Performance Ratio of Lightweight Concrete using Perlite
Team No. #2

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Introduction

The largest load on any structure is the weight of the building components, the dead load. There is a need to develop a lightweight concrete mix design to be used in structural applications. The light concrete reduces dead loads on the structure and can result in reduced materials and provide a more economical solution. Lightweight concrete densities are typically between 60-100 lbs/ft^3 (640.73-1601.84 kg/m^3). This is significantly lighter than what the industry considers normal weight concrete (145 lbs/ft^3). Typically, these lightweight concretes are used in insulation, sound reduction applications, and architectural features, but are not considered structural. The objective of this project is to develop an optimum ratio between the 28-day compressive strength and density. This ratio is often referred to as the performance ratio or specific strength (p-value). This project will look at the effects of the saturated curing time, water to cement ratio, and reducing the mixture density.

Lightweight concrete is produced by substituting coarse aggregates for less dense expanded shale, volcanic glass, or slate within the cement and water slurry. This experiment will use perlite as an aggregate. Perlite is a volcanic glass that has been heated in an oven until it transforms into a round white material. Perlite is a highly porous aggregate with a high water absorption ratio. The use of perlite does not provide strength to the concrete mixture and a large amount will adversely affect the required strength. However, fine aggregates do provide a considerable amount of strength in lightweight concrete, and a mix design will be developed for variations in proportions of the aggregates. Ottawa sand was chosen as the fine aggregate. Ottawa sand has naturally rounded grains of sands of pure quartz and is commonly used as a standard material in concrete. There is a direct correlation between the water to cement ratio of concrete and its compressive strength. To achieve the desired compressive strength, the ratio of water to cement will be modified and observed as implemented in two mix designs.

Approach

Lightweight concrete mixing was performed in order to achieve the maximum ratio between the compressive strength at 28 days (*f'c*), and the density of the concrete specimens. To achieve it, two mixing proportions were developed. The first concrete mixture, Experiment 1, was developed following ACI 211.2-98, Standard Practice for Selecting Proportions for Structural Lightweight

Concrete. The second concrete mixture, Experiment 2, was developed using the Overview of Perlite Concrete as a guideline.

The instruments utilized during the mixing process were: 2 cubic inch reusable brass molds (Figure 1), scale, graduated cylinder (Figure 2), rod for compaction (Figure 3), mixing trowel (Figure 4), and mixing platform (Figure 5). The instruments were cleaned thoroughly before use. The materials used for these experiments were: portland cement type I/II, tap water, ottawa sand, and perlite.

Figure 1. Steel Mold - 2 cubic inch

Figure 2. Graduated cylinder

Figure 3. Rod for tamping

Figure 4. Trowel

Figure 5. Mixing platform

To accurately calculate the water to cement ratio, the absorption of perlite was determined. Due to the amorphous structure of perlite, the absorption had to be determined experimentally by measuring the dry weight, saturated weight, and utilizing Equation 1. Therefore, the absorption of perlite was determined to be 68%. The properties of the materials used are summarized in Table 1.

$$Percent\ Absorption\ = \left(\frac{Saturated\ Weight - Dry\ Weight}{Dry\ Weight}\right) * 100 \qquad \text{Eq. 1}$$

Table 1. Properties of Materials

	Perlite	Portland Cement Type I/II	Ottawa Sand
Specific Gravity	2.30	3.15	2.65
Unit Weight	0.458	N/A	N/A
Fineness Modulus	N/A	N/A	2.4

Mixing procedures for the concrete are as follows:
Starting with the dry contributions, we first measured the ottawa sand which was placed in layer one. Then the measured portland cement was layered on top of the ottawa sand and mixed thoroughly until the mixture was homogenous. The perlite was then spread onto the ottawa sand and portland cement mixture and thoroughly combined. Water was then added in the center of the combined dry materials in three portions. Each time, turning the dry mixture towards the center

with the shovel until the consistency was uniform. The molds were prepared with a silicon release agent and made sure to be clean and free of debris and contaminants. Once the consistency of the concrete mix was uniform, the mix was placed in the prepared mold in three equal layers. Each layer was tamped with approximately 25-30 tamps. To maintain consistency, the same mixing procedure was performed for both Experiment 1 and Experiment 2.

Experiment 1 mixture design was conducted following ACI 211.2-98[3] and Concrete (2nd Ed.) by Mindess and Young [1]. The steps were performed as listed:

1. Determination of slump:
   In this case, a 1-2 inch slump was recommended for mass concrete based on Table 10.1 (Concrete p. 227 Mindess & Young).
2. Determination of fine aggregate size:
   A 3/8 inch maximum diameter was assumed for perlite which was considered our fine aggregate in Experiment 1.
3. Approximation of mixing water:
   Utilizing Table 3.2.2.2-Approximate mixing water and air content requirements for different slumps and nominal maximum size of aggregates from ACI 211.2-98. The values obtained from steps 1 and 2, determine the mixing water, 350 lb/yd^3.
   Determination of water to cement ratio (w/c):
   The relationships between the water-cement ratio and compressive strength of concrete was provided in Table 3.2.2.3 (a) of ACI 211.2-98. Based on the design parameters along with the desired compressive strength of 3000 psi (20,684.27 kPa) for lightweight concrete, a water to cement ratio of 0.68 for non-air-entrained concrete was selected.
4. Calculation of cement quantity:
   The quantity of cement was determined by dividing the approximate mixing water by the water to cement ratio. Thus, the cement quantity was calculated as 514.71 lb/yd^3.
5. Estimation of lightweight coarse aggregate:
   Lighting weight coarse aggregate was estimated by utilizing ACI 211.2-98 Table 3.2.2.4 - Volume of coarse aggregate per unit volume of concrete. The maximum aggregate size the coarse aggregate, 3/8 inch, and fineness modulus of ottawa sand, 2.40, is necessary for choosing the volume of the coarse aggregate. Therefore, the ratio of volume of coarse aggregate to concrete was determined to be 0.58. The weight of the aggregate was determined by utilizing Equation 2. The saturated weight of the aggregate was determined by multiplying the absorption of perlite and the weight of the aggregate, which was calculated to be 19.22 lbs.

$$\left(\frac{volume\ of\ coarse\ aggregate}{volume\ of\ concrete}\right) * (unit\ weight\ of\ perlite) * (ft^3\ to\ yd^3\ conversion\ factor) \quad \text{Eq. 2}$$

where the unit weight of perlite was 0.458 pcf, and the conversion factor from ft^3 to yd^3 is 27.

6. At this step, the mixing proportions of Experiment 1's mix was obtained. Table 3.2.2.5 - First estimate of weight of fresh lightweight concrete comprised of lightweight coarse aggregate and normal weight fine aggregate. We assumed lightweight coarse aggregate to have a specific gravity of 2 and air entrained at 4%.

The mixing proportions for experiments 1 and 2 are summarized in Table 2.

The second lightweight mixing design, Experiment 2, was developed using the *Overview of Perlite Concrete* [2] as a guideline, along with observations from Experiment 1's mixture. The Overview of Perlite publication summarizes the compressive strength of concrete with various design mixes. The mix design for Experiment 2 was adjusted for a desired compressive strength of 2,500 psi.

Table 2 summarizes the amount of materials used for the Experiment 2 mix proportion per batch. The batch values were adjusted to a theoretical volume of eight (8) cubic inches. The amount of water was increased proportionally by 8%. The amount of cement was reduced by 1.48% proportionally. The amount of perlite was increased by 40.30% proportionally. The amount of sand was reduced by 46.83% proportionally. Table 4.2 summarizes the difference of material proportions between the mix in Experiment 1 and 2 in percentage. The w/c ratio for Experiment 2 is 0.58. Although this w/c is less than Experiment 1, the level of saturation in the mix is more consistent. The difference in w/c between the two experiments is 15.87%. This may be due to the adjusted proportions of each material.

Table 2. Mix Proportions of Experiments 1 and 2					
Material	Experiment 1		Experiment 2		Difference in % Proportion
	Per batch (lbs)	% Proportion	Per batch (lbs)	% Proportion	
Water	0.36	10.26	0.316	18.26	8.00
Cement	0.53	15.10	0.55	13.62	-1.48
Perlite	0.02	0.57	0.16	40.87	40.30
Sand	2.60	74.07	0.72	27.25	-46.83
Total	3.51	100	1.741	100	

Several observations were noted through visual inspection of Experiment 1 and Experiment 2. One noticeable difference was the texture of the concrete during mixing. The wet mixture of Experiment 2 was a consistent, smooth paste with good workability during placement. The wet mixture of Experiment 1 was more porous and granular in texture. The absorption of perlite may have contributed to the reduction of water to cement ratio. This may also be attributed to the additional portland cement used in Experiment 2, along with the decrease in the amount of ottawa sand. Theoretically, by increasing portland cement and decreasing ottawa sand, the surface area of the paste has been increased, which results in an improved hydration of the paste as shown in Figure 6. Although Experiment 1 has a higher w/c ratio, 0.68, than Experiment 2, 0.58, the consistency of the mixture was not as well saturated, as previously explained. One reason for this conclusion may be due to the larger proportion of ottawa sand, 74.07%, compared to other materials within the design mix, only 25.93% for the remaining materials, in Experiment 1. The observations in Experiment 1 helped to adjust the material ratios resulting in a sample for experiment 2 with a higher p-value.

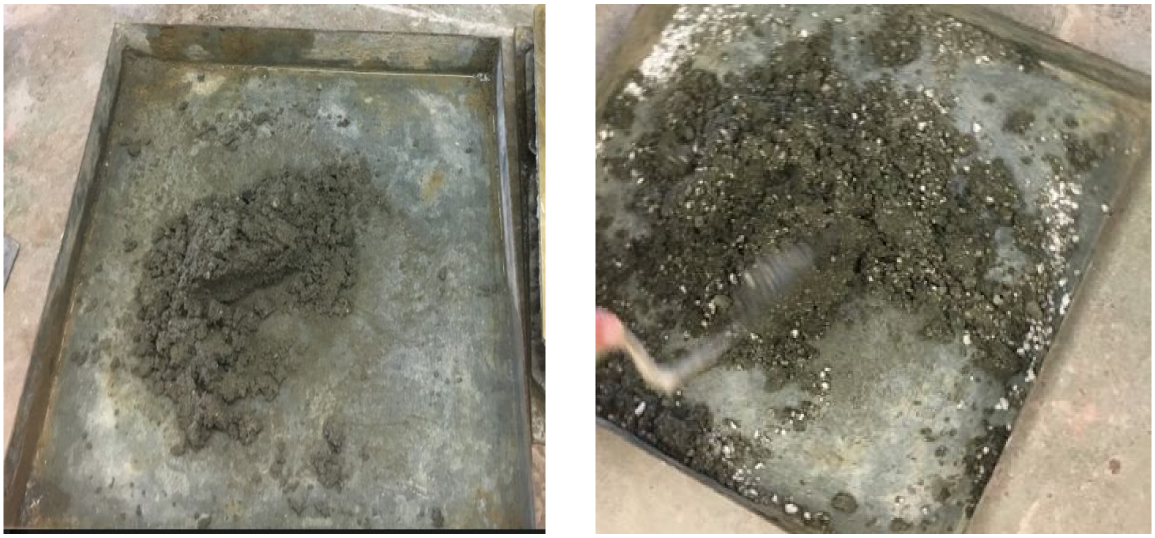

Figure 6. Experiment 1, Wet Cement Mixture & Experiment 2, Wet Cement Mixture

Once concrete specimens were molded, they were placed in an airtight bag with a moist paper towel and placed in an undisturbed location in the concrete lab, and allowed to cure at room temperature. The specimens were removed from the mold after curing for 24 hrs. The airtight bag and wet towel helped to maintain a constant humid environment that is beneficial to the hydration of concrete. Once the specimens had cured for 24 hrs, they were removed from the molds and placed in a temperature control water bath until compression testing 28-days after casting. Moist curing durations were varied during Experiment 1 to observe curing effects on compressive strength. This was done in an effort to establish the preferred wet cure time for Experiment 2 in order to achieve the greatest p-value.

Destructive testing was conducted following the ASTM C39/C39M-17b [6] and C109 methods. These testing standards were followed in the preparation and destructive testing of each specimen. The two testing machines were hydraulic rams that apply a constant increasing load to the unconfined specimen. Experiment 1 utilized the Soil Test Inc. CT-769. As shown below in Figure 6, the analog scale has a working range from 0 lbf to 250,000 lbf. The ASTM standard requires accuracy within ±1% of the load. For this reason, the Instron 1332 was used for the second experiment. The Instron 1332 is also a hydraulic ram used in compression testing of concrete specimens. This testing machine provided a greater degree of accuracy and controllability for testing these lower strength specimens. Both testing machines have the required seated metal bearing surface. No calibration records were present to review during testing, therefore it is unclear if either machine met the annual calibration requirement under ASTM C39. For defined symbols and abbreviations throughout this report, refer to Appendix A.

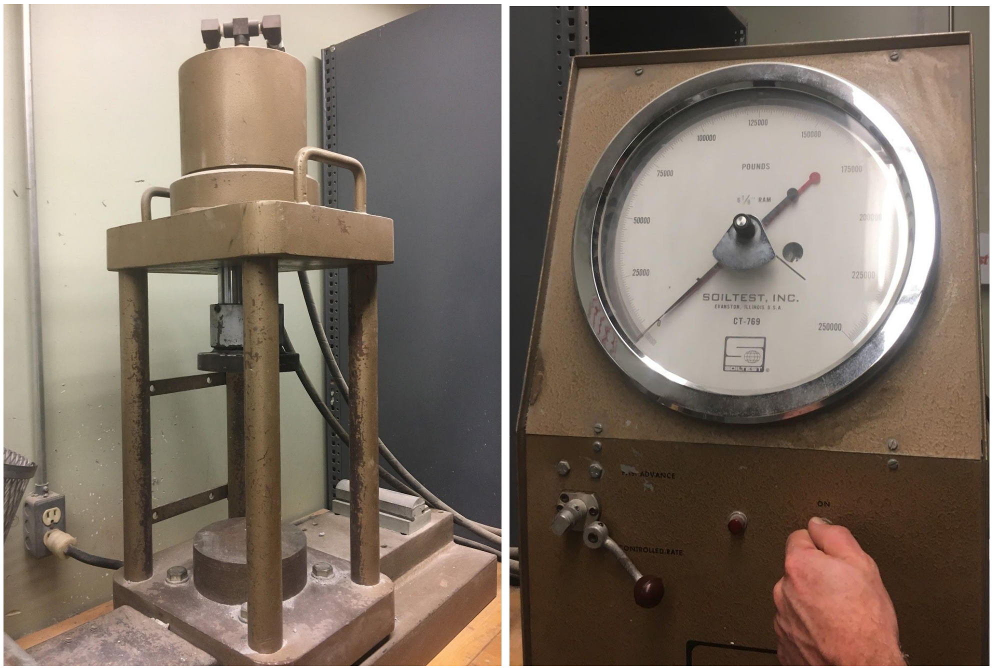

Figure 7. Compressive Strength Testing Apparatus used for Experiment 1, CT-769

Figure 8. Compressive Strength Testing Apparatus used for Experiment 2, Instron Model 1332

Result and Analysis:

A series of destructive tests were conducted to determine the maximum compressive load on the concrete specimens at 28-days. The compressive stress, $f'c$, is determined by dividing the compressive load, P, by the cross-sectional area, A, of the specimen, Equation 3:

$$f'_c = \frac{P}{A} \qquad \text{Eq. 3}$$

As stated previously, the objective was to obtain the performance ratio of the specimens. The performance ratio is calculated utilizing Equation 2:

$$p = \frac{f'c}{\rho} \qquad \text{Eq. 4}$$

where p is the performance ratio in kN-m/kg, $f'c$ is the 28-day compressive stress in kPa, and ρ = Density in kg/m^3.

Before the destructive test was conducted, the mass and volume of the specimens were obtained. The wet and dry densities of the experiments were determined utilizing Equation 3:

$$\rho = \frac{M}{V} \qquad \text{Eq. 5}$$

where ρ is density in kg/m^3, M is mass in kg, and V is volume in m^3.
Table 3 and Table 4 summarizes the masses, volumes, and densities for concrete specimens of Experiment 1 and 2, respectively.

Table 3. Experiment 1 - Mass, Volume, Density

Specimen	Wet Mass (kg)	Dry Mass (kg)	Moisture Mass (kg)	Volume (m^3)	Wet Density (kg/m^3)	Dry Density (kg/m^3)
1	0.237	0.216	0.021	0.00013109	1807.82	1647.63
2	0.228	0.207	0.021	0.00013109	1739.17	1578.98
3	0.249	0.232	0.017	0.00013109	1899.36	1769.68

Table 4. Experiment 2 - Mass, Volume, Density						
Specimen	Wet Mass (kg)	Dry Mass (kg)	Moisture Mass (kg)	Volume (m^3)	Wet Density (kg/ m^3)	Dry Density (kg/ m^3)
1	0.221	0.211	0.010	0.00013109	1685.77	1609.50
2	0.219	0.206	0.013	0.00013109	1670.52	1571.36
3	0.218	0.203	0.015	0.00013109	1662.89	1548.47

The difference in densities between each specimen in Experiment 1 is larger than the difference in densities between each specimen in Experiment 2. One reason for this difference is due to the geometric imperfection of Experiment 1, as shown in Figures 9, 10, and 11. The measurement of volume would be inaccurate due to the difficulties in measuring an imperfect shape. Another reason in the difference in densities between specimens is due to the variation in moist curing duration, which would vary mass due to the additional weight of water, and thus increase the strength of the specimens. In Experiment 1, the variation of moist cure are 9 days, 22 days, and 25 days for specimen 1, 2, and 3, respectively, as shown in Table 5. Lastly, the density of concrete is controlled by the individual densities of the contributing mixing elements. When comparing our mix proportions, seen in Table 2, between Experiment 1 and 2, Experiment 2 has a noticeable reduction in ottawa sand. Furthermore, not only was there a reduction in sand, which has a high mass, but an increase in perlite which has a low mass can be observed. By decreasing the overall masses without changing the final volume, the concrete's density decreases

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Figure 9. Experiment 1 Concrete Specimen 1

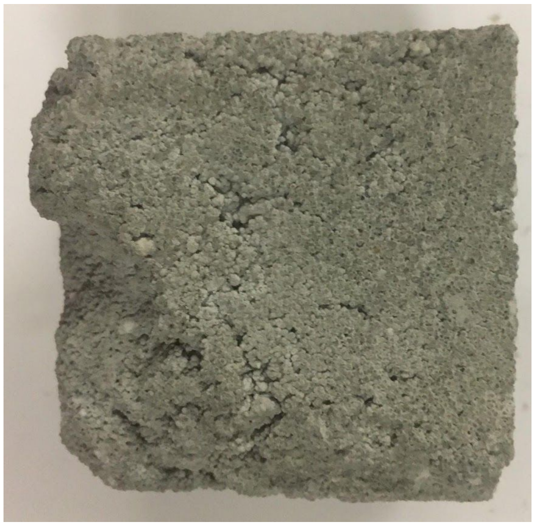


Figure 10. Experiment 1 Concrete Specimen 2

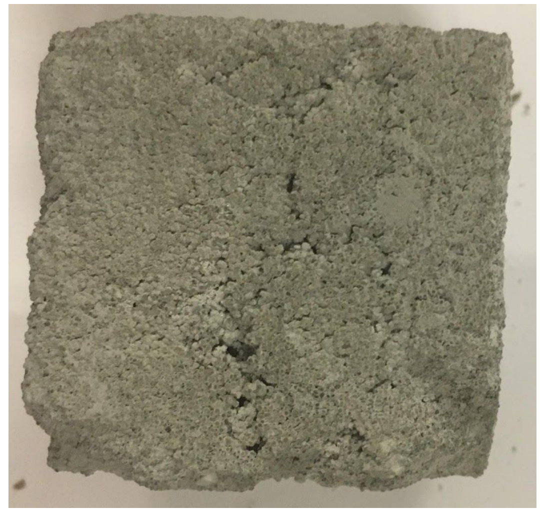


Figure 11. Experiment 1 Concrete Specimen 3

As previously stated, to determine the performance ratio, the compressive strength of the experiments was obtained through destructive testing, as shown in Figure 7. The compressive stress for Experiment 1 was determined using Equation 2 since the output provided using the CT-769 was in pounds force.

The compressive stress of specimens 1, 2, and 3 are 861.845 kPa, 861.845 kPa, and 1723.69 kPa, respectively, as shown in Table 5. The compressive stress of specimens 1 and 2 are the same, although there is variation in densities between the two specimens. Typically, higher density equates to higher compressive stress. The compressive stress of the specimens may not be accurate due to the precision of testing apparatus used for Experiment 1. Although the mix design for all specimens in Experiment 1 is the same, the compressive stress of specimen 3 is doubled that of both specimens 1 and 2. The variable between the specimens were duration of moist curing days. Therefore, the length of moist curing is shown to influence compressive stress of the specimens. The specimens with a longer moist curing duration produced a higher compressive stress, as observed in specimen 3. The desired compressive strength for Experiment 1 design was 3,000 psi (20,684.27 kPa) based on ACI 211.2-98 design guidance. It is apparent that the design of concrete for Experiment 1 did not produced the desired compressive strength. There are several factors that may contribute to the discrepancy between designed and actual compressive strengths, which will be addressed in the discussion section of this report.

Utilizing Equation 2, the performance ratios for specimens 1, 2, and 3 were determined to be 0.523 kN-m/kg, 0.545 kN-m/kg, and 0.974 kN-m/kg, respectively, as summarized in Table 5.

Although the compressive stress for specimen 1 and 2 are the same, it should be noted that the performance ratio between the two differs. This is due to the variation in density. Higher density equates to lower performance ratio. The performance ratio for specimen 3 is almost doubled that of the performance ratios of specimens 1 and 2 as expected, based on the compressive stress. The ratio of specimen 3 is not exactly doubled that of specimens 1 and 2 due to the density of the specimens, as stated previously.

Table 5. Experiment 1- Compressive Stress and Performance Ratio

Specimen	Date Casted	Date Removed From Water	Date of 28 day Test	Total Days of Moist Cure	Compressive Stress (psi)	Compressive Stress (kPa)	Performance, p (kN-m/kg)
1	10/9/17	10/18/17	11/06/17	9	125	861.845	0.523
2	10/9/17	10/31/17	11/06/17	22	125	861.845	0.545
3	10/9/17	11/03/17	11/06/17	25	250	1723.69	0.974

The compressive load of Experiment 2 was obtained using the destructive testing apparatus shown in Figure 8. Unlike the testing apparatus used in Experiment 1, Experiment 2's testing apparatus obtained and produced data points throughout the compressive test. The output data gives a comprehensive depiction of how the concrete specimen performed during the entirety of the test. The results of the compressive stress versus strain of specimen 1 and 2 of is depicted in Figure 12. It should be noted that specimen 3 did not undergo destructive testing due to project criteria, and therefore no further results and analysis will be done for this specimen.

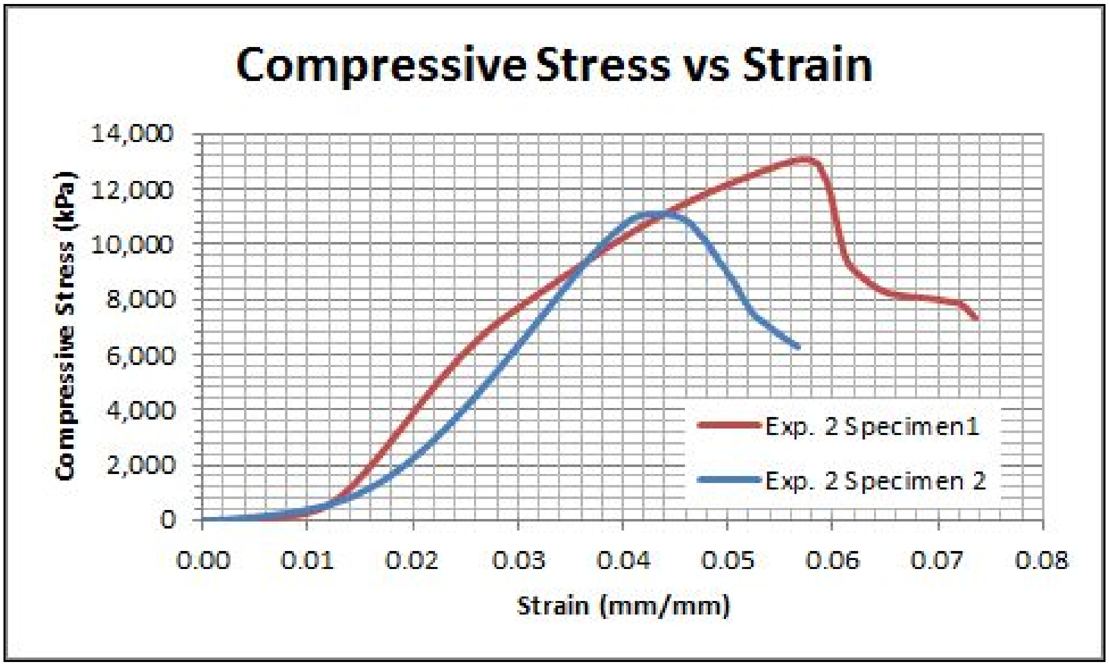


Figure 12. Comparison of Concrete Specimen 1 and 2 - Compressive Stress vs Strain of Experiment 2

It is apparent in Figure 12, as strain in the specimens increases, compressive stress increases. The elastic range of specimen 1 is greater than specimen 2, therefore the compressive stress is greater in specimen 1 than 2. The maximum compressive stress for specimens 1 and 2 are 13,071.208 kPa and 11,069.431 kPa, respectively. The strain maximum compressive stress for specimen 1 is 0.057 mm/mm and specimen 2 is 0.044 mm/mm.

Based on results from Experiment 1, moist curing durations for both specimens were longer than Experiment 1 to achieve the greatest performance ratio. Both specimens were moist cured for 26 days. The compressive stresses of specimens 1, and 2 are 13,071.21 kPa and 11,069.43 kPa, respectively, as shown in Table 6. It is important that the materials are mixed homogeneously to achieve the greatest strength. For instance, if perlite is incorporated thoroughly in the mix, then he location of the perlite and how it was dispersed within each specimen may be a contribution to the variation in compressive stress between specimens. If the perlite were to clump in one location within the mixed specimen, it would create a vulnerable area susceptible to stress cracking which could lead to total failure. The desired compressive strength for Experiment 2 design was 2,500 psi (17,236.89 kPa). It is apparent that the design of concrete for Experiment 2 did not produced the desired compressive strength. Similarly, there are several factors that may contribute to the discrepancy between designed and actual compressive strengths, which will be addressed in the discussion section of this report. Again, utilizing Equation 2 to determine the performance ratios for specimen 1, 8.121 kN-m/kg, and specimen 2, 7.044 kN-m/kg, summarized in Table 6. As compressive stress increases, the p-value increases. Therefore, it was expected that specimen 1 would have a greater p-value than specimen 2 due to the minimal difference, 0.91%, in densities.

Table 6. Experiment 2- Compressive Stress and Performance Ratio							
Specimen	Date Casted	Date Removed From Water	Date of 28 day Test	Total Days of Saturation	Compressive Stress (psi)	Compressive Stress (kPa)	Performance, p (kN-m/kg)
1	10/22/17	11/18/17	11/20/17	26	1895.82	13071.21	8.121
2	10/22/17	11/18/17	11/20/17	26	1605.49	11069.43	7.044
3	10/22/17	11/20/17	N/A	28	N/A	N/A	N/A

A plot of compressive stress versus density for specimens 1, 2, and 3 from Experiment 1, and specimens 1 and 2 from Experiment 2 was developed, as shown in Figure 13.

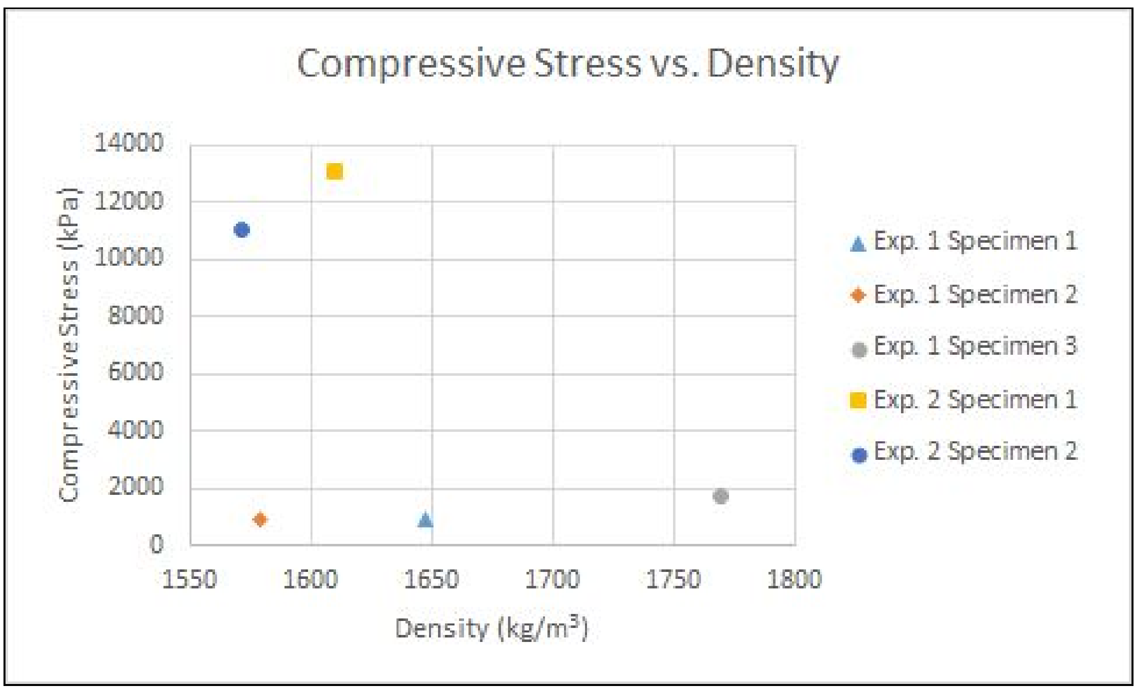


Figure 13. Comparison of All Concrete Specimens - Compressive Stress vs Density

In Experiment 1, the densities for specimens 1, 2, and 3 are 1,647.63 kg/m^3, 1,578.98 kg/m^3, and 1,769.68 kg/m^3, respectively. The compressive stress for specimens 1 and 2 is 861.845 kPa, and for specimen 3, the compressive stress is doubled the compressive stress of both specimens 1 and 2, which is 1,723.69 kPa. As shown in Figure 13, specimen 1 and 2 have the same compressive stress, however, the density varies by 4.25%. As previously stated, the deviation in density is partially due to geometric imperfections. In addition, the testing apparatus contributes to the output accuracy of the compressive strength values for each specimen. As expected, the compressive stress increases as density increases for specimen 3. The increase of density for specimens 1 and 3 is only 7.14%, while the increase of compressive stress is 66.67%.

In Experiment 2, the densities for specimens 1, and 2 are 1,685.77 kg/m^3 and 1,670.52 kg/m^3, respectively. The compressive stress for specimens 1 and 2 are 13,071.21 kPa and 11,069.43 kPa, respectively. In this experiment, as density increased, compressive strength increased, as expected. The increase of density for specimens 1 and 2 is only 0.91%, while the increase of compressive stress was 16.58%.

Although the densities of specimens in Experiment 1 are higher than specimens in Experiment 2, the compressive stress of both specimens in Experiment 2 are significantly greater, 11,347.52 kPa. Further discussion of effects on all the specimens that underwent destructive testing will be in the following section.

Discussion

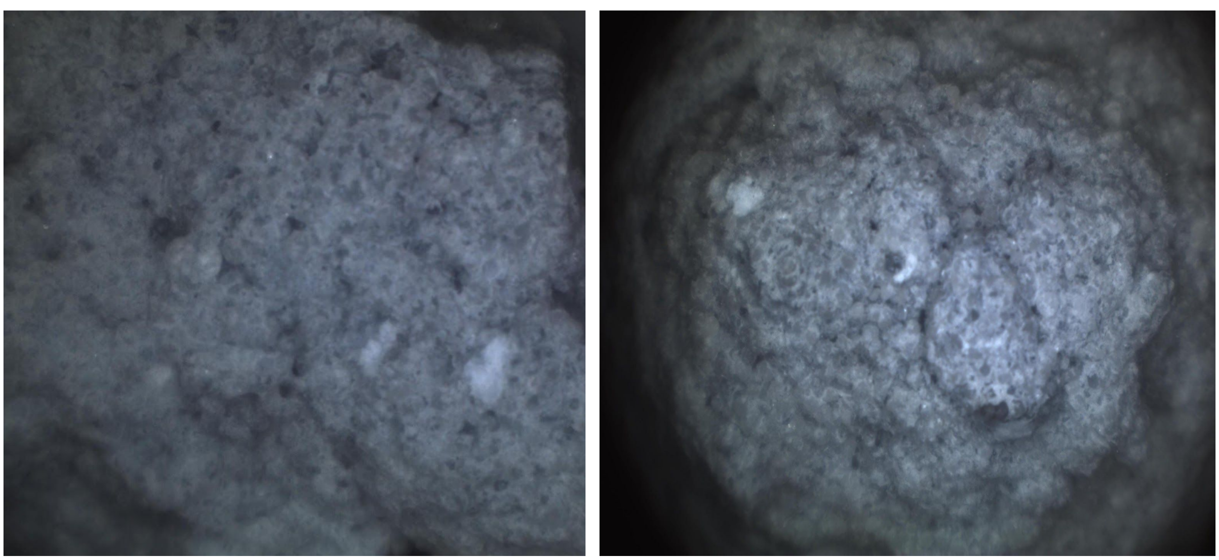
Several errors were introduced during the preparation of the specimens. One error, which was introduced in the experiment was the use of the Mettler PE24 balance. This scale has an operating range of 24 kg and a precision of 1g (+/-). Given that the batch size was relatively small (approximately 1 kg), the use of this scale introduced the greatest error range in weighing out the dry ingredients. To reduce the error, batch sizes were doubled from what was required.

A second error was introduced during the destructive testing of the first experiment. When performing the destructive testing for the first experiment, the Soil Test Inc. CT-769 concrete compression testing machine was utilized. The testing machine has an analog scale in increments of 500 lbf to perform the compression test. This significant figure would prove to be too high for determining accurate readings and immediately, it was observed that the data collected would have a large error. The analog readout of this machine allows for a highly inaccurate reading due to, interpretation of results by visually reading the needle's location instead of a digital output.

A third error was introduced during destructive testing, the operation of the hydraulic ram. The machine's advancement rate, the velocity at which the compressive force is applied, was not determined. This loading rate is important and used to find the accurate strength of the tested specimens. A slow constant load was a necessary application. If the loading rate is too fast, the specimen could show false strength, which would be at a higher value than if loaded at constant slow rate. The unknown advancement rate could lead to a large error in obtaining a false compressive strength. A secondary disadvantage to using the analog machine is the inability to collect data throughout the duration of the test. As shown in the testing of Experiment 2, the compression testing machine could develop a stress strain curve, unlike the CT-769. The stress strain curve is vital to understanding the characteristics of the concrete specimen and how the specimen performed when introduced to the loading. Without this data, it is more difficult to accurately compare the specimens. Finally, it is important to note that the calibration of the CT-769 Hydraulic Compression testing machine is unknown, therefore contributing to the list of errors observed. During testing, it was observed that the needle measuring the applied compressive force did not start at zero, but instead it began below the zero mark. It is unclear if this range accounts for compressive deformation in the load cell. Therefore, to account for this error, the final compressive force was adjusted to include the measurements produced by the machine.

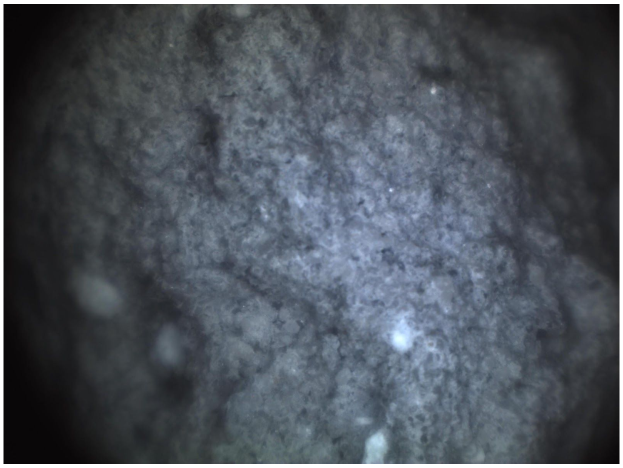
For the Experiment 2, more accurate information was desired, therefore the Instron 1332 Unconfined Compressive Testing Machine was used. This machine can obtain load, stress and strain data results throughout the test. The digital output also provides a greater degree of accuracy. The use of this machine greatly reduced the errors in load rate and total compressive load but did not eliminate errors entirely. As determined by the lab technician, up to a 30 percent error in the value of the deformation can be introduced. This is because the total measured deformation includes deflection in the load cell and the plywood bearing blocks. These errors will decrease with each test performed due to adjustments made to the Instron 1332 minimizing deformation. To reduce the error any further, the machine was set to load control, where the hydraulic ram increases the load applied at a constant rate of 2,000lbs/min. The use of a constant load rate is more accurate than the use of a constant velocity.

Understanding that an important part of curing is the molecular bonds that form during hydration between the mixing materials and the effects of the water to cement ratio, sand to cement ratio (s/c), and aggregate to cement ratio (a/c) can improve the performance ratio of the concrete. In Figure 13, Experiment 1 had a higher density than Experiment 2. The results of the compressive stress of the specimens did not perform as expected, as stated previously in the results and analysis of section of this report. This leads to the conclusion that the molecular bonds occurring during the hydration results impacted these results. Analyzing both experiment's proportions, the w/c, s/c, and a/c of Experiment 1 were 0.68, 4.90, and 0.04, respectively. While in Experiment 2, the w/c, s/c, and a/c ratios are 0.58, 1.31, and 0.29, respectively. As stated earlier, the w/c ratio between the two experiments differs by 15.87%. It was apparent, that when w/c was reduced, compressive strength increased, as expected. The difference in s/c is substantial. In Experiment 1, s/c is over three times that used in Experiment 2. Knowing density is driven by mass, s/c would account for the higher density in Experiment 1. Furthermore, understanding that ottawa sand has the lowest surface area (2.88 m^2/kg) [1] of all contributing materials, and that surface area increases hydration rate and bond strength, it could be determined that the hydration bond between the sand and cement would be less in Experiment 1 when comparing it to Experiment 2. This can be seen in Figure 14, which is the microscopic pictures of specimens 1 (Figure 14 (A)), 2 (Figure 14 (B)), and 3 (Figure 14 (C)), in Experiment 1. The specimen is granular and looks as though it may crumble, in which it did crumble when a load was applied. In Experiment 2, however, s/c was lower which also means a larger amount of cement contributed to the overall mixture. Cement compared to sand, has a much greater surface area, 300-400 m^2/kg [9], which contributes to a stronger bond throughout the concrete mix. This theory is also supported by comparing the a/c ratios. In Experiment 2, the amount of perlite is higher than the a/c in Experiment 1, which not only accounts for the density difference, but could explain why the bonds in Experiment 2 were stronger. In Figure 15, the microscopic picture of specimen 1 (Figure 15 (A)), 2 (Figure 15 (B)), and 3 (Figure 15 (C)) in Experiment 2, shows the increase of perlite used in Experiment 2. It can be observed that a more consistent texture and bond between the interacting elements can be seen throughout. It should be noted that Figure 15 (C) is an intact specimen, therefore the perlite isn't as visible as specimens 1 and 2.

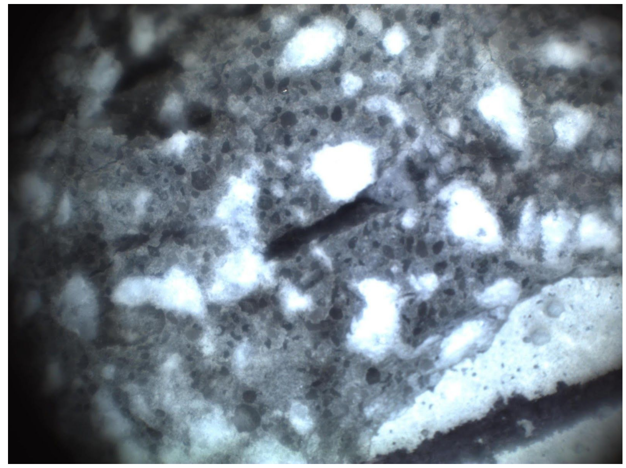


(A) Concrete Specimen 1 (Broken) (B) Concrete Specimen 2 (Broken)

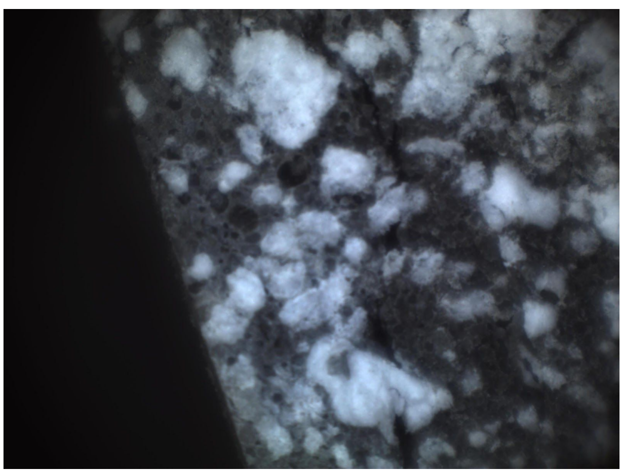
Figure 14. Microscopic Picture of Experiment 1 (A), (B), (C)



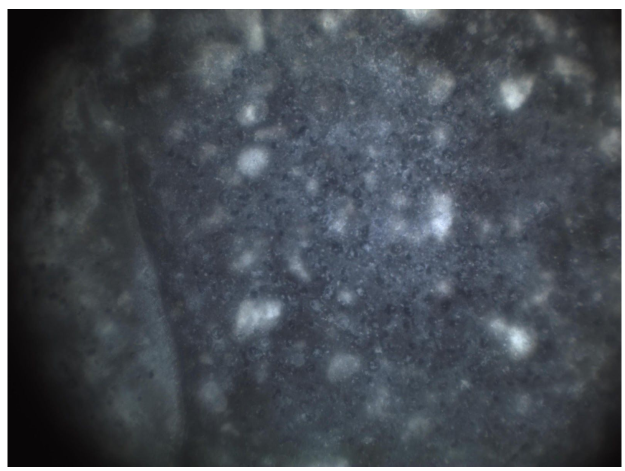
(C) Concrete Specimen 3 (Broken)
Figure 14. Microscopic Picture of Experiment 1 (A), (B), (C) (continued)



(A) Concrete Specimen 1 (Broken)
Figure 15. Microscopic Picture of Experiment 2 (A), (B), (C)



(B) Concrete Specimen 2 (Broken)



(C) Concrete Specimen 3 (Not broken)

Figure 15. Microscopic Picture of Experiment 2 (A), (B), (C)(continued)

Conclusion

The objective of this project was to determine an optimum p-value, ratio between fc' and density. Two different mix design methods were evaluated to determine a preferred method to develop concrete mix components.

From analyzing the data and results for both Experiment 1 and 2, a few conclusions can be drawn. First, decreasing the water to cement ratio from 0.68 to 0.58 in Experiment 1 to Experiment 2 showed an increase in compressive strength for the concrete specimens. This in turn, increased the p-value and achieved a more desired result. An increasing w/c ratio resulted in a decreased strength.

Second, decreasing the mixture's overall weight by substituting more perlite in lieu of fine aggregate, yet maintaining the total volume, results in a decrease in density for concrete in Experiment 2. As illustrated in Equation 4, there is an inversely proportional relationship between f'c and density. Therefore, the reduced density in Experiment 2 resulted in an increased p-value.

A third conclusion can be drawn from the results. The effects of curing and the environment which a specimen is cured in are related to the specimens' overall strength. If the specimen was subjected to a saturated environment for as long as possible but allowing a period to dry before submitted to testing, the overall load one specimen could undergo would be increased.

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Appendix A

Symbols and abbreviations

A	area
f'_c	Compressive strength
ft^3	cubic feet
hrs.	hours
kg	kilogram
kN	kilonewton
kPa	kilopascal
lbf	pound force
lbs	pounds
m	meter
M	mass
min.	minute
mm	millimeter
P	force
psi	pounds per square inch
V	Volume
yd^3	cubic yard
ρ	density