + \left(\frac{-1444.8g}{(549.2g)^2} \cdot 0.1g\right)^2}$$

$$\Delta x_s = 0.000512$$

$$x_w = \frac{m_w}{m_c}$$

$$\Delta x_w = \sqrt{\left(\frac{1}{m_c} \cdot \Delta m_w\right)^2 + \left(\frac{-m_w}{m_c^2} \cdot \Delta m_c\right)^2}$$

$$\Delta x_w = \sqrt{\left(\frac{1}{549.2g} \cdot 0.1g\right)^2 + \left(\frac{-219.7g}{(549.2g)^2} \cdot 0.1g\right)^2}$$

$$\Delta x_w = 0.000196$$

$$\sigma = \frac{F}{\pi r^2}$$

$$\Delta \sigma = \sqrt{\left(\frac{1}{\pi r^2} \cdot \Delta F\right)^2 + \left(\frac{-2F}{\pi r^3} \cdot \Delta r\right)^2}$$

$$\Delta \sigma = \sqrt{\left(\frac{1}{\pi \cdot (0.0506m)^2} \cdot 288N\right)^2 + \left(\frac{-2 \cdot 57,600N}{\pi \cdot (0.0506m)^3} \cdot 0.0001474m\right)^2}$$

$$\Delta \sigma = 55.0\, kPa$$

C Statistical Analysis

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Xa	2	418725710	209362855	9.44	0.008
Xs	2	1288323359	644161679	29.04	0.000
Xw	2	321479412	160739706	7.25	0.016
Xa*Xs	4	288824079	72206020	3.26	0.073
Xa*Xw	4	22439954	5609988	0.25	0.900
Xs*Xw	4	216465290	54116322	2.44	0.132
Error	8	177438821	22179853		
Total	26	2733696625			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4709.55	93.51%	78.90%	26.07%

Figure 11: ANOVA Results

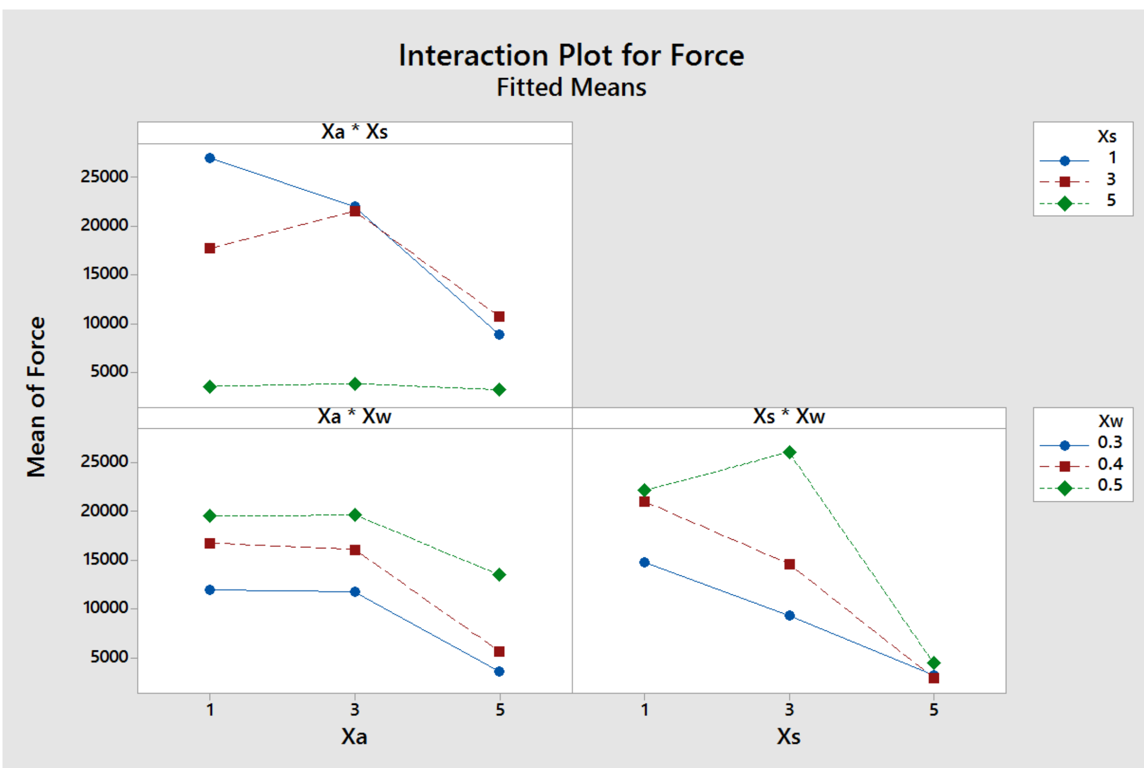

Figure 12: Interaction Plots From Minitab

D Raw Data

Table 5: Raw Data

Sample	Xa	Xs	Xw	Maximum Force [kN]	Compressive Stress at Maximum Force [MPa]
1	1	1	0.5	120.005	14.802
2	1	5	0.5	20.115	2.481
3	3	1	0.4	114.670	14.144
4	5	1	0.3	17.887	2.206
5	3	3	0.5	118.451	14.610
6	1	1	0.4	120.014	14.803
7	3	5	0.3	12.104	1.493
8	3	5	0.4	15.578	1.922
9	5	5	0.5	15.551	1.918
10	1	5	0.3	16.803	2.073
11	5	3	0.3	16.226	2.001
12	3	5	0.5	23.126	2.853
13	3	3	0.3	84.717	10.449
14	5	3	0.5	109.161	13.465
15	1	3	0.3	22.940	2.830
16	1	5	0.4	9.999	1.233
17	1	1	0.3	120.007	14.802
18	5	3	0.4	17.440	2.151
19	1	3	0.5	120.007	14.802
20	5	1	0.5	55.210	6.810
21	5	5	0.3	13.969	1.723
22	3	3	0.4	84.136	10.378
23	1	3	0.4	93.137	11.488
24	5	1	0.4	45.183	5.573
25	3	1	0.3	59.399	7.327
26	3	1	0.5	120.011	14.803
27	5	5	0.4	12.674	1.563
28	–	–	–	34.669	4.276

Note: Samples with passing compressive strengths are highlighted

Table 6: Inner Diameter Measurements of Molds

Diameter Measurements [cm]	
	10.144 10.103 10.114 10.117 10.165 10.072 10.135 10.149 10.085 10.140 10.174 10.155 10.097 10.117 10.104 10.118 10.154 10.150 10.083 10.124 10.190 10.160 10.130 10.165 10.103 10.120 10.113 10.113
Average	10.128
Std.Dev.	0.0295

Table 7: Price of each Component per kilogram

Material	**Price [$/bag]**	**Mass [kg/bag]**	**Price [$/kg]**	**Source**
Cement	9.97	41.96	0.238	Home Depot [5]
Aggregate	4.28	28.46	0.15	Home Depot [6]
Sand	3.98	22.68	0.175	Home Depot [7]
Water	2.40 ($/1000 gallons)	—	0.001	City of College Station [23]

E Predicted Data

Table 8: Predicted Compressive Strength of Each Sample

Sample	Predicted Strength [MPa]
1	8.62
2	8.62
3	12.07
4	15.51
5	11.03
6	11.38
7	14.82
8	12.07
9	10.00
10	14.13
11	17.24
12	9.31
13	16.55
14	11.72
15	15.86
16	11.38
17	14.13
18	14.48
19	10.34
20	10.00
21	15.51
22	13.79
23	13.10
24	12.76
25	14.82
26	9.31
27	12.76
28	14.00

Equations used are from Karni [24]

F Recipes

Table 9: Sample Component Ratios and Masses

Trial	x_a	x_s	x_w	**Mass Cement**	**Mass Aggregate**	**Mass Sand**	**Mass Water**
1	1	1	0.5	1060.7	1060.7	1060.7	530.3
2	1	5	0.5	525.3	525.3	2626.4	262.6
3	3	1	0.4	634.4	1903.3	634.4	253.8
4	5	1	0.3	452.6	2262.8	452.6	135.8
5	3	3	0.5	486.2	1458.6	1458.6	243.1
6	1	1	0.4	1060.7	1060.7	1060.7	424.3
7	3	5	0.3	394.1	1182.4	1970.7	118.2
8	3	5	0.4	394.1	1182.4	1970.7	157.7
9	5	5	0.5	315.4	1577.0	1577.0	157.7
10	1	5	0.3	525.3	525.3	2626.4	157.6
11	5	3	0.3	371.7	1858.6	1115.2	111.5
12	3	5	0.5	394.1	1182.4	1970.7	197.1
13	3	3	0.3	486.2	1458.6	1458.6	145.9
14	5	3	0.5	371.7	1858.6	1115.2	185.9
15	1	3	0.3	702.6	702.6	2107.8	210.8
16	1	5	0.4	525.3	525.3	2626.4	210.1
17	1	1	0.3	1060.7	1060.7	1060.7	318.2
18	5	3	0.4	371.7	1858.6	1115.2	148.7
19	1	3	0.5	702.6	702.6	2107.8	351.3
20	5	1	0.5	452.6	2262.8	452.6	226.3
21	5	5	0.3	315.4	1577.0	1577.0	94.6
22	3	3	0.4	486.2	1458.6	1458.6	194.5
23	1	3	0.4	702.6	702.6	2107.8	281.0
24	5	1	0.4	452.6	2262.8	452.6	181.0
25	3	1	0.3	634.4	1903.3	634.4	190.3
26	3	1	0.5	634.4	1903.3	634.4	317.2
27	5	5	0.4	315.4	1577.0	1577.0	126.2
28	-	-	-	3kg Quickrete	-	-	240

Note: all masses in grams unless otherwise specified

G Specimen Dimensions

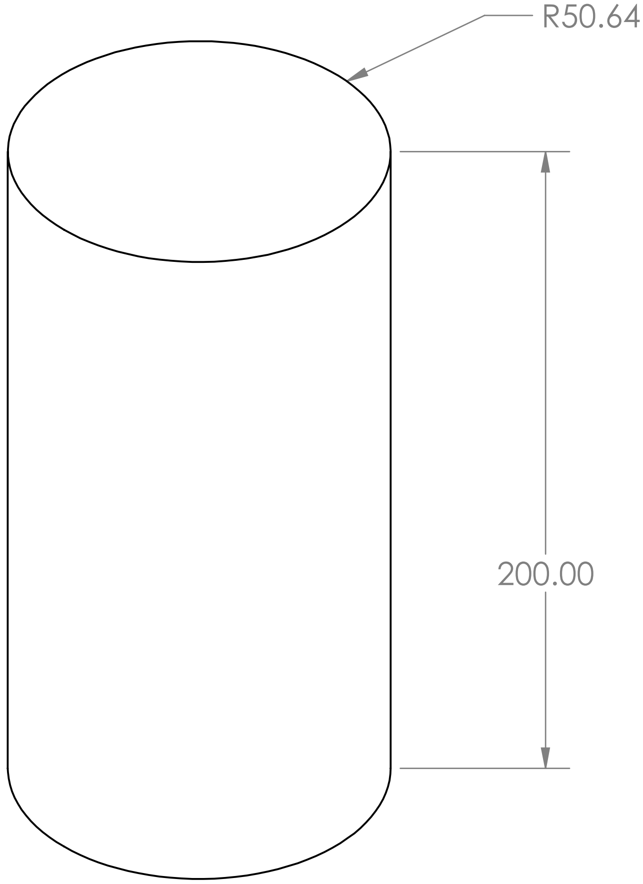

Figure 13: Specimen Dimensions in mm

H Matlab Code

```
% MEEN 404 - 905 Experiment 3
%
% Code for plotting resultant data collected for Lab 3


%% Constants
[X,Y] = meshgrid([1,3,5]);

C1(:,:,1) = ones(3);
C1(:,:,2) = zeros(3);
C1(:,:,3) = zeros(3);

```

```
C2(:,:,1) = zeros(3);
C2(:,:,2) = ones(3);
C2(:,:,3) = zeros(3);

C3(:,:,1) = zeros(3);
C3(:,:,2) = zeros(3);
C3(:,:,3) = ones(3);

W = [0.3,0.4,0.5];

err = [55e-3,55e-3,55e-3];
erra = [0.000496,0.000496,0.000496];
errs = [0.000512,0.000512,0.000512];
errw = [0.000196,0.000196,0.000196];


%% Predicted Values
Pred(:,:,1) = 0.00689476 * [...
    2050,2150,2250;...
    2300,2400,2500;...
    2050,2150,2250];

Pred(:,:,2) = 0.00689476 * [...
    1650,1750,1850;...
    1900,2000,2100;...
    1650,1750,1850];

Pred(:,:,3) = 0.00689476 * [...
    1250,1350,1450;...
    1500,1600,1700;...
    1250,1350,1450];

figure(1)
hold on
surf(X,Y,Pred(:,:,1),C1);
alpha 0.5
%axis([1,5,1,5,0,17]);

surf(X,Y,Pred(:,:,2),C2);
alpha 0.5

surf(X,Y,Pred(:,:,3),C3);
alpha 0.5

legend('X_w = 0.3','X_w = 0.4','X_w = 0.5')
```

```
xlabel('Aggregate to Cement Ratio');
ylabel('Sand to Cement Ratio');
zlabel('Compressive Stress at Failure [MPa]');
xticks([1,3,5])
yticks([1,3,5])
hold off


%% Plot raw data
Z1 = 6.89476 *...
    [2.1469,    1.0626,    0.3200;
     0.4104,    1.5156,    0.2903;
     0.3006,    0.2165,    0.2499];

Z2 = 6.89476 *...
    [2.1470,    2.0514,    0.8083;
     1.6662,    1.5052,    0.3120;
     0.1789,    0.2787,    0.2667];

Z3 = 6.89476 *...
    [2.1469,    2.1470,    0.9877;
     2.1469,    2.1191,    1.9529;
     0.3599,    0.4137,    0.2782];

figure(2)
hold on
surf(X,Y,Z1,C1);
alpha 0.5
axis([1,5,1,5,0,17]);

surf(X,Y,Z2,C2);
alpha 0.5

surf(X,Y,Z3,C3);
alpha 0.5

legend('X_w = 0.3','X_w = 0.4','X_w = 0.5')
xlabel('Aggregate to Cement Ratio');
ylabel('Sand to Cement Ratio');
zlabel('Compressive Stress at Failure [Pa]');
xticks([1,3,5])
yticks([1,3,5])
hold off
```

```
%% Aggregate
figure(3)

h1 = zeros(6,1);
h1(1) = plot(X(1,:),Z1(1,:),'r-'); hold on;
h1(2) = plot(X(1,:),Z2(1,:),'g-');
h1(3) = plot(X(1,:),Z3(1,:),'b-');
h1(4) = plot(X(1,:),Z1(1,:),'k');
h1(5) = plot(X(1,:),Z1(2,:),'--k');
h1(6) = plot(X(1,:),Z1(3,:),':k');

errorbar(X(1,:),Z1(1,:),err,err,erra,erra,'r')
errorbar(X(1,:),Z1(2,:),err,err,erra,erra,'--r')
errorbar(X(1,:),Z1(3,:),err,err,erra,erra,':r')
errorbar(X(1,:),Z2(1,:),err,err,erra,erra,'g')
errorbar(X(1,:),Z2(2,:),err,err,erra,erra,'--g')
errorbar(X(1,:),Z2(3,:),err,err,erra,erra,':g')
errorbar(X(1,:),Z3(1,:),err,err,erra,erra,'b')
errorbar(X(1,:),Z3(2,:),err,err,erra,erra,'--b')
errorbar(X(1,:),Z3(3,:),err,err,erra,erra,':b');hold off;

xlabel('Aggregate to Cement Ratio');
xticks([1,3,5])
ylabel('Compressive Stress at Failure [MPa]');
legend(h1,'X_w = 0.3','X_w = 0.4','X_w = 0.5','X_s = 1','X_s = 3',
    'X_s = 5','location','eastoutside');

%% Sand
figure(4)
h2 = zeros(6,1);
h2(1) = plot(X(1,:),Z1(:,1),'r-'); hold on;
h2(2) = plot(X(1,:),Z2(:,1),'g-');
h2(3) = plot(X(1,:),Z3(:,1),'b-');
h2(4) = plot(X(1,:),Z1(:,1),'k');
h2(5) = plot(X(1,:),Z1(:,2),'--k');
h2(6) = plot(X(1,:),Z1(:,3),':k');

errorbar(Y(:,1),Z1(:,1),err,err,errs,errs,'r');
errorbar(Y(:,1),Z1(:,2),err,err,errs,errs,'--r');
errorbar(Y(:,1),Z1(:,3),err,err,errs,errs,':r');
errorbar(Y(:,1),Z2(:,1),err,err,errs,errs,'g');
errorbar(Y(:,1),Z2(:,2),err,err,errs,errs,'--g');
errorbar(Y(:,1),Z2(:,3),err,err,errs,errs,':g');
errorbar(Y(:,1),Z3(:,1),err,err,errs,errs,'b');
errorbar(Y(:,1),Z3(:,2),err,err,errs,errs,'--b');
```

```
errorbar(Y(:,1),Z3(:,3),err,err,errs,errs,':b');

xlabel('Sand to Cement Ratio');
xticks([1,3,5])
ylabel('Compressive Stress at Failure [MPa]');
legend(h2,'X_w = 0.3','X_w = 0.4','X_w = 0.5','X_a = 1','X_a = 3','X_a = 5','location','eastoutside');


%% Water
figure(5)
Zw1 = [Z1(1,:);Z2(1,:);Z3(1,:)];
Zw2 = [Z1(2,:);Z2(2,:);Z3(2,:)];
Zw3 = [Z1(3,:);Z2(3,:);Z3(3,:)];

h3 = zeros(6,1);
h3(1) = plot(W,Zw1(:,1),'r-'); hold on;
h3(2) = plot(W,Zw2(:,1),'g-');
h3(3) = plot(W,Zw3(:,1),'b-');
h3(4) = plot(W,Zw1(:,1),'k');
h3(5) = plot(W,Zw1(:,2),'--k');
h3(6) = plot(W,Zw1(:,3),':k');

errorbar(W,Zw1(:,1),err,err,errw,errw,'r');
errorbar(W,Zw1(:,2),err,err,errw,errw,'--r');
errorbar(W,Zw1(:,3),err,err,errw,errw,':r');
errorbar(W,Zw2(:,1),err,err,errw,errw,'g');
errorbar(W,Zw2(:,2),err,err,errw,errw,'--g');
errorbar(W,Zw2(:,3),err,err,errw,errw,':g');
errorbar(W,Zw3(:,1),err,err,errw,errw,'b');
errorbar(W,Zw3(:,2),err,err,errw,errw,'--b');
errorbar(W,Zw3(:,3),err,err,errw,errw,':b');

xlabel('Water to Cement Ratio');
xticks([0.3,0.4,0.5])
ylabel('Compressive Stress at Failure [MPa]');
legend(h3,'X_s = 1','X_s = 3','X_s = 5','X_a = 1','X_a = 3','X_a = 5','location','eastoutside');
```

I Selected Images

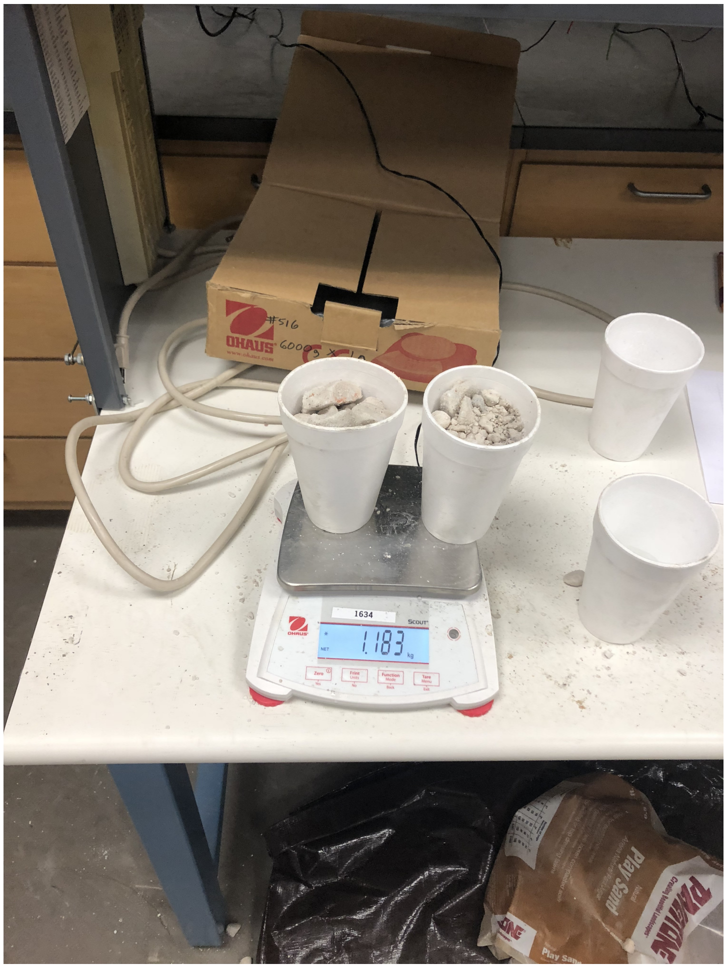

Figure 14: Weighing out the Constituent Materials

Figure 15: Mixing the Materials by Hand

Figure 16: Station for Making the Samples

Figure 17: Opening a PVC Mold

Figure 18: A Compression Sample Post Failure