EFFECTS OF REPEATED WET-DRY CYCLES ON COMPRESSIVE STRENGTH OF FLY-ASH BASED RECYCLED AGGREGATE GEOPOLYMER CONCRETE (RAGC)

by

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Khaled Sobhan, Department of Civil Engineering, and has been approved by the members of her supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

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Title: Effects of Repeated Wet-Dry Cycles on Compressive Strength of Fly-Ash Based Recycled Aggregate Geopolymer Concrete (RAGC)

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Geopolymer concrete (GC) is a sustainable construction material and a great alternative to regular concrete. GC is a zero-cement material made from a combination of aluminate, silicate and an activator to produce a binder-like substance.

This investigation focused on the effects of wet and dry cycles on the strength and durability of fly ash-based recycled aggregate geopolymer concrete (RAGC). The wet-dry cycles were performed approximately according to ASTM D559 standards.

RAGC specimens with nearly 70% recycled materials (recycled aggregate and fly ash) achieved a compressive strength of approximately 3600 psi, after 7 days of heat curing at 60ºC. Although the recycled aggregate is prone to high water absorption, the compressive strength decreased by only 4% after exposure to 21 wet-dry cycles, compared to control specimens that were not exposed to the same conditions. Accordingly, the RAGC material developed in this study can be considered as a promising environmentally friendly alternative to cement-based regular concrete.

DEDICATION

This investigation is dedicated to my family, especially to my patient and amazing husband Jody Mendelson, who has supported me and encouraged to continue working hard during my many years spent at school. To my children Nathan and Andrew, always remember that you can achieve anything, if you are willing to work hard for it. Thank you for cheering me on along the way, and giving me the strength to make it to the finish line.

I also dedicate this work to my mother Maria Nelly, she taught me the meaning of perseverance and hard work. Thank you mami for being with me every step of the way, for your love, and for your support. I love you all.

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

The production of cement for use in concrete is believed to be a major contributor to environmental pollution thorough the dispersal of fines and the heating and production process that uses fossil fuels. Constant exploitation of natural resources for cement production accentuate the issue that there is a finite amount of aggregates available, and that mining for these materials is a significant issue for local communities. One option is to recycle crushed concrete aggregate from construction sites, thus reducing the stress on the production and mining process. Over the years scientists have tried to develop environmentally friendly materials to minimize the harmful effects of construction to environmental pollution. However, the need for Portland cement has remained and is continuously increasing.

In search of a sustainable material, Davidovits (1979) developed a binder like substance called Geopolymer. Geopolymers are chains of mineral molecules linked with covalent bonds to form a binder. The process involves a fast-chemical reaction between alkaline liquids such as sodium hydroxide, potassium hydroxide or sodium silicate. Geopolymerization is believed to reduce the carbon dioxide production at Portland cement factories since it only needs one third of the fuel required by cement production. Geopolymerization does not require high temperature kilns, and does not rely on the calcinations of calcium carbonate (Bondar, 2015). As a result, geopolymer concrete is a very promising concept for the concrete industry.

This research intends to evaluate the strength characteristics of geopolymer concrete with crushed aggregate containing fly ash to create an innovative, environmentally friendly concrete mix that will reduce waste, save energy, decrease harmful emissions, and reduce the space needed for landfills (Thornmark, 2000). This relatively new construction material contains nearly 70% recycled materials.

To evaluate the durability and strength of this sustainable material, two batches of twelve 4”x 8” cylinders were prepared. The cylinders underwent a series of wet dry cycles to simulate environmental conditions suffered by concrete exposed to the elements, the test was performed in accordance with ASTM, (2003). The changes in moisture content experienced by concrete, generally enhance shrinkage and cracking as moisture is lost to the environment. Bissonnette (1999) determined that the magnitude of shrinkage strain experienced by the material is often proportional to the amount of moisture lost. Exposure to wet-dry cycles could alter the interior humidity of the material and decrease its strength and durability.

Another important contributor to loss of moisture could be the recycled aggregate that was used in the mix. Typically, recycled aggregate exhibits higher water absorption and lower specific gravity than natural aggregate, producing concrete with higher shrinkage and creep. Further investigation on wet-dry cycles on RAGC are essential to determine how the changes in moisture of the material can affect the compressive strength of the cylinders.

Menglim, et al (2017) research on the effects of the wet-dry cycles on asphalt concrete using geopolymer determined that the compressive strength was reduced over time during exposure to wet-dry cycles. Additionally, the said study determined that recycled asphalt pavement containing 20% of fly ash increased the compressive strength on cycles 1 through 6, and subsequently decreased the compressive strength presenting mild surface cracks and loss of moisture content during the drying stage. Given that asphalt concrete is used primarily for road and parking surfaces, this loss may not be critical, however, no similar studies could be found on the moisture effects in recycled aggregate–fly ash geopolymer concrete.

Geopolymer technology is at its beginning stages of development. Research on this field needs to be further developed to determine its behavior when interacting with other materials. Since geopolymer technology was introduced by Davidovits (1979), researchers have combined geopolymer with other cementing materials such as fly ash, silica fume, granulated blast furnace slag, rice husk etc. to develop alternative binders to Portland cement in order to produce and effective mix that presents high durability performance and comparable physical and mechanical properties to those of Portland cement concrete.

1.2 RESEARCH OBJECTIVE

The RAGC specimens used in this study contain nearly 70% recycled and waste materials with no cement. Therefore, it is important to evaluate if the material is reaching sufficient strength to be used in structural applications. Moreover, due to the high-water absorption rate of recycled aggregate, it is significant to monitor the loss of degradation of its properties when exposed to repeated wet-dry cycles.

Specific objectives to of this investigation were:

1. To determine the compressive strength of fly ash based geopolymer concrete with recycled aggregate, and compare it with the strength of control specimens not subjected to wet-dry cycles.

2. To determine the effects of wet-dry cycles on the compressive strength of RAGC
3. To identify any changes in volume and density on RAGC due to wet-dry cycle exposure.
4. To determine a correlation between the number of wet-dry cycles and the maximum compressive strength of RAGC.

1.3 RESEARCH SIGNIFICANCE

The alkali activated geopolymerization caused by fly ash is considered a cleaner process due to lower carbon dioxide emissions (Bondar, 2015). As a result, geopolymer concrete cylinders have shown to be a very promising solution for the concrete industry. Since geopolymerization is still in development, is necessary to study the material's performance when interacting with other sustainable materials to minimize the negative effects of construction on the environment and carbon footprint.

. In previous years fly ash was released into the atmosphere, however, due to new air pollution control standards, fly ash is required to be captured before being released into the environment. In the US, fly ash is generally stored in power plants until it is transported to the landfill. Reusing fly ash has become a necessity to reduce the need of landfill space, to reduce the wear and tear of the roads during hauling, and to save the costs of transportation. The addition of fly ash to the geopolymer mix not only enhances the hardening attributes, but also improves performance, bond, durability and mechanical properties of the material. Using fly ash ranging from 40 to 60 percent of the mix, produces concrete that can be used in structural applications with high performance and strength

Producing concrete requires billions of tons of natural aggregates per year, mining and transporting of these aggregates is costly and produces abundance of greenhouse gases. The high demand of aggregate has motivated the construction industry to start using recycled aggregate as a construction material. Recycling concrete is a relatively simple process, that requires breaking, removing and crushing concrete debris from a construction site. Recycling aggregate reduces the amount of material that ends up in the landfills, reduces the use of virgin aggregates and mining, reduces the costs of transportation, and minimizes the negative impact to the environment.

Using recycled aggregate can be difficult due to its high-water absorption. This investigation seeks to determine the effects of wet dry-cycles on recycled aggregate fly ash geopolymer concrete (RAGC). Since wet-dry cycles can alter the internal humidity of concrete and affect concrete's performance, durability and strength, it is necessary to determine if the compressive strength levels are affected by the exposure to simulated environmental conditions, while determining if this revolutionary material can be a good replacement for Portland cement concrete.

1.4 SCOPE OF WORK

This experimental research involves the evaluation of the compressive strength of fly ash based geopolymer concrete and the effects of wet-dry cycles on compressive strength. The mix design used was limited to the method developed by Wallah & Rangan, 2006.

Water absorption by the recycled aggregate was not measured, however the changes in density were evaluated, ASTM D559, (2003) was approximately followed. No micro-structure properties of the RAGC were studied.

CHAPTER 2: LITERATURE REVIEW

Research on geopolymer, recycled aggregate, and fly ash, showed that each of these materials possess positive characteristics that can be beneficial when used in combination to cement to produce concrete. Geopolymer use is still in the early stages of development and very little information is found on their combination with recycled aggregate to produce concrete. This investigation includes background information on each of these materials, as well as their combined use to determine if their individual properties can enhance each-other's weaknesses.

2.1 BACKGROUND INFORMATION ON GEOPOLYMER

Geopolymerization is explained as the process of combining many small molecules into a covalently bond, and is carried out through oligomers (dimer, trimer, tetramer, pentamer). This process involves a substantially fast chemical reaction that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al bonds (Davidovits, 1994). Geopolymers are classified in two branches, organic and inorganic polymers. The organic polymers based include natural, synthetic and natural polymers, such as rubber, textile fibers, plastics, etc. Inorganic polymers are carbon-based such as silicon. Geopolymers include three classifications of inorganic polymers which depend on the ratio of Si/Al in the structures:

- a) Poly (sialite) (-Si-O-AL-O-)
- b) Poly (sialate-siloxo) (-Si-O-Al-O-Si-O-)
- c) Poly (sialate-disiloxo) (-Si-O-Al-O-Si-O-Si-O-)

The distribution and relative amounts of each different Al and Si building blocks affects the chemical and physical properties of the final product (Bondar, 2015).

The most common alkaline liquid used in the process of geopolymerization is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate. (Suresh, et al. 2013). Studies performed on the influence of Sodium hydroxide solution on 7 days compressive strength for (ASTM, 2013) class F fly ash, determined that the optimum sodium hydroxide concentration was 6M and produced a compressive strength of 22MPa (Ridtirud, et al. 2011). Other conclusion from this investigation revealed that excessive silicate in the mix reduced its compressive strength by disrupting the formation of three dimensional networks.

Figure 1 represents the process of geopolymerization simplified in 2 simple steps. First the solid material is dissolved into the alkaline, normally NaOH or Na_2SiO_4 solution and the polycondensation process leading to formation of an amorphous to semi-crystalline polymer.

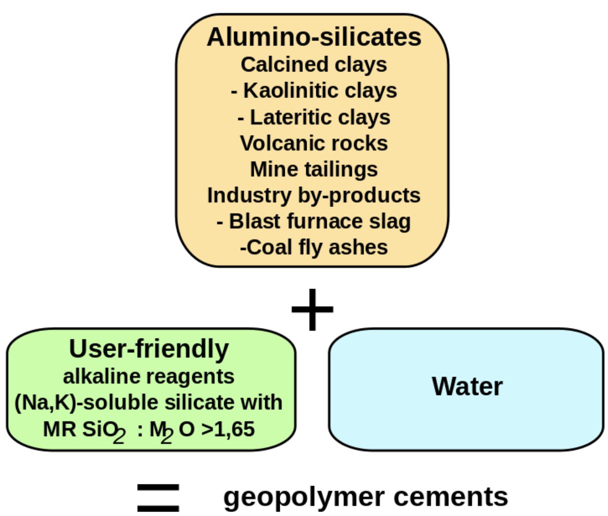


Figure 1. Geopolymer Process (Davidovits, 2015)

Other investigations have reported that the important parameters for satisfactory polymerization are the relative amounts of Si, Al, K, Na molar ratio of Si to Al present in the solution, the ratio of alumina silicate mineral to kaolinite (when added), the type of alkaline activator, the water content and the curing temperature. (Barbosa, et al. 2000) (Rowles & O'Connor, 2003)

In 1970, Joseph Davidovits introduced the idea that such alkaline liquids could react with other chemicals such as aluminum silicon to create a binder like substance. Since then, scientists are testing the use of geopolymer in combination with recycled materials to produce concrete. Investigations performed on Fly ash geopolymer concrete concluded that the combination of these materials produce a strong concrete with excellent compressive strength and with elastic properties similar of those or Portland cement concrete. (Rangan, et al. 2008).

Some of the advantages of using geopolymer concrete include high fire resistance, excellent adhesion to concrete surfaces, less degradation under UV lighting, and having comparable results to those of Portland Cement Concrete (Balaguru, et al. 1997). Investigations on geopolymer determined that this technology possesses high resistivity to freeze-thaw cycles which are a major attack to cement and concrete (Trofimov, et al. 2017), and even after exposure to 150 freezing-thawing cycles, geopolymer concrete showed no sign of damage (Temuujin, et al. 2014).

Other advantages of using geopolymer concrete include superior dimensional stability and durability which are directly related to the mechanical properties exhibited by the curing regimen and chemical activator used during the mixing process. (Davidovits, 2015) (Xiao, et al. 2015), (Krishnan, et al. 2014).

Some known limitations of geopolymer concrete include the quick setting time, loss of workability, and the need for heat during curing to gain strength. If exposed to excessive high curing temperatures, it can suffer rapid evaporation which can produce an incomplete geopolymerization (Ahmari & Zhang, 2011) and can result in the dehydration, shrinkage and ultimately decrease of compressive strength (Palomo, Grutzeck, & Blanco, 1999).

Somna, et al. (2011) proposed that by replacing 10% of the Portland cement on mass basis with fly ash can increase the strength in geopolymer at room temperature conditions over a prolonged period of curing time. Other related investigation found that the composition and pore structure of fly ash enhances the escape of moisture and helps avoid damaging during heating. Temuujin, et al (2014) and Rickard, et al (2011) determined that iron oxides in fly ash directly affected the thermal properties of geopolymer by changing the morphology after heating, and improving its mechanical properties and durability of geopolymer. Additionally, it was determined that presence of silicate ions in the alkaline solution substantially improves the mechanical strength and modulus of elasticity.

Other investigations performed by Jaarsveld et al (2002) have focused on the benefits of using different curing methods for geopolymer to enhance performance, their research reported that high temperatures for long periods of time can weaken the structure of the hardened material, however longer curing times and higher curing temperatures increased the compressive strength in fly ash based geopolymer concrete. This increase in compressive strength may not be significant for curing at 60°C or higher and periods longer than 48 hours (Hardito, et al 2004a) (Hardito D,Wallah, et al (2004c).

Fly ash based geopolymer concrete's use is rapidly growing. Some of the most common applications include using it as an absorbent and an immobilizer of toxic metals. GC has performed more efficiently than Portland cement concrete, and has been used as a sealant to store CO_2 in the underground. Combined with strong alkali solutions, geopolymer concrete, can be adapted in other applications such as pre-cast concrete, railway traverse, waste water pipe lines, hydraulic structures and pre-tension concrete structures. (Bondar, 2015). Considering the low cost and low emissions of CO_2, low energy emission geopolymer cement can be considered as a great green alternative compared to Portland cement concrete.

2.2 RECYCLED MATERIALS AND GEOPOLYMER CONCRETE (USGS, 2000).

The use of recycled materials in construction has proven to minimize the environmental footprint caused by current the construction processes as well as to be a profitable solution for the construction industry. Currently, 100 million tons of concrete is recycled into usable aggregate (USGS, 2000). It is estimated that there has been a total savings of $224 million in construction since 1979, which included reduced tippage and freight charges. Other benefits associated with using recycled aggregate include a decrease in transportation costs, reduction on material hauling, a decrease of landfill space required for debris, and a decrease of gravel mining.

Figure 2 summarizes the multiple benefits of using recycled materials in combination with geopolymer concrete.

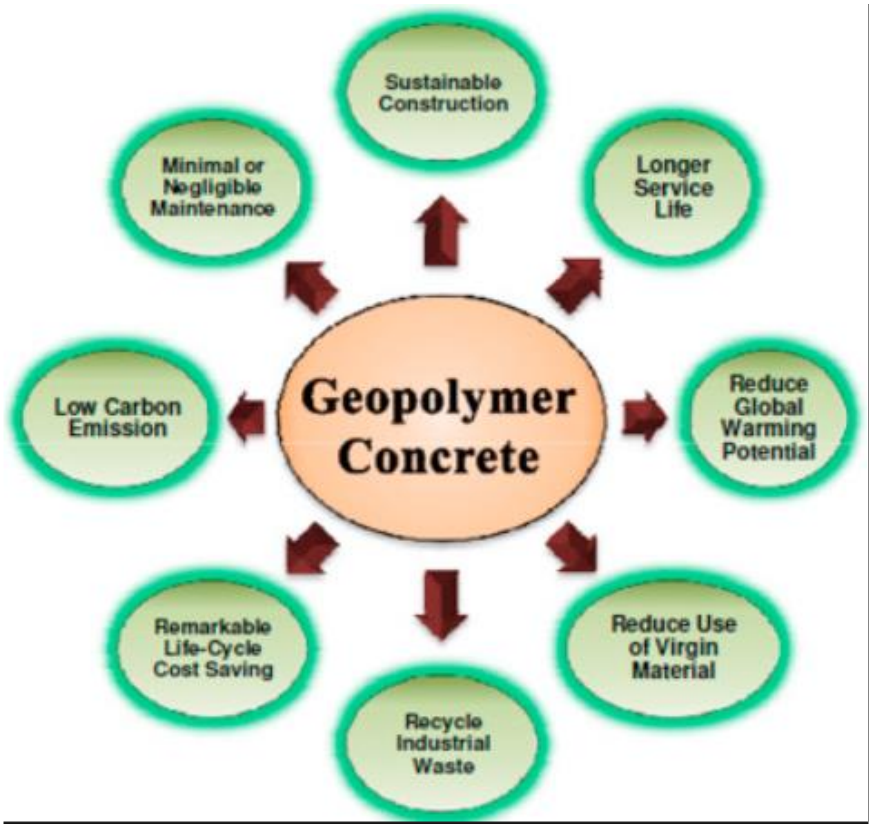


Figure 2. Benefits of using Geopolymer Concrete in Construction

2.3 FLY ASH AND GEOPOLYMER (WALLAH & RANGAN, 2006)

The geopolymer technology proposed by Davidovits is a promising alternative for the replacement of Portland cement in the concrete industry. The Geopolymer Concrete Research Group at Curtin University of Technology developed several studies on fly ash geopolymer concrete, inspired on the fact that fly ash is currently a waste material. Their investigations focused on the manufacture and engineering properties of hardened concrete. Their research concluded that higher concentrations (molar) of sodium hydroxide solution results in higher compressive strength of fly ash based geopolymer. Furthermore, higher ratios of sodium silicate to sodium hydroxide by mass, produces higher compressive strength on fly ash based geopolymer. Additionally, it was determined that longer curing time and higher temperatures during curing produce higher compressive strength of fly ash-based geopolymer and adding superplasticizer up to 4% of fly ash by mass, improves workability of the material with little decrease in compressive strength. (Hardito & Rangan, 2005)

Other results from (Hardito & Rangan, 2005) investigation concluded that increasing the ratio of water to geopolymer solids by mass decreases the compression strength of the fly ash-based geopolymer concrete, their study established that the average density, modulus of elasticity, and Poisson's ratio of FAGC are similar to those obtained by Portland cement concrete.

Based on the results of their investigation, Hardito and Rangan (2005) proposed a geopolymer mixture design process for fly ash based geopolymer concrete. The mixture design process is summarized in Figure 3. Their mixture design is based on performance required, and the performance depends on the application of the FAGC. The illustration shows that the performance criteria is either compressive strength or workability, which determines the mixing process (Hardito & Rangan, 2005).

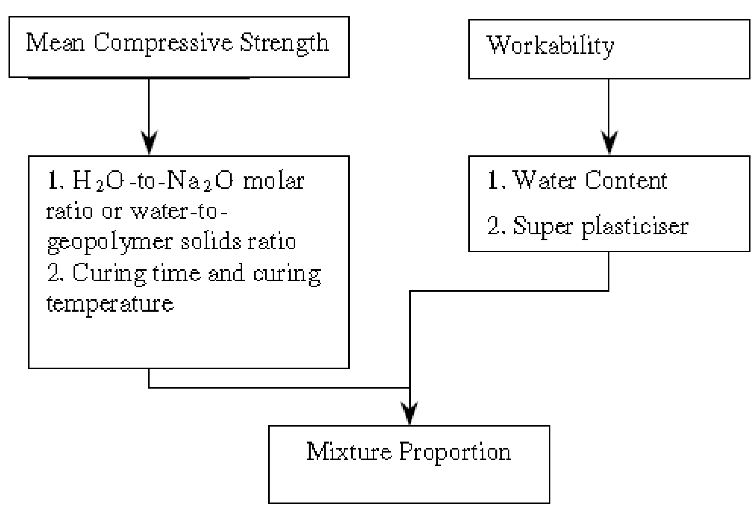


Figure 3. Preliminary Mixture Design Process (Hardito & Rangan, 2005)

A second investigation performed by Wallah & Rangan (2006) on low-calcium fly ash-based geopolymer concrete, focused on investigating creep behavior under sustained load, drying shrinkage behavior, and resistance to sulfuric acid of the fly ash geopolymer concrete. Their study indicated that fly ash based geopolymer concrete showed a decrease in creep as the compressive strength increased. Furthermore, fly ash-based geopolymer concrete undergoes less creep compared to Portland cement concrete (Wallah & Rangan, 2006)

Their research also found that heat-cured low calcium fly ash geopolymer has excellent compressive strength which increases with age and temperature, while suffering very little drying shrinkage, low creep, excellent resistance to sulfate attack, and good acid resistance (Wallah & Rangan, 2006). Other related investigations on fly ash based geopolymer concrete's resistance, determined that abrasion is higher when the mixture contains alkali activation. Annapurna (2015) compared experimental and theoretical results for five different values of alkaline liquid ratio. The results of the investigation indicated that the 7 and 28-day compressive strength increased by increasing the amount of alkaline liquid ratio.

2.4 COMPRESSIVE STRENGTH OF SODIUM ACTIVATED GEOPOLYMER MODELS (Fillenwarth, 2013)

A study focused on determining the compressive strengths of geopolymer paste mixes by using optimization models, concluded that an appropriate curing regime can achieve maximum potential of a mix in one day. Additionally, the investigation determined that geopolymers cured at 85°C for 24 hours will develop full potential if they are properly covered to prevent desiccation.

Fillenwarth (2013) investigation determined the factors affecting the behavior of concrete, which include the contents of H_2O, Na_2O and CaO, where CaO is responsible for the flash set, while the H2O and Na_2O contents inhibit flash set. Additional findings from this investigation included that the CaO does not have a substantial impact on the strength of the development. The formula used by the model to predict the maximum potential strength (NS) of the geopolymer mix is illustrated in Equation 1.

Equation 1. Maximum Potential Strength Equation

$$\mathrm{NS} = 0.7893\ \mathrm{exp.}\,(0.3866\mathrm{c}\frac{0.2379\mathrm{a}}{b^2} + \frac{2.1\mathrm{abc}}{-0.3452c + 1.267b^2 + c^2} - 4.726\ a * b^2)$$

Where a=6*(H_2O-0.14), b=^*Na_2O, c=10(R.SiO_2-0.07), NS= (7/100)*S (ksi), and S= total Na silicate in the mix. (Fillenwarth, 2013)

2.5 RECYCLED AGGREGATE AND FLY ASH BASED CONCRETE

Previous studies sought to confirm that by using recycled aggregate in combination with fly ash to produce concrete, the material that sufficiently perform in terms of safety and serviceability (Corinaldesi, et al. 2000). Recycled aggregate's properties have shown to be comparable to those of natural aggregate, with exception to water absorption, which increased by 12% compared to natural aggregate concrete which displayed a drying shrinkage was about 25% after the first year of preparation (Sagoe, 2002). Summary of the properties of natural and recycled aggregate are displayed in Table 1. The properties of the two elements, show minimal differences except when evaluating the percentage of water absorption. The results show that the percentage of water absorption in recycled aggregate is almost 4 times higher than natural aggregate.

Table 1. Properties of Natural and Recycled Aggregates

(Jagannadha et al. 2016)

Type of mix	Fineness Modulus	Specific Gravity	% Water Absorption	Bulk Density (kg/m^3)	% Voids
Natural aggregate	6.83	2.8	0.5	1567	44.03
50% RCA	6.85	2.67	1.94	1434	46.2

The research also evaluated the difference in tensile and compressive strength for Portland cement concrete mixed with recycled or natural aggregate. The investigation concluded that fresh and hardened recycled aggregate concrete's splitting tensile/compressive strength ratios are comparable to results obtained for conventional concrete made with natural aggregate concrete. (Sagoe, 2002).

Figure 4 illustrates the compressive strength results on concrete cylinders stored under moist conditions for up to 365 days. The results show no significant difference between the strength of Portland cement as a function of aggregate type.

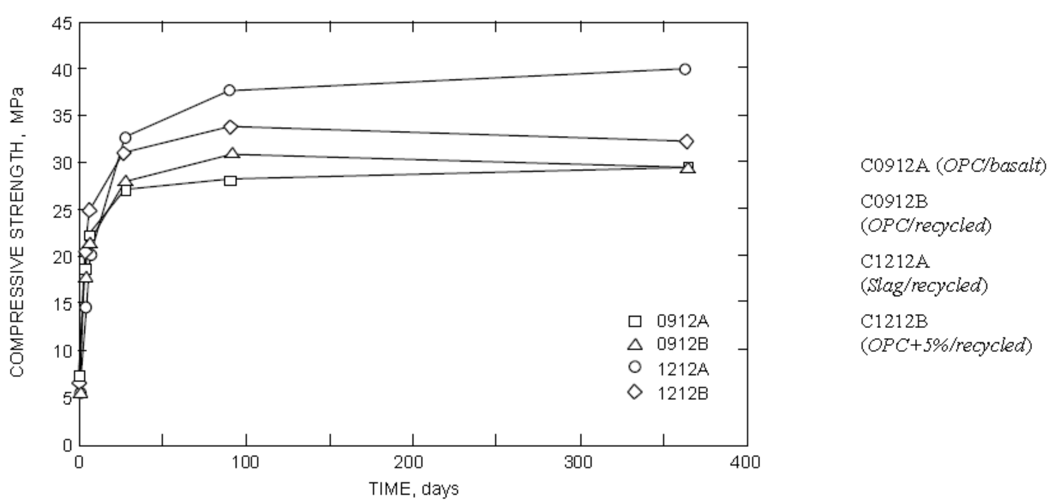


Figure 4. Development of Concrete Compressive Strength with Age (Sagoe, 2002)

Further analysis concluded that using mineral admixtures like fly ash and silica fume may increase the resistance to acid exposure by making the concrete relatively less permeable (Jagannadha, Rao, & Sastri, 2016). These investigations determined that fly ash added to recycled aggregate concrete improves the pore structure since the volume of macro pores is reduced, which causes benefits in terms of compressive, tensile and bond strength (Corinaldesi & Moriconi, 2001). Additionally, it was also observed that fly ash protects and enhances the other materials preventing them from corrosion.

Table 2 summarizes the changes in Portland cement concrete properties when regular aggregate is replaced by recycled concrete aggregate.

Table 2. Changes in Portland Cement Concrete Properties when Virgin Aggregate is Replaced by RCA ((NCHRP), 2013)

Property	Expected changes in properties	
	Coarse RCA only	Coarse and fine RCA
Specific gravity	0–10 % lower	5–15 % lower
Compressive strength	0–24 % lower	15–40 % lower
Tensile strength	0–10 % lower	10–20 % lower
Strength variability	Slightly greater	Slightly greater
Modulus of elasticity	10–33 % lower	25–40 % lower
Creep	30–60 % higher	30–60 % higher
Drying shrinkage	20–50 % higher	70–100 % higher
Permeability	0–500 % higher	0–500 % higher
Coefficient of thermal expansion	0–30 % higher	0–30 % higher
Corrosion rate	May be faster	May be faster
Freeze–thaw durability	Dependent on air void system	Dependent on air void system
Carbonization	65 % greater	65 % greater
Sulfate resistance	Dependent on mixture	Dependent on mixture

Investigations on the properties of concrete containing fly ash and recycled concrete aggregate, determined that the coefficient of permeability increased to a small degree by fly ash or recycled concrete aggregate. The modulus of elasticity decreased when either fly ash or reduced concrete were incorporated into the concrete mix. Fly ash preserved the strength of the specimens under environmental exposure to water, improved the strength, and increased the stiffness of the mix, while decreasing the effects of deformation caused by load application (Sagoe, 2002).

A previous study on the prediction of compressive strength of concrete with and without fly ash by using regression models determined that concrete containing fly ash performed favorably and achieved a higher compressive strength than its counterpart. Additionally, the research indicated that the regression coefficients of the mix with fly ash is better than those without (Chopra, Sharma, & Kumar, 2014).

A related investigation performed at Florida Atlantic University focused on testing the compressive strength of recycled aggregate concrete after exposure to wet-dry cycles. The results concluded that the density of the material for samples containing fly ash remained stable after long periods of wet-dry cycling exposure, which protected the samples from water intrusion and deterioration. Additionally, cylinders exposed to wet and dry cycles containing fly ash provided a longer prediction on the age of the material (Gonzalez, 2010).

Other conclusions drawn from this investigation were that the stiffness of the samples increased as the number of cycles increased, the higher increase occurred in samples containing fly ash. As per the maximum compression strength, the study indicated that the compressive strength decreased by approximately 13% as the number of cycles increased, however the decrease was lesser in the cylinders containing fly ash. (Gonzalez, 2010).

2.6 COMPRESSIVE STRENGTH OF RECYCLED AGGREGATE CONCRETE (Koenders, et al. 2013).

Research using models of the maximum compressive strength achieved in mixes containing dry recycled aggregate combined with cement concrete, and saturated recycled aggregate with cement concrete determined saturated recycled aggregate hardly contributed to the compressive strength of the mix. The lack of contribution of the saturated recycled aggregate could be due to high water absorption of RA or its shrinkage after hydration. Additionally, the results showed that dry aggregates achieved high values of compressive strength approximately of 35 MPa. The study concluded that uncertainty remains about the actual strength of RA once saturated, since a strong reduction in strength was needed to obtain good agreement (Koenders et al. 2013).

2.7 EFFECT OF WET DRY CYCLES ON COMPRESSIVE STRENGTH OF ASPHALT PAVEMENT GEOPOLYMER (Menglim et al. 2017).

Previous investigations focused on evaluating the effects of wet-dry cycles on recycled asphalt geopolymer pavement, determined that samples exposed to less than 6 cycles presented an increase in strength due to chemical reactions. Additionally, it was reported that samples exposed to more than 6 wet-dry cycles, presented cracks due to loss of moisture content during the drying stage and they showed signs of decreased strength.

The recycled aggregate pavement – fly ash geopolymer with higher NaOH content exhibits higher durability performance which can be attributed to the stable cross-linked geopolymer structure (Menglim et al. 2017).

Figure 5, illustrates the changes of unconfined compressive strength of the mix, the results show the compressive strength increase from cycles 1 through 6. The strength decreases past the 6th cycle possibly due to the exterior deterioration of the cylinders and water loss, where micro-cracks form on the surface and increase in number with increased number of wet dry cycles. It was determined that recycled aggregate pavement mixed with 20 percent of fly ash provided higher durability when exposed to wet-dry cycles and geopolymer with higher contents of NaOH exhibit better durability performance, which ultimately can be attributed to the formed stable cross-linked polymer structure (Menglim, et al. 2017).

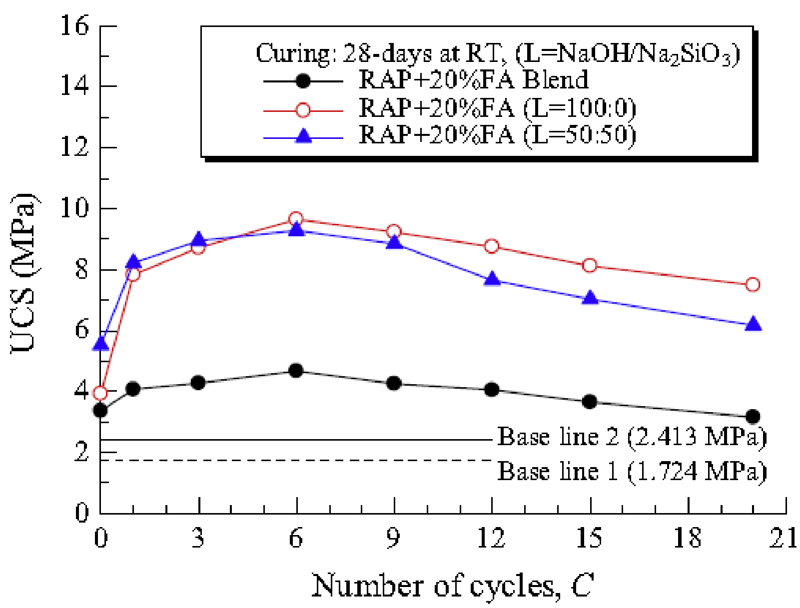


Figure 5. Relationship Between Strength and Number of W-D cycles of RAP Blend + 20% Fly Ash blend and RAP + 20% Fly Ash geopolymers. (Menglim, et al. 2017)

Related investigations performed at Florida Atlantic University on the effect of wet-dry cycles on pavement foundation made with recycled aggregate concrete concluded that samples exposed to wet dry cycles had a lower compressive and flexural strength of about 13.5 % compared to cylinders that did not undergo environmental exposure. As per residual compressive strength, the investigation determined that by increasing the number of cycles and stress ratio, the residual compressive strength decreased. Lastly, it was determined that the performance of cylinders containing 80% recycled materials not exposed to wet dry cycles were comparable to traditional Portland cement concrete. (Sobhan, Gonzales, & Reddy, 2015).

2.8 THERMAL PERFORMANCE OF GEOPOLYMER CONCRETE VS. ORDINARY CONCRETE (Aslani, 2015)

Aslani (2015) determined the effects of elevated temperatures on the properties of geopolymer concrete. This investigation demonstrated that the compressive strength and modulus of elasticity of geopolymer concrete increases with increased temperatures as opposed to ordinary concrete. Additionally, the study indicated that the flexural strength of geopolymer concrete increased while Portland cement concrete decreased and it was observed that geopolymer concrete expanded at temperatures below 100°C and it shrank at temperatures ranging from 200 to 1200°C.

2.9 CHANGES IN INTERIOR HUMIDITY OF CONCRETE AFTER WET – DRY CYCLES (Zhang, et al. 2012).

Studies on wet-dry cycles are critical to determine the durability of structures. Studies performed by Ahang (2012) to determine the variation of interior humidity in concrete have found that only interior moisture varies within a certain depth from the drying/wetting face.

The previously mentioned experiment measured the internal relative humidity in concrete from the time of casting until the end of the wet-dry cycles. The internal humidity was simultaneously represented graphically in a chart that considered the cement hydration and the moisture diffusion. Figure 6 illustrates the results of the humidity distribution of concrete under exposure to a pre-determined number of wet-dry cycles. The study revealed that changes in moisture occur in the region of influence which changes periodically under wet-dry cycles. The research affirms that when the concrete is exposed to wet cycles, the interior humidity of the specimens increased rapidly reaching approximately 100%. However, when the cylinders are exposed to the dry part of the cycle, their interior humidity does not decrease immediately but in a paced manner. (Zhang, et al. 2012)

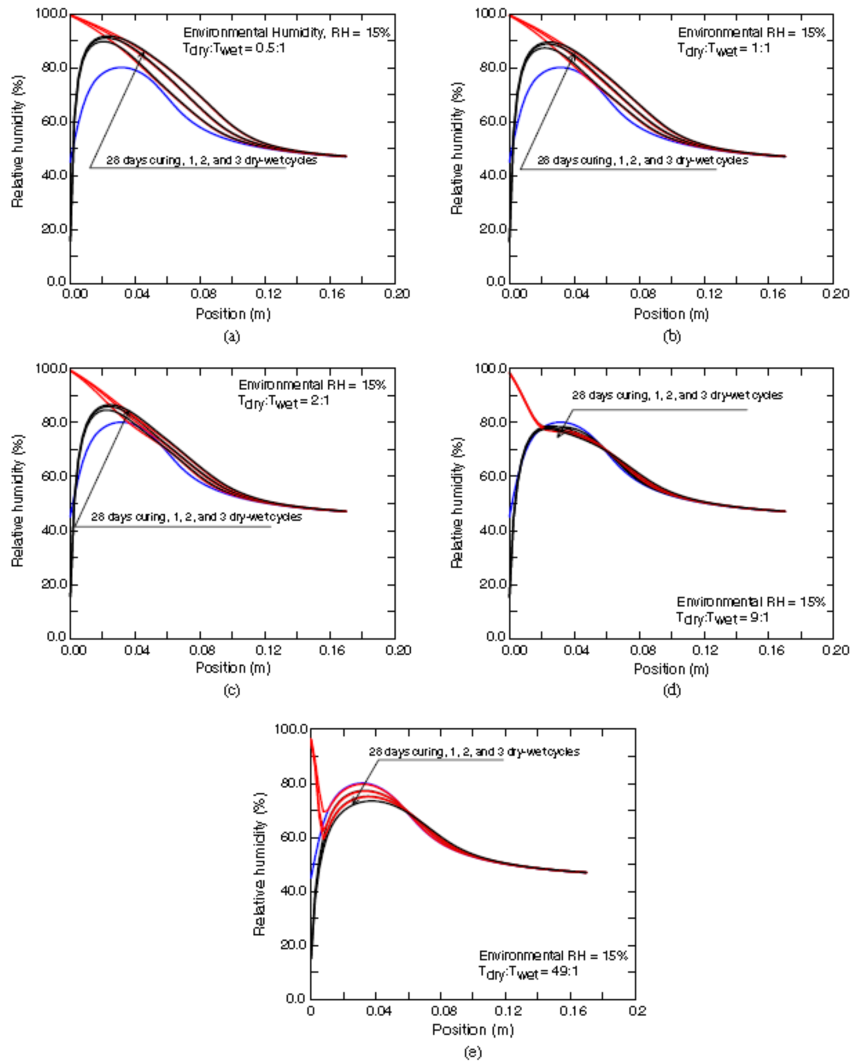


Figure 6. Humidity Distribution in C80 Concrete Slab at Typical Ages Under Wet-dry Cycles with different ratios of Drying and Wetting Time Zhang, Yuan, & Yudong, 2012)

2.10 COMPRESSIVE STRENGTH AND DURABILITY OF CONCRETE AFTER WET-DRY CYCLES (Toutanji, et al. 2004)

Toutanji (2004) studied the effects of 14-days of wet dry cycling exposure on strength, durability and resistance of concrete combined with a variety of cementitious materials. The research concluded that combining 10% silica fume, 25% slag, and 15% fly ash in the mixture produced higher strength and higher resistance to freeze thaw and wet dry cycle exposures compared to other mixes (Toutanji, et al. 2004).

The study determined that there was a positive correlation between the contents of fly ash and slag and the increase in compressive strength of the concrete mixes. For samples containing 20% of fly ash, the increase in strength was about 16%, compared to specimens containing 30% which reached a higher amount. Additionally, the study demonstrated that the compressive strength of plain concrete specimens decreased due to wet dry cycles using salt water in comparison to specimens not exposed to similar conditions.

Figure 7 illustrates the compressive strength of plain concrete specimens after exposure to wet dry cycles. The different combination names and mix for all the sample types are explained and summarized in Table 3.

Table 3.Mixed Proportions Used for Investigation

Mix proportions

Mix	Cement (%)	Silica Fume (%)	Slag (%)	Fly ash (%)	Superplasticizer (%)
Control	100	0	0	0	2
8% SF	92	8	0	0	2
10% SF	90	10	0	0	2.5
15% SF	85	15	0	0	2.5
60% S	40	0	60	0	1.5
70% S	30	0	70	0	1.5
80% S	20	0	80	0	1.5
20% FA	80	0	0	20	1.5
25% FA	75	0	0	25	1.5
30% FA	70	0	0	30	1.5
Combined A	50	10	25	15	2.0
Combined B	50	5	35	10	2.0
Combined C	50	7.5	30	12.5	2.0
Combined D	50	0	40	10	2.0
Combined E	50	0	30	20	2.0
Combined F	50	0	25	25	2.0

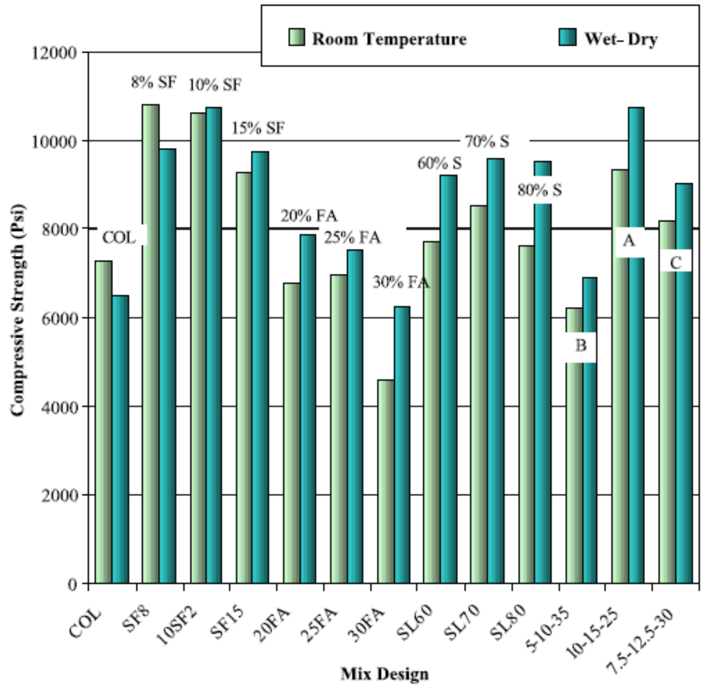


Figure 7. Compressive Strength Data for Both Room Temperature and Wet Dry Conditions (Toutanji et al. 2004)

2.11 DURABILITY OF FLY ASH GEOPOLYMER CONCRETE EXPOSED TO MARINE ENVIRONMENT (D.V. Reddy, 2013)

A related research performed at Florida Atlantic University evaluated the durability characteristics of low calcium fly ash based geopolymer concrete after being subjected to corrosive marine environment conditions. Geopolymer concrete beams containing fly ash with 8M and 14M concentrations of NaOH and SiO_2, were reinforced with 13mm rebar and were tested for accelerated corrosion exposure with artificial seawater wet-dry cycles (D.V. Reddy, 2013).

The study determined the primary difference in behavior and properties between geopolymer concrete and ordinary Portland cement concrete. The results of the investigation indicated that geopolymer concrete is more homogeneous and bonds well to the aggregate. Additionally, fly ash based geopolymer had improved crack resistance and long-term durability. The investigation demonstrated a compressive strength increase between 7 and 28 days and the compressive strength results were higher for geopolymer concrete than ordinary Portland concrete (D.V. Reddy, 2013).

Table 4 summarizes the results of the compressive strength test. The average values obtained indicated that the tensile strength for 8 and 14M geopolymer concrete exceeded the values recommended by ASTM, 2011 (10-15% of the compressive strength for OPC mixtures). For the compression test, the results indicated that the strength achieved by geopolymer concrete were greater than those obtained by ordinary Portland concrete.

Table 4. Compressive and Splitting Tensile tests at 7 and 28 days.

Mixture	Curing type	Mean compressive strength (MPa)	Mean splitting tensile strength (MPa)
Mixture 1	Dry curing (oven)	29.7[a]	4.77[a]
		39.9	9.65
Mixture 2	Dry curing (oven)	56.2[a]	11.9[a]
		60.2	23.0
Control	Ambient conditions	22[a]	2.64[a]
		33	4.68

[a]These tests at were performed 7 days, and the remaining tests at 28 days.

D.V. Reddy, (2013) indicated that geopolymer concrete presented reduced cracking when exposed to marine environment conditions, which implied a permeability reduction and the electrical resistivity of geopolymer concrete was not significantly affected over time. Furthermore, the investigation concluded that the binder performed effectively to create a strong bond between the aggregates and the paste which prevented separation between them during failure.

2.12 DURABILITY OF RECYCLED AGGREGATE CONCRETE EXPOSED TO ACCELERATED AGING (Gonzalez, 2010)

Another investigation on mixes containing recycled aggregate performed at Florida Atlantic University focused on the effects of accelerated aging on recycled aggregate fly ash cement concrete. The samples were subjected to elevated temperatures and wet dry cycles. The results of the investigation indicated that samples containing 80% dry weight in form of RCA, 10% cement and 10% of fly ash performed better and achieved a higher compressive strength than the mix composed of 80% of dry weight in form of RCA and 20% in form of cement.

The research also determined that the specimens containing fly ash performed better after being exposed of wet dry cycles. The results demonstrated that the decrease in strength for the 80-20 RCA was significantly higher than the mix with fly ash. The research also determined that the compressive strength of the specimens decreased as the number of cycles increased (Gonzalez, 2010).

Figure 8 summarizes the results of the investigation, the chart illustrates the compressive strength of the cylinders not exposed to wet dry cycles which ranges around 3100 psi and those exposed to 12 cycles reached approximately 2700 psi. (22 Mpa and 19 Mpa respectively).

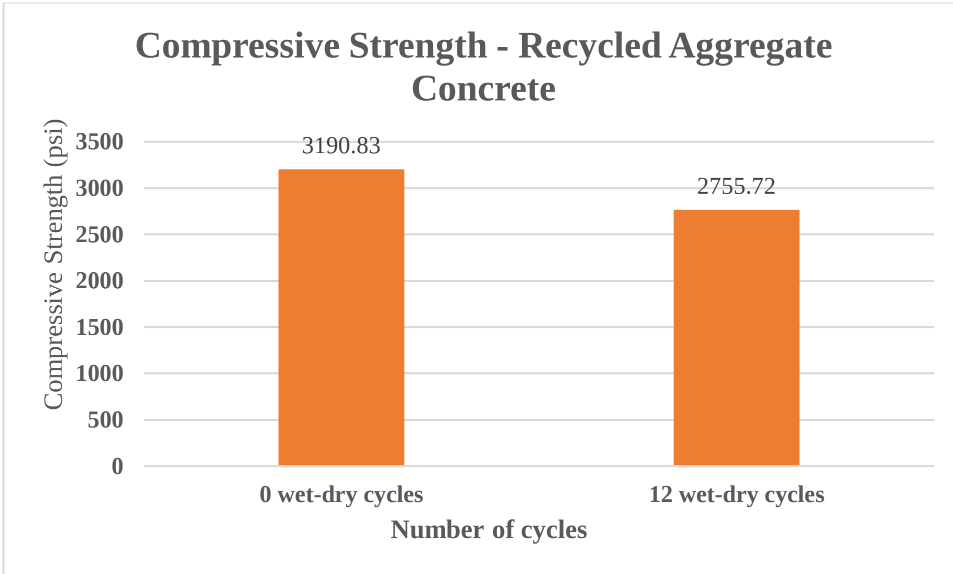


Figure 8. Compressive Strength Before and After Wet-dry Cycles (Gonzalez, 2010)

2.13 EFFECTS OF DIFFERENT HEAT CURING METHODS ON COMPRESSIVE STRRENGTH OF RAGC. (Gerasimovich, 2016)

A related unpublished investigation performed at Florida Atlantic University by Gerasimovich (2016) focused on the effects of different curing methods on compressive strength of recycled aggregate fly-ash based geopolymer concrete. The study tested RAGC exposed to a variety of curing times and temperatures to determine which combination achieved maximum compressive stregnth. The heat curing time tested were 1, 3 and 7 days and the temperatures used for oven curing were 60°, 75° and 90° Celsius. The results of the investigation indicated that the maximum compressive stength achieved was 3602 psi, and occurred by the cylinders exposed to 7 days of heat curing in the oven at 60 degrees celsius. The results of the investigation are summarized on Table 5.

Table 5. Compressive Strength Results for 7-day Curing at 60 Degrees Celsius (Gerasimovich, 2016)

7 day 60 degree curing						
	Sample 1		Sample 2		Sample 3	
	Weight (lb)	Density (lb/ft^3)	Weight (lb)	Density (lb/ft3)	Weight (lb)	Density (lb/ft3)
	8.28	142.24	8.28	142.24	8.28	142.24
	8.23	141.38	8.23	141.38	8.23	141.38
	8.06	138.58	8.09	139.01	8.10	139.23
Compressive Strength	3596.90 psi		3756.06 psi		3453.66 psi	
Average Compressive Strength	**3602 psi**					

CHAPTER 3: MATERIALS USED

The materials used in this investigation were determined by Wallah & Rangan (2006) investigation on geopolymer concrete developed at Curtin University. The mix design specified the use of of sand, aggregate, fly ash, sodium silicate solution, sodium hydroxide solution, superplasticizer and water. For this investigation, the mix design was meticulously followed with the exception of incorporating recycled aggregate instead of regular aggregate. The description of the materials used for this experiement and their properties are included as follows.

3.1 RECYCLED CONCRETE AGGREGATE

Recycled aggregate, is a granular material collected from demolition sites and put through a crushing machine to be reused in a variety of applications. The main difference between regular aggregate and recycled aggregate is the presence of adhered mortar and has a higher superficial roughness which can cause loss of workability.

The characteristics of recycled concrete aggregate include high angularity, rough surface, smaller specific gravity, lower strength, higher water absorption and higher possibility of abrasion compared with regular construction aggregate. Additionally, recycled aggregate’s grading is similar to the one obtained by natural coarse aggregate. The critical strength and modulus properties of Portland concrete cement with recycled aggregate are up to 40% lower, creep is up to 60% higher, drying shrinkage is 100% higher and permeability properties improved up to 500% compared to concrete made with regular aggregate. (NCHRP, 2013) It was noted while performing the sieve analysis that recycled aggregate particles ranging between 1.18mm and 4.75mm were not present in the sample, which classifies the recycled aggregate as poorly graded according to the Unified Soil

Classification System and the aggregate size distribution did not match the grain size distribution of other regions of the country. Figure 9 illustrates the fine recycled aggregate used for this investigation.

Figure 9. Recycled Aggregate Used for Study

3.2 FLY ASH

Fly ash is a supplementary cementitious material obtained to from coal combustion and is commonly used to enhance the performance and bonding properties of concrete.

Depending on the application, specification, and climate, fly ash has been used in an average of 20% by mass of the cementitious material in concrete. A range between 30 and 50 percent has been used for massive structures.

Fly ash is a pozzolanic material, amorphous alumino-silicate which is finely divided. Typical components of fly ash include SiO_2, $Al2O_3$, CaO, and Fe_2O_3, which exist in the form of amorphous and crystalline oxides of various minerals. (Xiao, et al., 2015). Its various levels of calcium react with the calcium hydroxide released by the combination of Portland cement with water in order to produce calcium-silicate hydrates (C-S-H) and calcium aluminate hydrates. According to Davidovits (1994) and McLellanet al (2011), the production of fly ash geopolymer has lower Carbon Dioxide emissions compared to the production of limestone.

The pozzolanic properties of fly ash increases the amounts of the cementitious binder phase (C-S-H), which improves the strength of the concrete and increases its durability. According to Thomas (2007), using good quality fly ash with a high fineness and low carbon content reduces the water demand of concrete when compared to Portland cement concrete mixes of the same workability. Additionally, fly ash increases the cohesiveness and reduces segregation of concrete, reduces the amount of bleeding, increases retardation of setting time, and increases long-term strength development.

Figure 10 illustrates the compressive strength effects when replacing a certain portion of mass of Portland cement with a low calcium fly ash. The results demonstrate that the ultimate strength achieved by concrete increases with increased fly ash content up to levels remaining within 50 percent. Typically, selecting the correct water-to-cement ratio for the mix for the cement and fly ash can achieve the desired minimum strength in 28 days. Additionally, the water-to-cement ratio required varies depending on the level of the fly ash replacement, composition of the ash, and the age and strength specified. (Thomas, 2007)

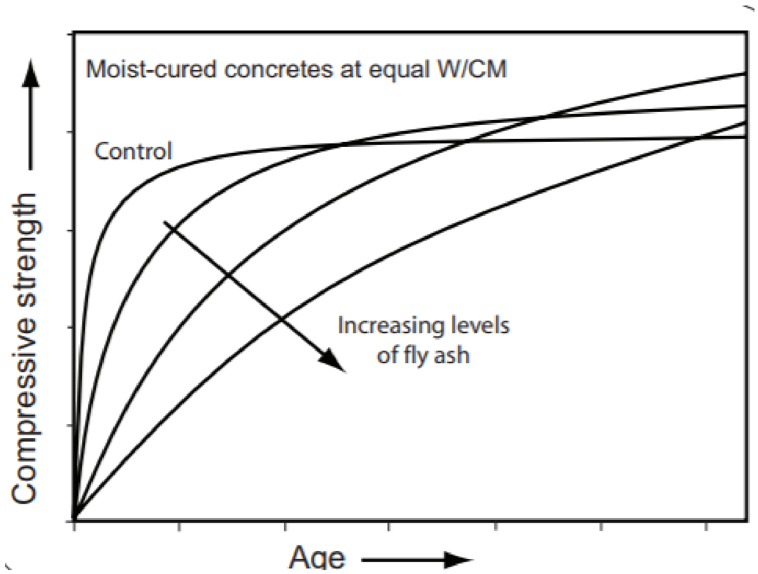


Figure 10. Effect of fly ash on compressive strength development of concrete

(Thomas, 2007)

Figure 11 illustrates that by using temperature-matched curing, the strength of fly ash concrete is increased up to 28 days.

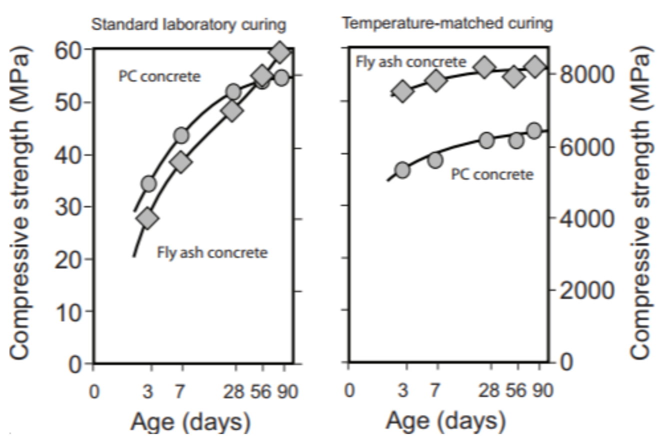


Figure 11. Strength development of concrete subjected to standard laboratory and

temperature-matched curing (P.B Bamforth, 1980)

Fly ash usage offers many advantages. One of the most important benefit is the reduction of permeability to water and other chemicals. Fly ash creates a denser concrete when properly cured, increases strength and can result in better workability, cohesiveness, ultimate strength, and durability.

In North America the most used specification for fly ash is ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (AASHTO, 2015). The ASTM C618 divides fly ash into two different categories depending on calcium content. *Table 6* summarizes the description of the fly ash classes based on their chemical requirements (ASTM, 2017).

Table 6. ASTM Specifications for Fly Ash

ASTM Specification for Fly Ash		
Class	**Description in ASTM C**	**Chemical Requirements**
F	Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this class as given herein. This class of Fly ash has pozzolanic properties.	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$
C	Fly ash normally produced from ignite or sub-bituminous coal that meats the applicable requirement for this class as given herein. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties. Some Class C fly ashes may contain lime contents higher than 10%	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$

Class F fly ash was used for this investigation as designated in ASTM C618, 2017. Fly ash class F consists mainly of alumina and silica, it has lower calcium content than class C fly ash. The fly ash used in the mix worked as a replacement of portland cement by approximately 20% of the total mass of the mix as previously determined by the mix design formulated by Wallah & Rangan (2006). The Class F fly ash used for this investigation was provided by Titan America and is illustrated in Figure 12.

Figure 12. Class F fly ash used for study

3.3 ALKALINE LIQUID

Alkaline liquid was the combination of sodium silicate solution and sodium hydroxide obtained in pellets composed of 99% assay sodium hydroxide to help improve the strength properties of geopolymer concrete. The sodium hydroxide used is illustrated in Figure 13 and the individual pellets can be seen in Figure 14.

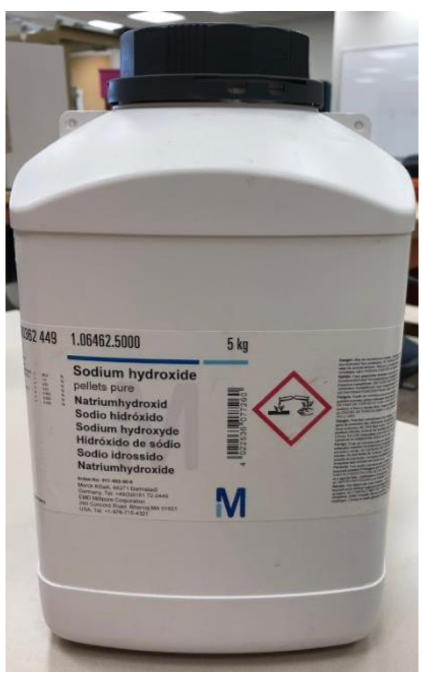


Figure 13. Sodium Hydroxide 99% purity in pellets

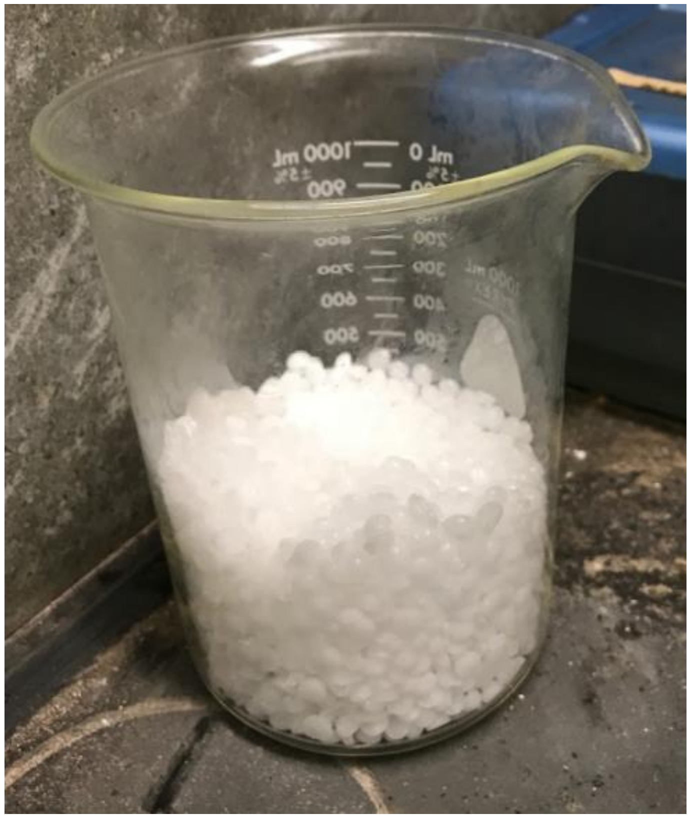


Figure 14. Sodium Hydroxide Pellets used for study

The concentration of the sodium hydroxide used was 14 Molars, this number will be used to determine the number of grams of NaOH solids per liter of solution. The amount is obtained by multiplying the weight of NaOH by the required molarity = 40x14=560 gr of NaOH per litter of solution. Following Wallah & Rangan, (2006) mix design is necessary to calculate the mass of NaOH solids to make the 14 Molar solution, this value is calculated to be 404 grams per kg of solution. The sodium siliclate used for this investigation can be seen in Figure 15.

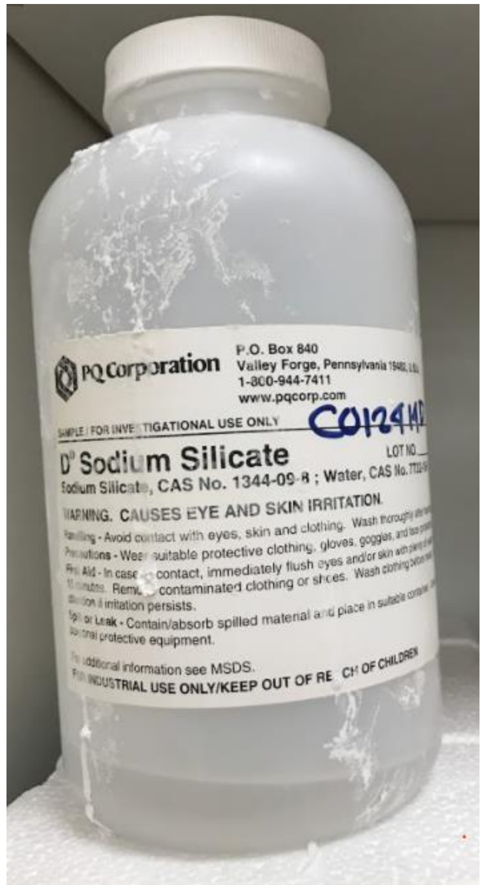


Figure 15. Sodium Silicate used for study

Once the quantities were determined, the sodium hydroxide pellets were mixed with ionized water until the pebbles fully dissolved. The process occurred on a magnetic mixer plate and the solution became hot. Once the sodium hydroxide was prepared, the solution was mixed with the sodium silicate and allowed to react with each-other covered under a lab hood for 24 hours. The liquid alkaline being mixed is shown in Figure 16

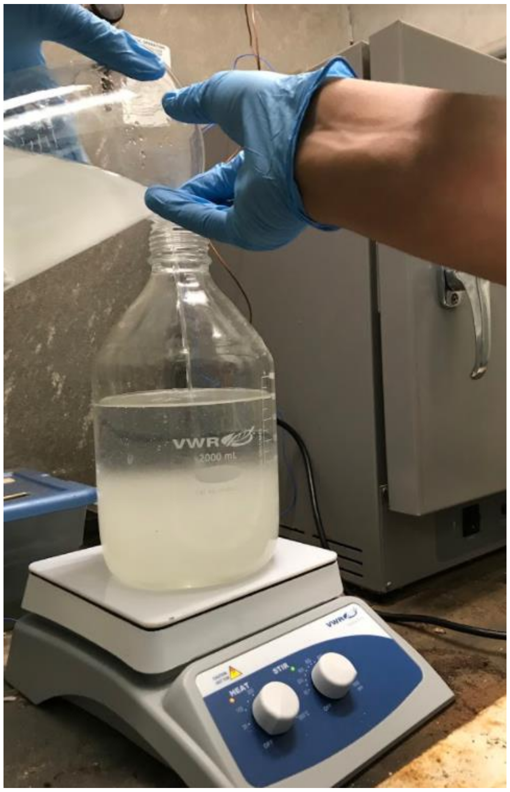


Figure 16. Alkali liquid

3.4 SUPERPLASTICIZER

Superplasticizers are admixtures for concrete, used to reduce the water content in a mixture to modify the properties of concrete to make it more suitable to work with, and to slow down the mixture's setting rate. Superplasticizers are used as determined in the standard specification for chemical admixtures for concrete (ASTM, 2012).

The superplasticizer used was a polycarboxylate-based type F high-range water reducer, and it was added in liquid form to the mixture. According to the International Journal for Technological Research in Engineering, using superplasticizer can delay the start of curing of geopolymer concrete at elevated temperatures up to 60 minutes without significant effect on the compressive strength. Figure 17 illustrates the superplasticizer used for the mix, which significantly improved workability of the geopolymer mix.

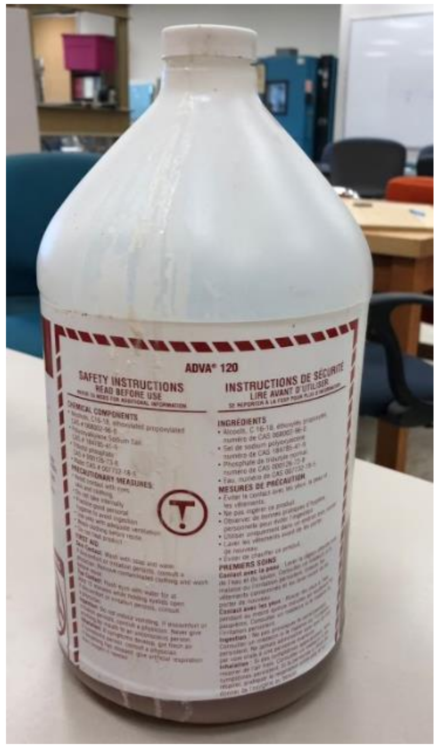


Figure 17. Superplasticizer

CHAPTER 4: MIX DESIGN OF GRCA

Mix design of low-calcium fly ash geopolymer has been developed by Wallah & Rangan, (2006). Their experimental work concluded that higher concentrations of sodium hydroxide, and curing the mix at temperatures in the range of 30°C and 90°C result on higher compressive strength. Adding superplasticizer approximately by 4% of fly ash by mass improves the workability of the fly ash geopolymer concrete. However, it was noted compressive strength decreased slightly when superplasticizer exceeded 2% (Rangan & Wallah, 2006). The mixture design followed some of the current practices in Portland cement manufacturing. The recycled materials used totaled approximately 70% of the mix, while the rest consisted on the chemicals and admixtures used to provide workability. Table 7 illustrates the mix design used for this investigation.

The curing method followed for this investigation was determined by a previous unpublished investigation on recycled aggregate concrete performed at Florida Atlantic University by Gerasimovich (2016). The study followed Rangan & Wallah's (2006) mix design and determined that maximum compressive strength of the mix was achieved when the geopolymer cylinders were exposed to 7 days heat curing time in the oven at 60° C.

Table 7. Wallah & Rangan's Mix Design)

Materials		Weight (lb/ft^3)
Recycled Aggregate	1/2 in	40
	1/4 in	40
Sand		34
Class F Fly Ash		25
Sodium Silicate Solution		6.42
Sodium Hydroxide Solution		2.55
Superplasticizer		0.374

(Wallah & Rangan, 2006)

The mix incorporated a 2.5 ratio of sodium silicate solution to sodium hydroxide, while it was determined that the molarity of the sodium hydroxide should range between 8M and 16M to increase the compressive strength of the material, this investigation used 14M of sodium hydroxide for the alkali mix. Additionally, it was determined that the aggregates should be approximately 75% to 80% of the mixture by mass, a similar value to that of Portland cement concrete. The only variation to the mix was the use of recycled aggregate instead of natural aggregate. Table 8 summarizes the exact quantities used to mix a batch of 12 cylinders.

Table 8. Mix Design Proportions for 12 Cylinders

Concrete Mixture Proportions		
	Number of Cylinders	Total Weight (lb)
Recycled Aggregate	12	59.22
Fine Sand	12	25.35
Fly Ash (Low Calcium)	12	16.84
Sodium Hydroxide Solution	12	2.43
Sodium Silicate ($SiO_2/Na_2O=2$)	12	5.99
Super Plasticizer	12	0.27

CHAPTER 5: METHODOLOGY

5.1 GRAIN SIZE ANALYSIS

The first step of this investigation involved determining the particle size distribution of the recycled aggregate used for the mix. The American Association of State Highway and Transportation Officials (AASHTO) has established standard specifications for recycled aggregate use in soil-aggregate base course, these standards are not specific for concrete used in structural construction, however, these standards were followed for this part of the investigation. The standards for sieve analysis for finer and coarse aggregates (ASTM C136, 2014) determine the particle size distribution by sieving. The No. 4 sieve is the designated division between fine and coarse aggregates. Figure 18 illustrates the coarse aggregates used in the mix with particles which are greater than 9.74mm. Coarse aggregates usually range between 9.5mm and 37.5mm in diameter

Figure 18. ½ in Coarse Recycled Aggregate

Figure 19 shows the finer aggregates used for the mix which are generally smaller than 9.5mm.

Figure 19. 1/4in Fine Recycled Aggregate

The sieve analysis was performed by collecting 1000 grams of recycled aggregate. 6 sieves of the following sizes were selected: #100, #4, #3/8, #½ and #¾. The sieves were stacked together by positioning the sieves with larger openings on top and the smaller ones at the bottom. A pan was placed under the bottom sieve to collect the material and a cover is placed on the top sieve as shown in Figure 20.

Figure 20. Stack of Sieves & Sieve Shaker

The stack of sieves was run through a sieve shaker for about 15 minutes. The weight of each sieve was recorded and the results were organized in a data sheet to represent the results graphically. The process was performed according to the guidance of the Standard test method for sieve analysis of fine and coarse aggregates (ASTM C136, 2014). Figure 20 represents the final sand and aggregate collected in each sieve at the end of the experiment which was evaluated to determine the particle size distribution.

Figure 21. Grain Size Separation During Sieve Analysis

Table 9 shows the percent of mass retained on each sieve (Rn), the cumulative percent retained (∑Rn) and the percent finer represented as (100-∑Rn). The results were used to create a graph plotted in a Log scale to illustrate percent finer vs. grain size.

Table 9. Sieve analysis results

Sieve Size	Sieve Openinge	Weight Before (kg)	Weight After (kg)	Total Weight Remaining	Percent of mass	Cumulative Percent	Percent Finer 100- c
3/4"	19mm	0.55	0.60	0.05	5.56	5.56	94.44
1/2"	12.5mm	0.55	1.00	0.45	50.00	55.56	44.44
3/8"	9.5mm	0.55	0.75	0.20	22.22	77.78	22.22
#4	4.75mm	0.55	0.80	0.25	27.78	105.56	0.00
#50	1.18mm	0.40	0.40	0.00	0.00	105.56	0.00
#100	150nm	0.35	0.40	0.05	5.56	111.11	0.00
Tray		0.35	0.35	0.00	0.00	111.11	

Sieve Size	Sieve Openinge	Weight Before (kg)	Weight After (kg)	Total Weight Remaining	Percent of mass	Cumulative Percent	Percent Finer 100- c
3/4"	19mm	0.55	0.60	0.05	5.56	5.56	94.44
1/2"	12.5mm	0.55	0.95	0.40	44.44	50.00	50.00
3/8"	9.5mm	0.55	0.75	0.20	22.22	72.22	27.78
#4	4.75mm	0.55	0.85	0.30	33.33	105.56	0.00
#50	1.18mm	0.40	0.40	0.00	0.00	105.56	0.00
#100	150nm	0.35	0.40	0.05	5.56	111.11	0.00
Tray		0.35	0.35	0.00	0.00	111.11	

Sieve Size	Sieve Openinge	Weight Before (kg)	Weight After (kg)	Total Weight Remaining	Percent of mass	Cumulative Percent	Percent Finer 100- c
3/4"	19mm	0.55	0.65	0.10	11.11	11.11	88.89
1/2"	12.5mm	0.55	1.00	0.45	50.00	61.11	38.89
3/8"	9.5mm	0.55	0.65	0.10	11.11	72.22	27.78
#4	4.75mm	0.55	0.85	0.30	33.33	105.56	0.00
#50	1.18mm	0.40	0.40	0.00	0.00	105.56	0.00
#100	150nm	0.35	0.40	0.05	5.56	111.11	0.00
Tray		0.35	0.35	0.00	0.00	111.11	

The results obtained from the sieve analysis clearly demonstrate a fair representation of all sizes of aggregate and soil ranging from 19mm to 150nm.

Figure 22 illustrates the results on a logarithm scale chart in which is noticeable that aggregates ranging from 1.18 to 4.75mm are missing from the sample. Furthermore, based on the results of the sieve analysis and the lack of all sizes of aggregate it can be determined that the aggregate that was used for the research can be categorized as poorly graded recycled aggregate.

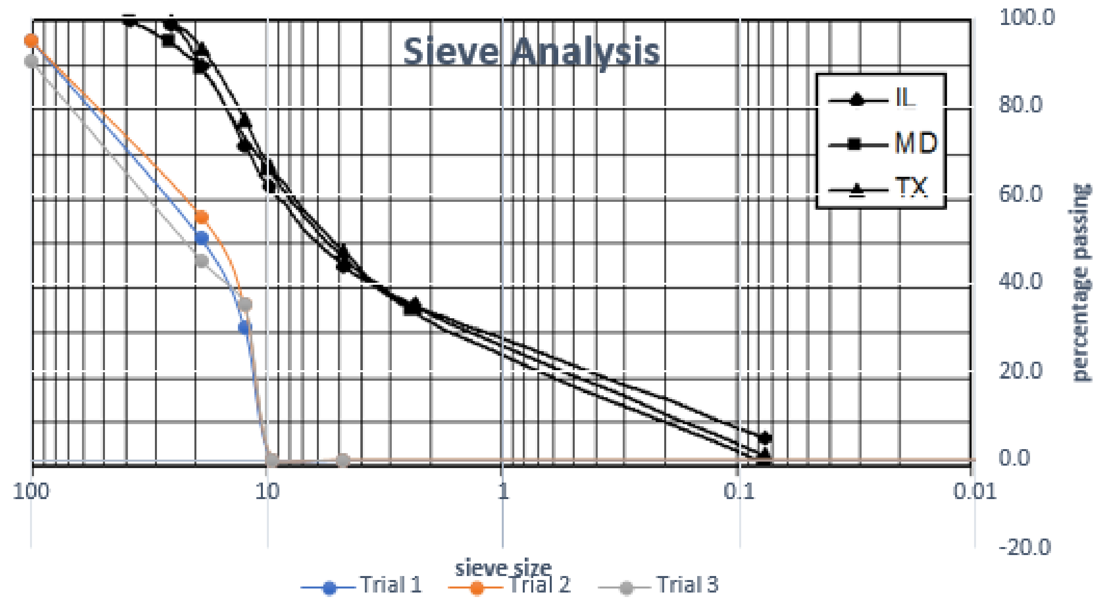


Figure 22. Sieve Analysis Log-scale Diagram

5.2 MIXING PROCESS

This investigation followed the mix design used by Wallah & Rangan (2006). The mix design was altered to increase workability, and to enhance the bonding properties of geopolymer. Table 10 provides the specific amount of chemicals used for this investigation. The mix design was altered by a 5% increased of all ingredients to compensate for evaporation and loss of materials.

Table 10. Concrete Mixture Proportions

Concrete Mixture Proportions					
	lb/ft^3	1 Cyl Vol	Number of Cylinders	Correction (%)	Total Weight (lb)
Recycled Aggregate	80.78	0.058	1	5	4.93
Fine Sand	34.59	0.058	1	5	2.11
Fly Ash (Low Calcium)	22.97	0.058	1	5	1.40
Sodium Hydroxide Solution	3.31	0.058	1	5	0.20
Sodium Silicate (SiO2/Na2O=2)	8.18	0.058	1	5	0.50
Super Plasticizer	0.37	0.058	1	5	0.02
Additional Water					0.00

The first step of the mixing process required preparing the Alkaline Liquid. This solution was prepared 24 hours before the recycled aggregate concrete was mixed. The process was followed as specified by Wallah & Rangan's investigation (2006). First the sodium hydroxide pellets were dissolved in deionized water using a magnetic plate mixer as seen Figure 23.

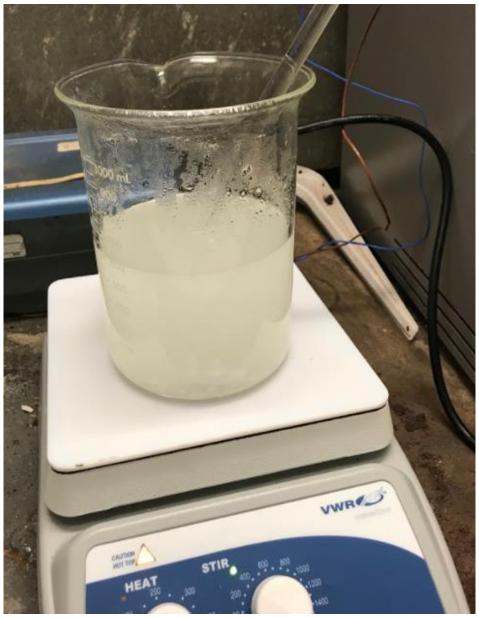


Figure 23. Sodium Hydroxide Pellets Dissolved in Water

Once the sodium pellets were completely dissolved, the sodium hydroxide of 14M were mixed with the Sodium silicate already in liquid form. The mix was left covered under a fume hood for 24 hours. Figure 24 illustrates the mix of these solutions.

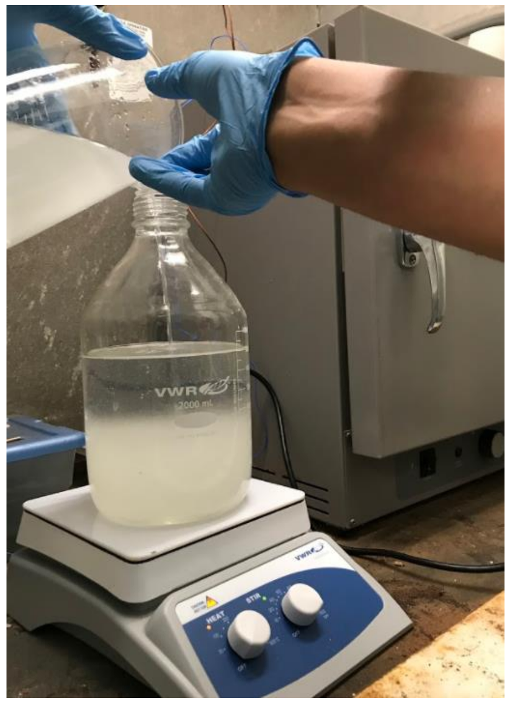


Figure 24. Sodium Hydroxide Mixed with Sodium Silicate

Next the superplasticizer was added to the alkaline solution prior to starting the concrete mix. In order to prevent excessive dryness of the recycled aggregate, the aggregate was soaked in water over night and drained previously to starting the mix. After 24 hours, the dry materials (recycled aggregate, sand, fly ash) were mixed together for 10 minutes prior to being placed in the mixer as shown on Figure 25.

Figure 25. Dry Elements Mixed by Hand

Once the dry elements were placed in the concrete mixer, the alkali liquids and superplasticizer were added to the dry mix. Figure 26 shows the complete mix of all the elements.

Figure 26. Recycled Aggregate & Geopolymer Concrete Mix

5.3 CASTING

Once the mix was homogeneous, the mixture was placed into 4” x 8” cylinders, approximately following ASTM, (2013) Standards for making and casting of test specimens in the laboratory. The cylinders were casted in two layers, each layer was manually tapped, 25 and 10 times respectively. Lastly, all the specimens had to be smoothed with a spatula and covered with a plastic cap. The cylinders were left to set in the mold for 24 hours at room temperature. Figure 27 shows the casting process for all 12 cylinders made.

Figure 27. Recycled Aggregate Geopolymer Placed in 4"x8" Cylinders

5.4 CURING

The recycled aggregate fly ash geopolymer cylinders tested in this investigation were mixed and placed in molds for 24 hours at room temperature conditions, the next day the cylinders were taken out of the mold and prepared to proceed with the curing process.

A previous unpublished investigation performed by Gerasimovich, (2016) in Florida Atlantic University on the effects of different curing methods on compressive strength of geopolymer recycled concrete, was based on the curing regimens previously developed by (Hardito & Rangan, 2005). The investigation determined that the optimal curing time was achieved at 7 days, and the curing temperature that reached the highest compressive strength was noted to be 60°C. Gerasimovich, (2016) implemented an innovative method to prevent water evaporation during curing, the method consisted on individually wrapping the samples with aluminum foil before placing them in the oven for heat curing at 60° C.

Once the cylinders were demolded, the samples were individually wrapped in aluminum foil following Gerasimovich's (2016) method. Wrapping the samples minimized water evaporation and helped maintain optimal moisture to prevent crumbling. Figure 28 shows one of the specimens after being demolded.

Figure 28. Recycled Aggregate Geopolymer Concrete Cylinder After Drying Over Night

Figure 29 shows the recycled aggregate -geopolymer cylinders wrapped and ready to begin the heat curing process.

Figure 29. Recycled Aggregate Geopolymer Concrete Cylinders Placed in Oven for 7 days.

Once the cylinders were taken out of the oven after 7 days, they were individually weighed and the results were used as control values to determine any changes in weight and density while the cylinders were undergoing the wet-dry cycles.

5.5 TESTING

5.5.1 WET-DRY CYCLES

Wet -dry cycles are recognized as one of the aggressive environmental conditions experienced by concrete. Regions where concrete experiences severe dry – wet conditions are regarded as critical parts of the structures (Hobbs, et al. 1998)

Wet-dry cycles are important to the prediction and prevention of shrinkage-induced cracking, and to determine the impact of environmental exposure to the durability of concrete.

One typical wet-dry cycle consists on immersing the concrete cylinders in water for a pre-determined time followed by the cylinders taken out to air-dry. The purpose of this form of testing is to subject concrete samples to a specific number of cycles, monitor them to determine any physical changes, and to determine any decrease on durability or strength. Exposing the recycled aggregate -geopolymer concrete to wet-dry cycles may affect the concrete's durability and strength since recycled aggregate is prone to high water absorption. Stronger concrete's characteristics typically include lower water content, higher cement content, and higher densities.

By exposing concrete to wet-dry cycles, the water-to-cement ratio is altered by raising the water content, consequently the concrete could be less durable and weaker. This part of the investigation intends to determine the relationship between curing time and the physical changes experienced by the samples after being exposed to the wet-dry cycles.

In this study, the wet- dry cycles consisted of 24 hours of wetting process followed by 24 hours of drying process at room temperature approximately following ASTM (2003) standards. Cylinders being exposed to the wet and dry parts of the cycle are shown Figure 30 and Figure 31 respectively.

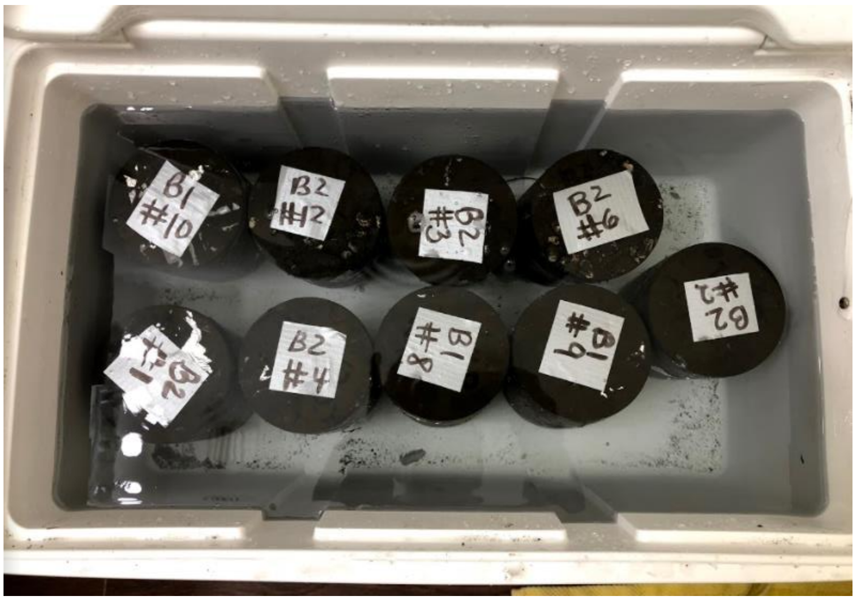


Figure 30. Recycled Geopolymer Concrete Cylinder Exposed to Wet Cycle

Figure 31. Recycled Aggregate Geopolymer Concrete Cylinders Exposed to Dry Cycle

5.5.2 COMPRESSIVE STRENGTH (ASTM, 2004)

The test was carried out with a Forney Premium Tester FHS-500 hydraulic compression testing machine with digital display. This machine tests in the range of 5000 to 500,000 lbf. Figure 32 displays the testing machine used during the compression test. The test was performed approximately using the ASTM C-39 Standards (2013).

Figure 32. Forney Premium Tester FHS-500 Compression Machine

The cylinders were placed in the chamber to be compressed to breaking point, the cylinder information was input into the computer and the digital display showed the maximum compressive load reached, loading rate and maximum stress experienced by the cylinder immediately before failure.

Before testing, the cylinders were shaved down to avoid any imperfections, and to create a flat surface as seen on Figure 33.

Figure 33. Cylinders Being Shaved Down to Perform Compressive Strength Testing

Once the cylinders were shaved down, they were carefully measured to determine the exact surface area and length of the specimens, this information was useful to calculate volume and density as shown in Figure 34.

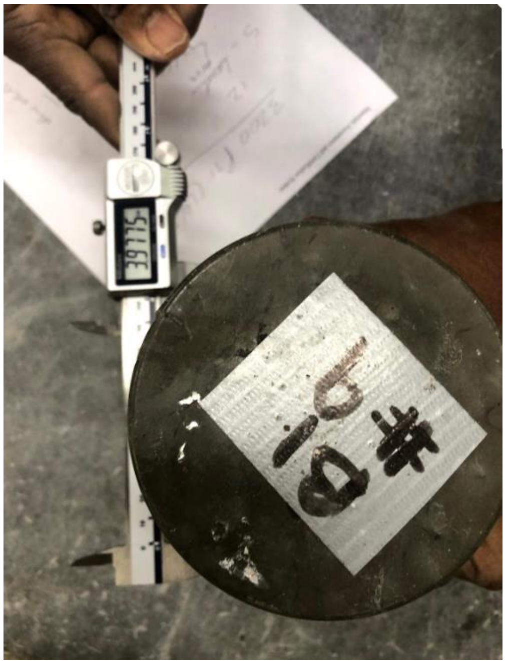


Figure 34. Cylinders Being Measured

The next step consisted on applying a compressive load to the concrete cylinders until failure occurred. The compressive strength is calculated by dividing the maximum load obtained during the test by the cross-sectional area of the cylinder. Caution and care must be exercised during the test and in the interpretation of the significance of the maximum value. The values obtained with this test will vary depending on the size and shape of the specimen, batching, mixing procedure, methods of sampling, molding, fabrication, age, temperature, and moisture conditions while curing.

Figure 35 shows a test in progress and Figure 36 shows a specimen after failure. Figure 37 shows the screenshot of the maximum strength and other relevant data at the end of the test.

Figure 35. Cylinder Being Tested for Maximum Compressive Strength

5.5.3 FAILURE

Figure 36. Recycled Aggregate Geopolymer Concrete Cylinder at Failure

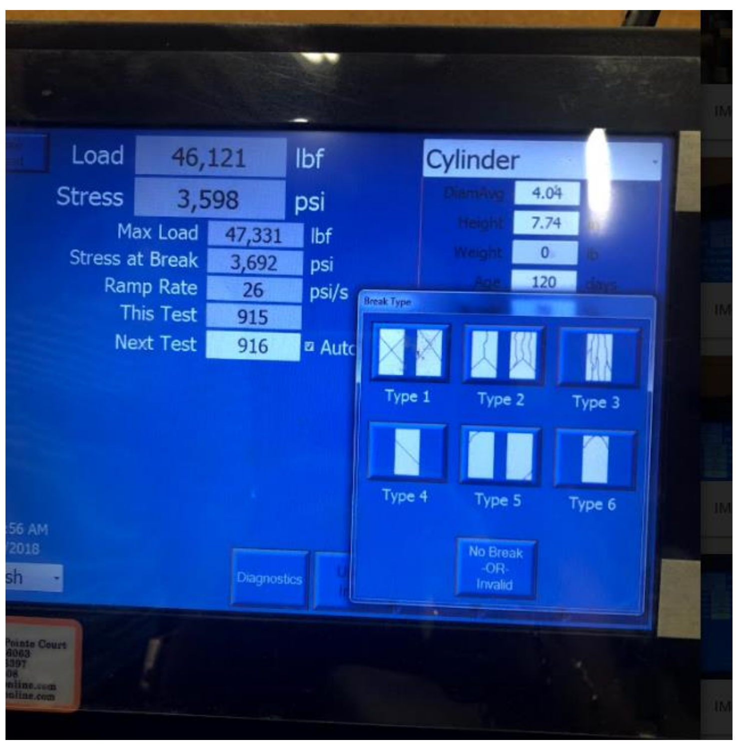


Figure 37. Typical Maximum Compressive Strength Results

The results were compared to the compression test fracture type chart to determine the type of failure experienced by the cylinder and estimate the quality of the cylinder tested.

Based on the observed Figure 38, it appears that most of the RAGC specimens approximately followed type 2 and 3 failure patterns. Additionally, it was noted that the plane of failure occurred through the recycled aggregate which suggested that the binder made a strong hold between the recycled aggregates and the paste, which prevented separation and failure between the two.

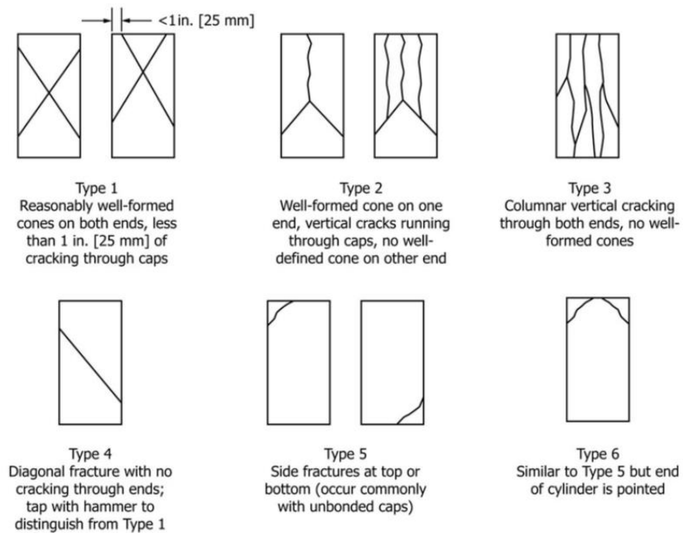


Figure 38. Compression Test Typical Fracture Patterns

(ASTM C39, 2004)

CHAPTER 6: TESTING PROCEDURE

Two batches of 12 recycled aggregate - fly ash -geopolymer cylinders were made to be used for testing. The two batches were prepared at different times due to equipment delays. The first batch was prepared, cured and kept for approximately 120 days wrapped in aluminum foil at room temperature. The second batch of cylinders was prepared to confirm accuracy in the results of the first batch and to determine if prolonged curing affected the compressive strength of the cylinders over time. Both batches of RAGC cylinders were exposed to 7, 14, and 21 wet-dry cycles.

6.1 TESTING MATRIX

The samples were prepared in 2 different batches, each containing 12 cylinders. The first batch was prepared, cured and stored in room temperature conditions for 120 days, wrapped in aluminum foil to prevent moisture evaporation.

The two batches were divided into 4 groups of 3 cylinders, the first group was used as the control specimen and was tested for compressive strength without any exposure to wet dry cycles.

The second group of three cylinders was exposed to 7 cycles of wet-dry exposure. Each cycle consisted of 24 hours of water submersion, and 24 hours of air dry at room temperature. The weight of the cylinders was noted at the end of each day to determine changes in density of the material. The third group of three cylinders was exposed to 14 cycles of wet-dry exposure (total of 28 days). The wet-dry process was performed in accordance to the process described for the second group of cylinders. The fourth group of three cylinders was exposed to 21 cycles of wet-dry exposure (total of 42 days). The process was followed similarly to the previously described groups.

Figure 39 illustrates the procedure followed to separate the cylinders and the number of wet-dry cycles. Additionally, the figure shows the number of days the cylinders were stored from the time they came out of the oven until beginning of wet dry cycle exposure.

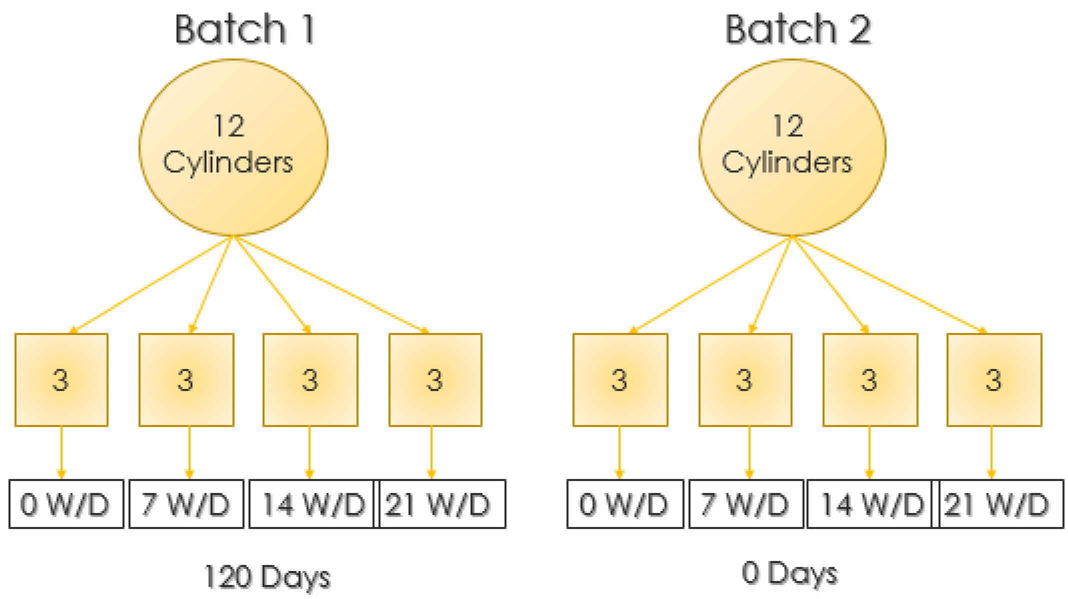


Figure 39. Testing Matrix

Once the wet dry exposure was finalized, the cylinders were tested for compressive strength. The average compressive strength was calculated for each group and they were compared to the control group. Table 11 illustrates the testing matrix for batch 1 prepared with 120 days of anticipation and stored at room temperature.

Table 11. Sample Testing Matrix Batch 1

Testing Matrix						
Batch 1						
Curing time			7 days			
Storage time			120 days			
Set 1	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	0					
Sample 2	0					
Sample 3	0					
Set 1	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	7					
Sample 2	7					
Sample 3	7					
Set 2	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	14					
Sample 2	14					
Sample 3	14					
Set 2	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	21					
Sample 2	21					
Sample 3	21					

Batch 2 testing matrix is illustrated in Table 12, it followed the same wet-dry cycle regimen and the results were evaluated and recorded in the same manner as batch 1.

Table 12. Sample Testing Matrix Batch 2

Testing Matrix						
Batch 2						
Curing time			7 days			
Storage time			0 days			
Set 1	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	0					
Sample 2	0					
Sample 3	0					
Set 1	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	7					
Sample 2	7					
Sample 3	7					
Set 2	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	14					
Sample 2	14					
Sample 3	14					
Set 2	# Cycles	Initial Weight	Final Weight	Initial Density	Final Density	Compressive Strength
Sample 1	21					
Sample 2	21					
Sample 3	21					

Other essential information such as number of cycles, storage time, length, diameter, area, weight, density, break type, and compression strength achieved by each cylinder after exposure to wet dry cycles was collected daily as shown in the appendix. This information was recorded daily and was key to determine a behavioral pattern and to identify the effects of a specific number of wet dry cycles on the properties of the material.

CHAPTER 7: RESULTS

After the compressive test took place, the results were graphed to illustrate the relationship between the wet-dry cycles and compressive strength.

The results illustrated on Figure 40 indicate that compressive strength achieved by batch 1 and 2 not exposed to wet-dry cycles, reaching similar results for all samples. The average compressive strength calculated for batch 1 is 3621 psi while batch 2's results average 3611 psi. These average results were illustrated in Figure 41 and were used as control values for comparison during the rest of the investigation.

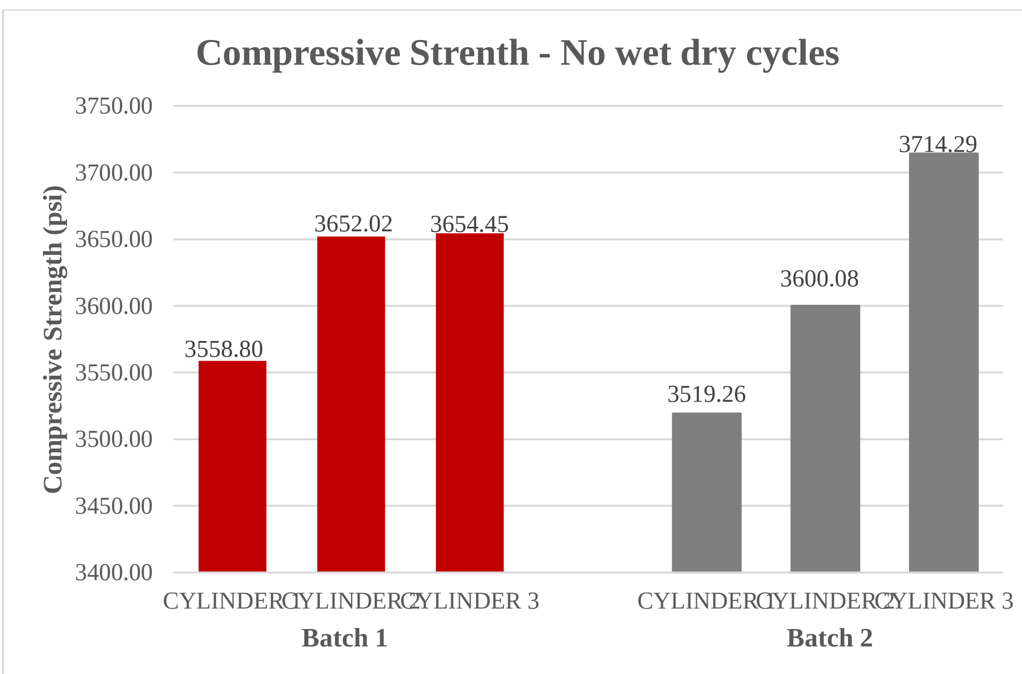


Figure 40. Compressive Strength for Batch 1 and 2 per Sample

(No wet -dry exposure)

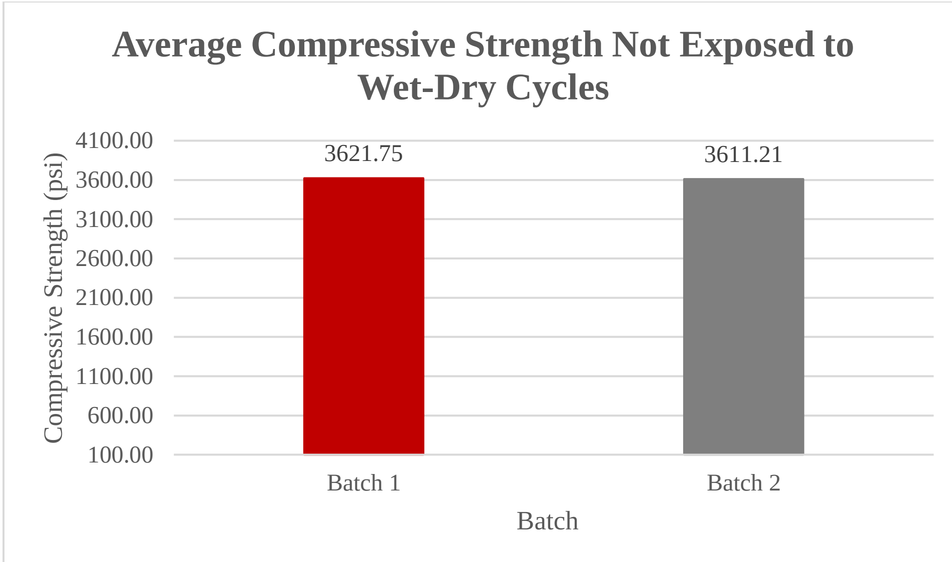


Figure 41. Average Compressive Strength for Batch 1 and 2

(No Wet-dry Cycle Exposure)

Once the averages were calculated for Batch 1 and Batch 2, the results were compared to the results obtained by recycled aggregate concrete not exposed to wet-dry cycles in the investigation performed by Gonzalez, (2010). Figure 42 shows that the compressive strength reached by recycled aggregate concrete cylinders was 12% less than recycled aggregate geopolymer concrete. The average values for geopolymer concrete were 3616 psi and the average for concrete are 3190 psi.

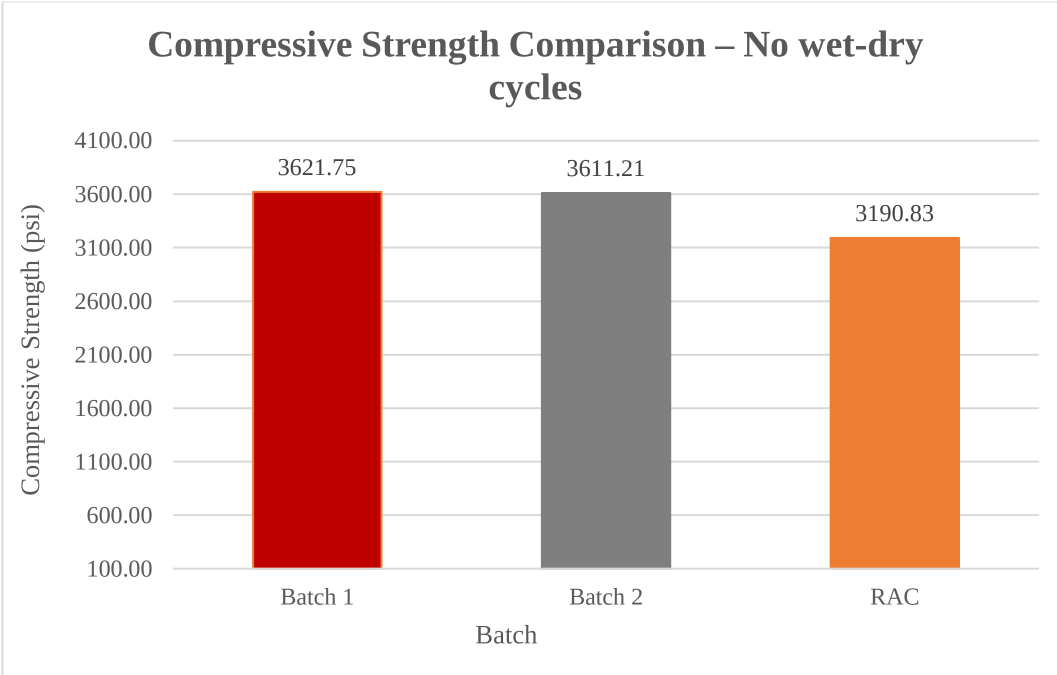


Figure 42. Compressive Strength of RAGC vs RAC at 0 cycles

Figure 43, shows the compressive strength results for batch 1 and 2 exposed to 7 wet-dry cycles. It was found that RAGC specimens easily achieved more than the minimum desired value of 3000 psi.

The average compressive strength for each batch was calculated and illustrated in Figure 44. The calculated compressive strength for batch 1 was found to be 3532 Psi while batch 2 values was 3395 psi. It was found that RAGC specimens easily reached higher values than the desired value of 3000 psi.

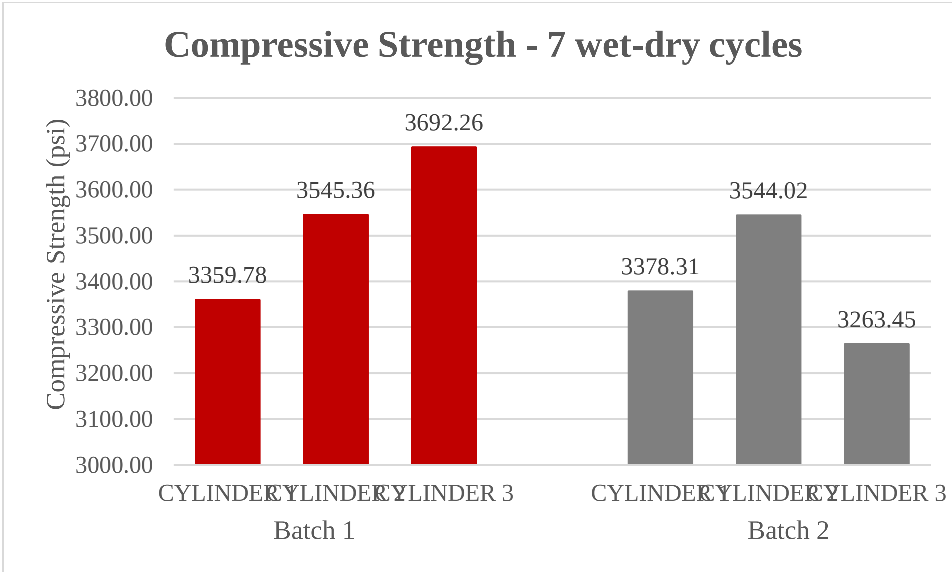


Figure 43. Compressive strength for Batch 1 and 2 per Sample

(7 Wet-dry Cycles)

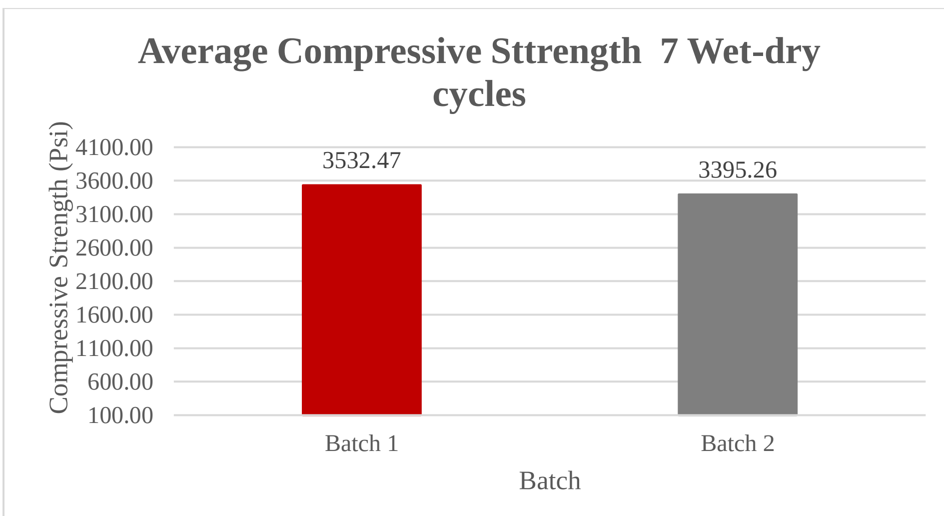


Figure 44. Average Compressive Strength for batch 1 and 2

(7 Wet-dry Cycles)

Once the averages were calculated for Batch 1 and Batch 2 after 7 wet-dry cycles, the results were compared to the results obtained by recycled aggregate concrete exposed to 7 wet-dry cycles in the investigation performed by Gonzalez, (2010). Figure 45 indicated that aggregate concrete achieved 17% less compressive strength than minimum amount obtained by recycled aggregate geopolymer concrete.

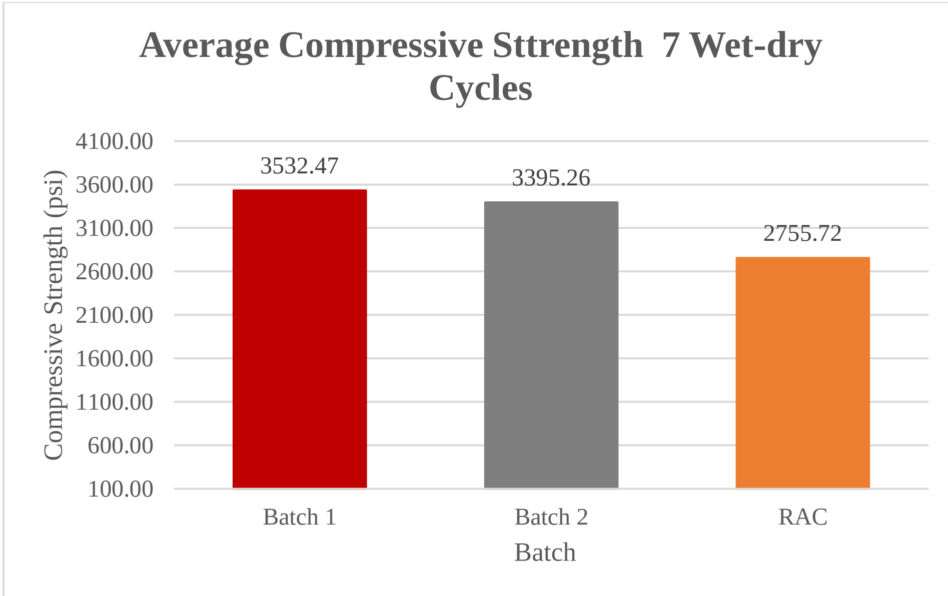


Figure 45. Compressive Strength of RAGC vs RAC at 7cycles

Figure 46 illustrates the results for samples exposed to 14 wet-dry cycles. The compressive strength average for batch 1 was calculated to be 3416 psi, while batch 2 average was 3100 psi. The values illustrated in Figure 47, were used as basis for comparison during the rest of the investigation.

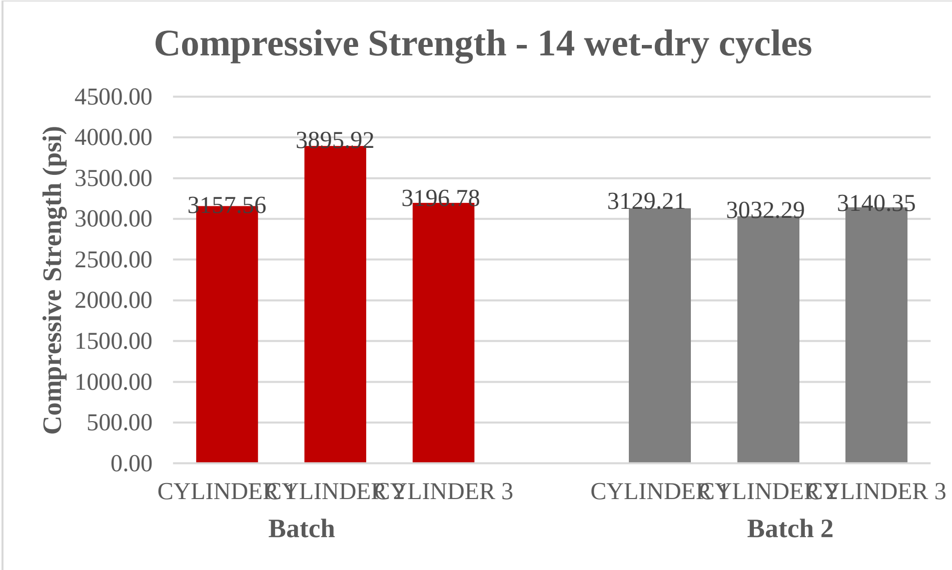


Figure 46. Compressive strength for batch 1 and 2 per sample

(14 Wet-dry Cycles)

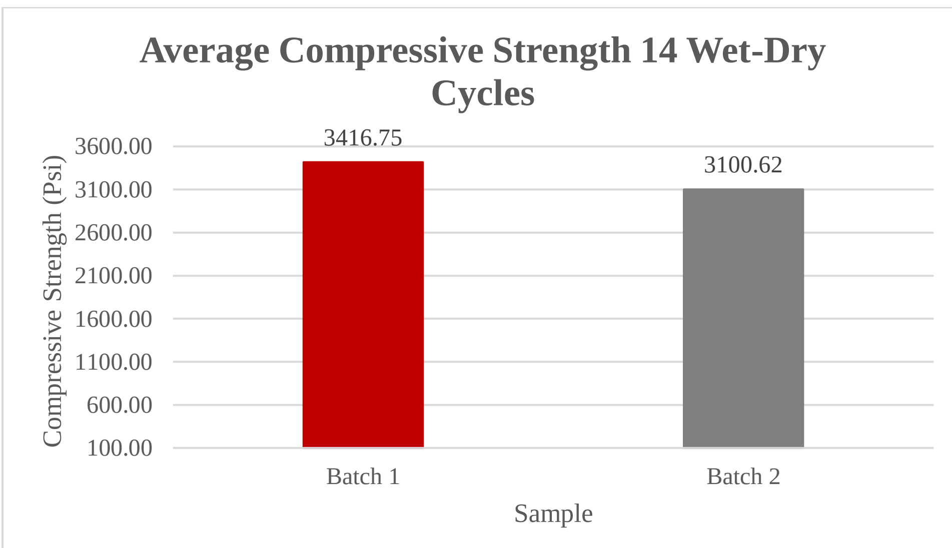


Figure 47. Average Compressive Strength for batch 1 and 2

(14 Wet-dry Cycles)

Once the averages were calculated for Batch 1 and Batch 2, the results were compared to the results obtained by recycled aggregate concrete expose do 14 wet-dry cycles in the investigation performed by Gonzalez, (2010). Figure 48 The results indicated that aggregate concrete achieved 12% less compressive strength than recycled aggregate geopolymer concrete.

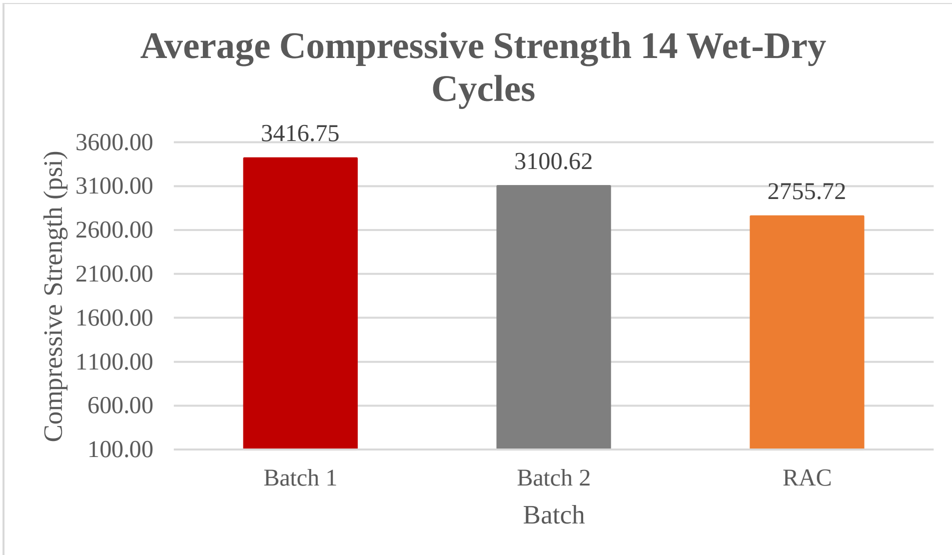


Figure 48. Compressive Strength of RAGC vs RAC at 14 cycles

The compressive strength results for batch 1 and 2 exposed to 21 wet-dry cycles are illustrated in Figure 49. The values were used to calculate the average compressive strength achieved for each cycle. The values were determined to be 3338 psi for batch 1 and 3053 psi for batch 2. The results shown in Figure 50 were used as reference for the rest of the investigation.

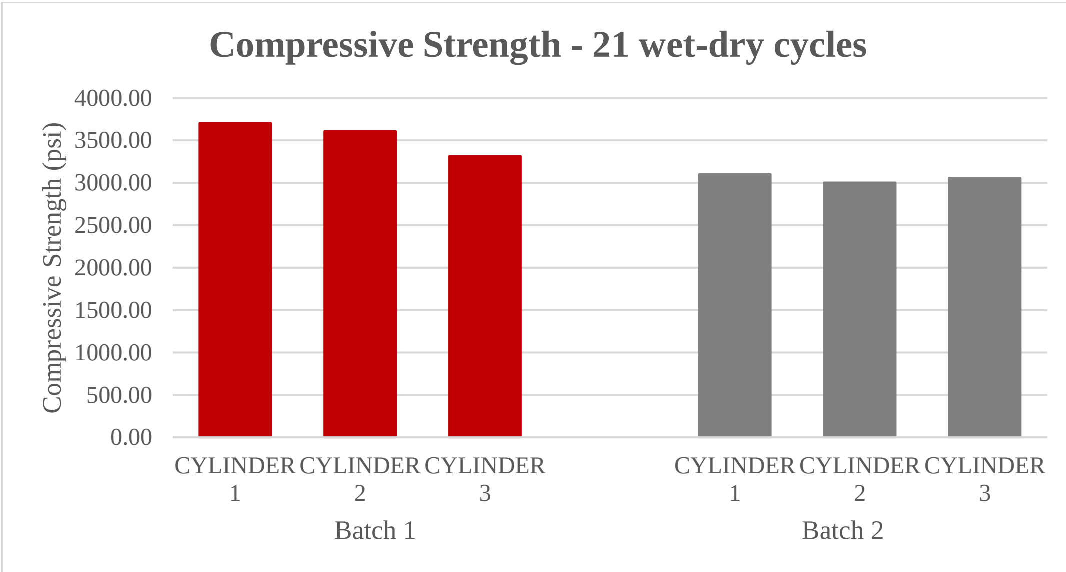


Figure 49. Compressive Strength for Batch 1 and 2 per Sample

(21 Wet-dry Cycles)

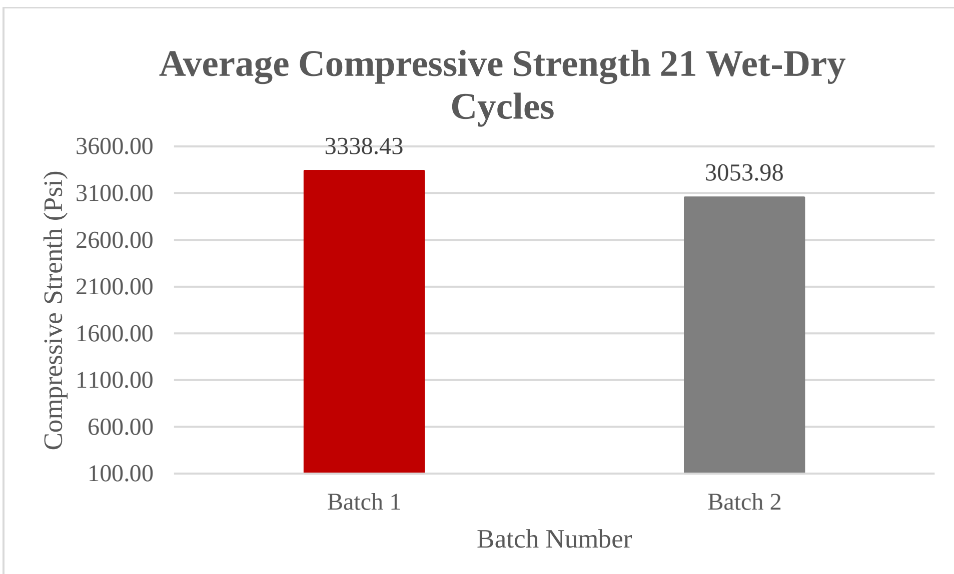


Figure 50. Average Compressive Strength for Batch 1 and 2

(21 wet-dry cycles)

Once the averages were calculated for Batch 1 and Batch 2, the results were compared to the results obtained by recycled aggregate concrete exposed to 12 wet-dry cycles in the investigation performed by Gonzalez, (2010). Figure 51 illustrates The results indicate that aggregate concrete achieve 12% less compressive strength than recycled aggregate geopolymer concrete.

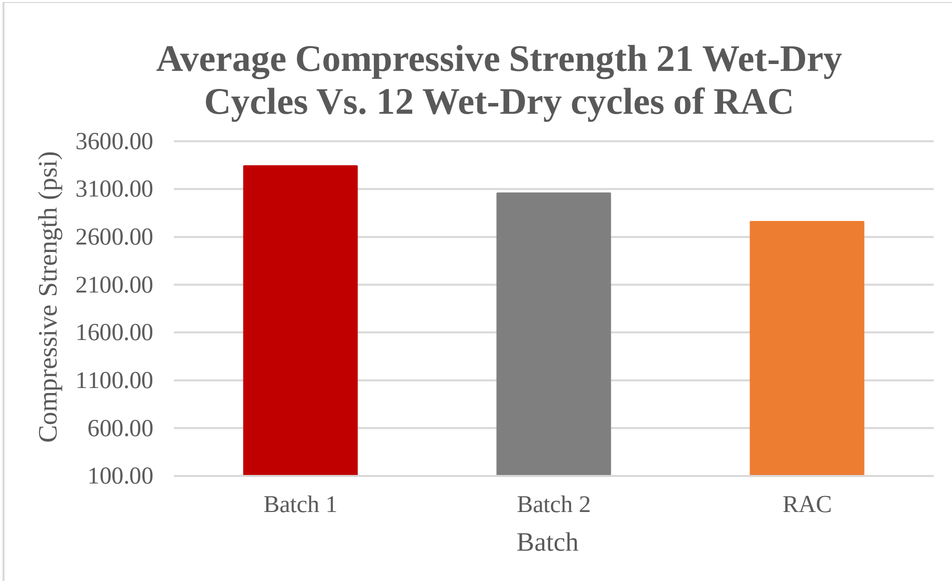


Figure 51. Compressive Strength of RAGC vs RAC at 21 cycles and 12 cycles

Figure 52 summarizes the results of the average compressive strength calculated per cycle and per batch. The chart indicates a decrease in compressive strength which occurred with increased number of cycles. The decrease in compressive strength was more drastic for batch 2. It is important to point out that the first batch was mixed and remained wrapped in room temperature conditions for 120 days previously to compressive strength testing.

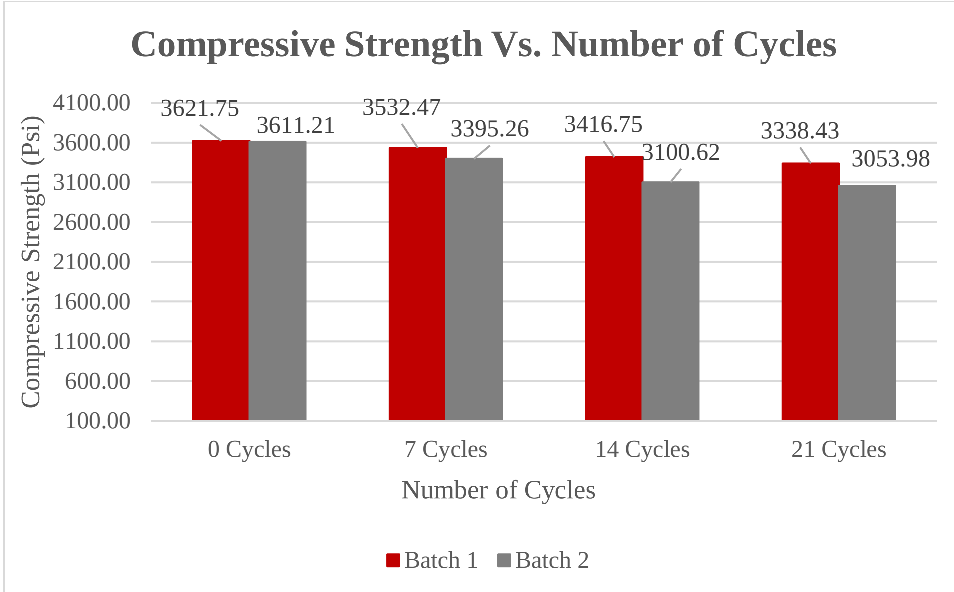


Figure 52. Compressive Strength Results for Batch 1 and 2 over time

The compressive strength trend is shown in Figure 53, the graph illustrates the decrease in compressive strength for both batches of the mix, the graph also shows the results for the investigation in recycled aggregate concrete. The results demonstrate a higher decrease in compressive strength for batch 2 than batch 1. Similarly, the Portland cement concrete samples display a higher decrease in compressive strength than the geopolymer concrete specimens. Furthermore, the compressive strength values achieved by samples not exposed to wet-dry cycles reflect a drastic difference between the geopolymer samples and the cement concrete samples. The Portland cement concrete samples consistently display a lower performance than RAGC samples.

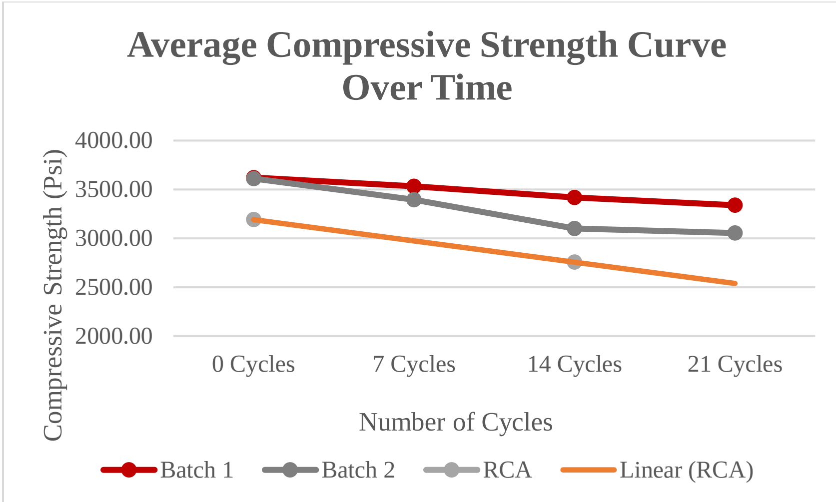


Figure 53. Compressive Strength Behavior Over Number of Cycles for Batch 1 and 2 compared to the results of RAC

Lastly, the compressive strength of the cylinders was compared to the density values calculated for every specimen. The changes in density were noted by weighing the cylinders daily and calculating the density. The results of this evaluation can be seen in Figure 54 and they indicate that cylinders exposed to more cycles achieve less compressive strength even though the density values are within the same range.

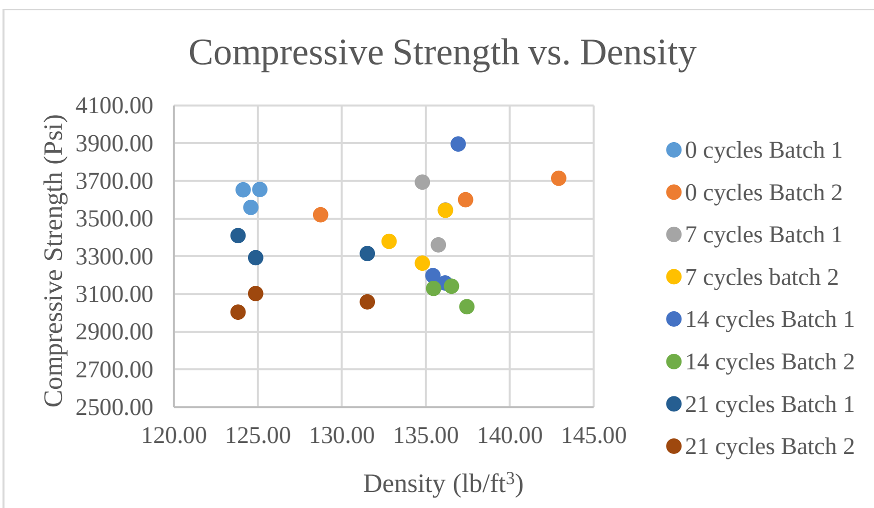


Figure 54. Compressive strength compared with density

7.1 PHYSICAL CHANGES

Figure 55 shows the physical deterioration presented by the specimens, which was observed as the number of wet-dry cycles increased. Micro cracks started developing on the cylinder's surface. Additionally, it was noted that small pores started to form on the cylinder's surface which might have contributed progressively to the decrease of compressive strength.

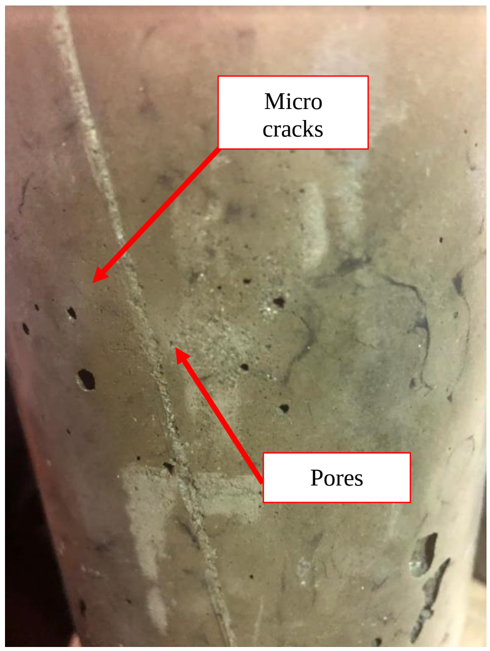


Figure 55. Physical deterioration of samples after wet-dry cycle exposure cylinders

CHAPTER 8: CONCLUSIONS & DISCUSSION

This study focused on finding the effects of wet and dry cycles on the compressive strength of recycled aggregate fly ash geopolymer concrete. The compressive strength of the control samples for batch 1 and 2 achieved compressive strength values ranging between 3700 and 3500 psi respectively. It's important to note that batch 1 had been stored and wrapped in aluminum foil for 120 days at room temperature prior to testing which coincides with the theory of compressive strength gain over time formulated by Somna (2011).

The compressive strength results obtained after wet dry testing, demonstrate that wet-dry cycles decrease the compressive strength of the material by approximately 1 to 4 percent.

Recycled aggregate typically has higher water absorption and produces concrete with higher drying shrinkage and creep. However, geopolymer acted as a shield protecting all the elements from water, maintaining the internal moisture levels and preventing rapid deterioration of the materials and loss of strength.

The plane failure surfaces of the cylinders after compression test showed that the failure plane occurred through the recycled aggregate which suggested that the binder made a strong hold between the recycled aggregates and the paste, which prevented separation and failure between the two.

Additionally, it was concluded that the density remained relatively constant, which suggest that using fly ash in the recycled aggregate concrete geopolymer mix, makes the material less susceptible to variations in density caused by water exposure. In terms of compressive strength and its relationship with density, it was determined that samples with the same density values presented a lower compressive strength after wet-dry cycle exposure. These results could be consequence of mild exterior deterioration experienced by the surface of the cylinders. The cylinder's surface presented micro-cracks and formation of pores as early as the 7 wet-dry cycle, which could have contributed to the minor decrease in compressive strength without allowing moisture intrusion and moisture accumulation in the material.

The results of the study concluded that recycled aggregate fly ash geopolymer concrete presented high strength and high durability performance. This was observed when most of the cylinders did not achieve complete destruction after failing under compressive strength. Even though the compressive strength results are favorable, further investigation needs to be performed to determine when the compressive strength stops decreasing and stabilizes after wet-dry cycle exposure.

The specific conclusions gathered from this investigation are as follows:

- Although nearly 70% of the composite is recycled or waste material (Recycled aggregate and Fly ash), the mix containing no cement reached an average compressive strength value of 3600 psi. In a related study geopolymer concrete following a similar mix design with virgin aggregate achieved a compressive strength of 3190 psi. (Gonzalez, 2010)
- There was negligible difference in compressive strength between specimens which were tested right after the 7-days heat curing and specimens that were stored for an additional 120-days in lab temperature before testing. This

implies that geopolymer concrete achieved its full-strength potential at a very early age, which may expedite the construction process.

- Recycled aggregate is commonly prone to high water absorption, wet-dry cycles were conducted to determine if the strength of the material decreased. Similar studies with cement-based recycled aggregate concrete (Gonzalez, 2010) suffered a 12% decrease in compressive strength due to 12 wet-dry cycles. RAGC compressive strength decrease ranges between 1 to 4 percent. Using geopolymer concrete has increased strength and improve the resistance to rapid deterioration.
- Density variation due to wet-dry cycles were found to be negligible possibly because fly ash acted as a shield on the material, allowing only minimal exterior deterioration and maintaining the internal moisture levels stable.
- The increased durability of the cylinders stored for 120 days in room temperature conditions can be linked to pH changes of the mixture, which could be caused by leaching of sodium hydroxide. Further analysis should be performed to clarify this assumption.

8.1 LIMITATIONS OF THE STUDY

Although the overall purpose of this study was achieved and the changes in compression strength were determined to take effect after the wet-dry cycles were applied, the investigation had to overcome certain limitations that made the process challenging.

Equipment malfunction led to a delay between the preparation of the two mixes. For this reason, Batch 1 was stored at room temperature conditions for approximately 120 days. Further delay was avoided by reaching out to the Florida Department of

Transportation – Materials laboratory who allowed us to perform the remaining compressive strength testing at their facilities.

The time constraint, also affected the investigation by limiting the number of wet-dry cycles that would be applied to the cylinders. The experiment could have benefited from performing more cycles to determine if the compressive strength decrease would eventually stabilize and plateau.

The experiment intended to determine the relationship between deflection and compressive strength, however, those results were not available since the equipment was not set to provide those results.

8.2 RECOMMENDATIONS FOR FUTURE WORK

- Future investigation on recycled aggregate fly ash geopolymer, could benefit from having a more extensive exposure to wet-dry cycles. It is important to determine at what point the compressive strength stops decreasing and reaches equilibrium. This information is essential to ensure that the material will continue to comply with minimum requirements of strength and durability.
- Further research on the surface damage and compressive strength relationship should be necessary to determine how much moisture penetration is allowed by the surface deterioration caused by wet-dry cycles.
- Changes in internal moisture should be monitored more extensively to determine water accumulation over time and how it affects all the properties of the material.
- To perform further investigation on the changes in pH of the recycled aggregate geopolymer concrete cylinders while exposed to wet dry cycles to identify any chemical leaching.

APPENDICES

APPENDIX A: GLOSSARY

Covalent Bonds: A covalent bond is a chemical bond that involves the sharing of electron pairs between atoms.

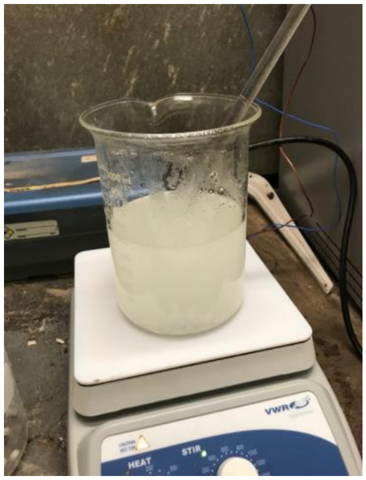
Oligomers: A polymer whose molecules consist of few repeating units.

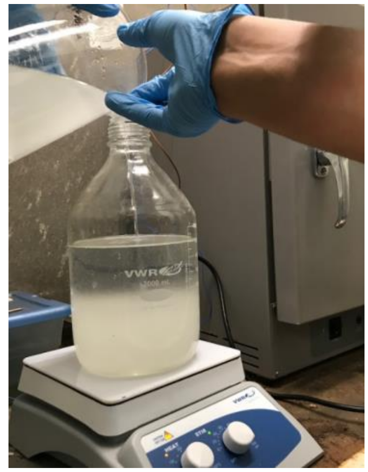
Polymer: A substance that has a molecular structure consisting of many similar units bonded together.

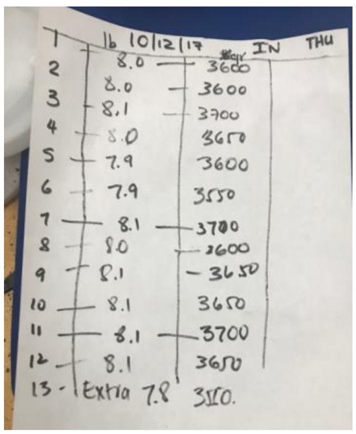
Self-desiccation: Refers to the taking up of free water by hydration of Portland cement to until there is not enough water to cover the surfaces of un-hydrated particles or to maintain 100 percent of relative humidity inside the concrete.

Metakaolin: Substance (crystalline compound) containing no water that is the form of the clay mineral kaolinite. Its particles are smaller in size than cement particles but they are not as fine as silica fume.

APPENDIX B: FIGURES

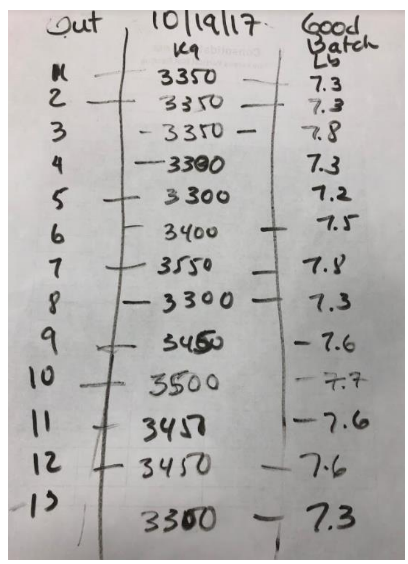






1 lb 10/12/17 IN THU
8.0 3600
2 8.0 3600
3 8.1 3700
4 8.0 3650
5 7.9 3600
6 7.9 3550
7 8.1 3700
8 8.0 3600
9 8.1 3650
10 8.1 3650
11 8.1 3700
12 8.1 3650
13 - Extra 7.8 3550.

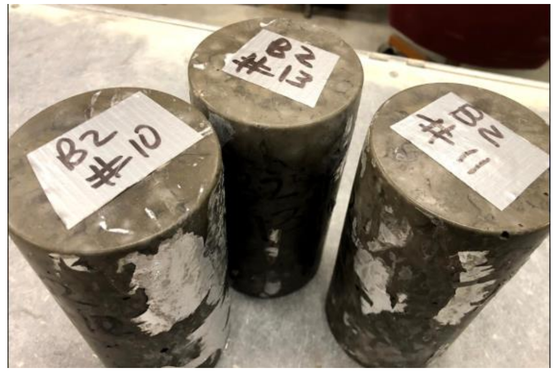
Explorer Pro
3380.42



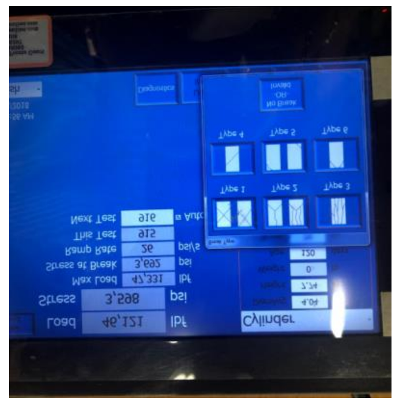
Out 10/19/17 Good Batch
Kg Lb
1 3350 7.3
2 3350 7.3
3 3350 7.8
4 3380 7.3
5 3300 7.2
6 3400 7.5
7 3550 7.8
8 3300 7.3
9 3450 7.6
10 3500 7.7
11 3450 7.6
12 3450 7.6
13 3300 7.3


B1
#7
B1
#6


B1
#10


B2
#10
B2
#13
B2
#11


Load 21,731 lbf
Stress 1,712 psi
Max Load 44,999 lbf
Stress at Break 3,545 psi
Ramp Rate 26 psi/s
This Test 914
Next Test 915
Cylinder
DiamAvg 4.02 in
Height 7.845 in
Weight 0. lb
Age 120 days
Type 1
Type 2
Type 3
Type 4
Type 5
Type 6



APPENDIX C: WEIGHT TABLES

B1	14 DAYS		
	Sample 1	**Sample 2**	**Sample 3**
	7.116	7.130	7.129
out	7.126	7.144	7.144
in	7.114	7.132	7.132
out	7.130	7.153	7.151
in	7.114	7.139	7.135
out	7.128	7.154	7.151
in	7.115	7.141	7.138
out	7.132	7.157	7.153
in	7.112	7.140	7.137
out	7.132	7.155	7.154
in	7.117	7.139	7.136
out	7.131	7.156	7.153
in	7.115	7.138	7.139
out	7.132	7.156	7.154

B2	14 DAYS		
	Sample 1	**Sample 2**	**Sample 3**
out	7.108	7.087	7.096
in	7.123	7.112	7.119
out	7.110	7.100	7.106
in	7.130	7.116	7.121
out	7.110	7.100	7.109
in	7.123	7.114	7.127
out	7.108	7.107	7.110
in	7.126	7.115	7.121
out	7.109	7.101	7.102
in	7.123	7.116	7.121
out	7.107	7.101	7.105
in	7.125	7.115	7.120
out	7.110	7.103	7.108
in	7.124	7.114	7.121

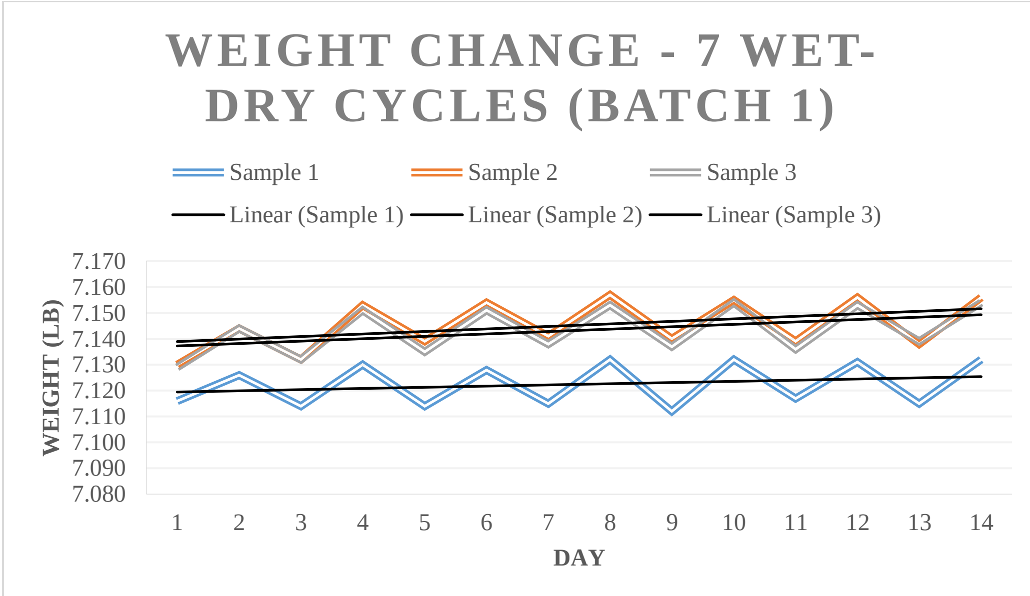
B1	**28 DAYS**		
	Sample 1	**Sample 2**	**Sample 3**
out	7.094	7.132	7.155
in	7.112	7.135	7.153
out	7.096	7.119	7.152
in	7.114	7.134	7.159
out	7.099	7.116	7.135
in	7.115	7.135	7.148
out	7.103	7.118	7.145
in	7.127	7.137	7.158
out	7.101	7.118	7.148
in	7.116	7.134	7.161
out	7.105	7.121	7.144
in	7.128	7.142	7.157
out	7.103	7.117	7.150
in	7.119	7.134	7.163
out	7.108	7.114	7.140
in	7.117	7.133	7.153
out	7.101	7.116	7.141
in	7.118	7.137	7.154
out	7.104	7.120	7.145
in	7.117	7.132	7.158
out	7.100	7.114	7.142
in	7.116	7.133	7.155
out	7.105	7.117	7.143
in	7.120	7.135	7.156
out	7.103	7.117	7.146
in	7.116	7.132	7.157
out	7.098	7.114	7.140
in	7.104	7.133	7.158

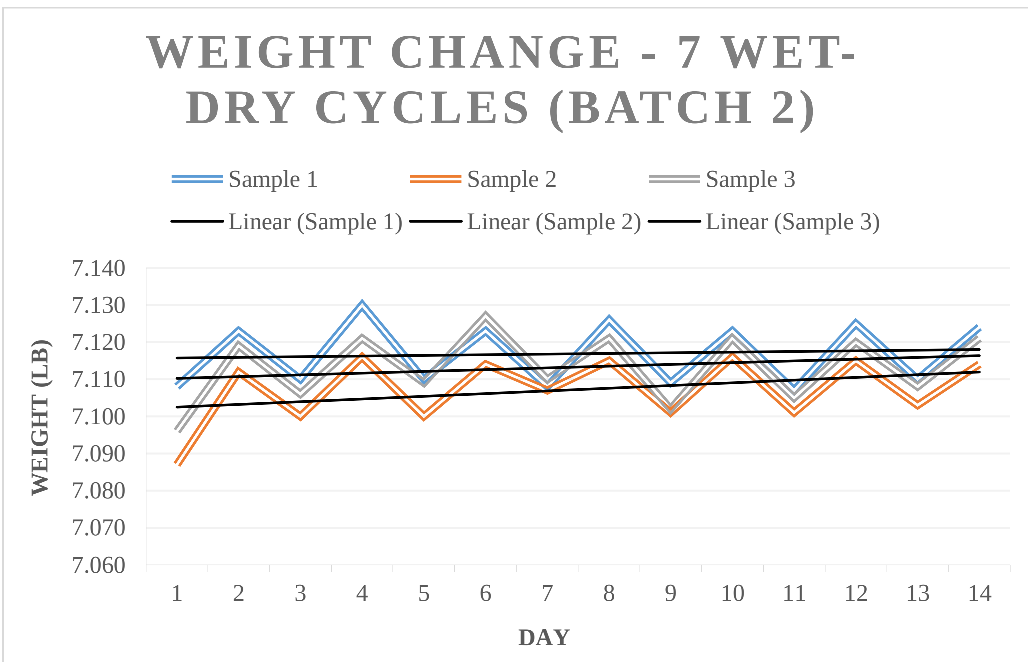
B2	28 DAYS		
	Sample 1	**Sample 2**	**Sample 3**
out	7.104	7.105	7.100
in	7.125	7.126	7.115
out	7.106	7.108	7.101
in	7.124	7.128	7.116
out	7.106	7.108	7.101
in	7.124	7.128	7.116
out	7.108	7.113	7.103
in	7.128	7.132	7.120
out	7.109	7.112	7.102
in	7.124	7.128	7.118
out	7.106	7.112	7.104
in	7.125	7.134	7.125
out	7.110	7.116	7.105
in	7.125	7.129	7.118
out	7.105	7.112	7.100
in	7.124	7.128	7.117
out	7.104	7.112	7.099
in	7.124	7.130	7.119
out	7.111	7.115	7.105
in	7.122	7.127	7.116
out	7.107	7.110	7.100
in	7.122	7.126	7.116
out	7.107	7.111	7.102
in	7.126	7.130	7.119
out	7.107	7.114	7.105
in	7.126	7.125	7.116
out	7.105	7.105	7.098
in	7.125	7.131	7.119

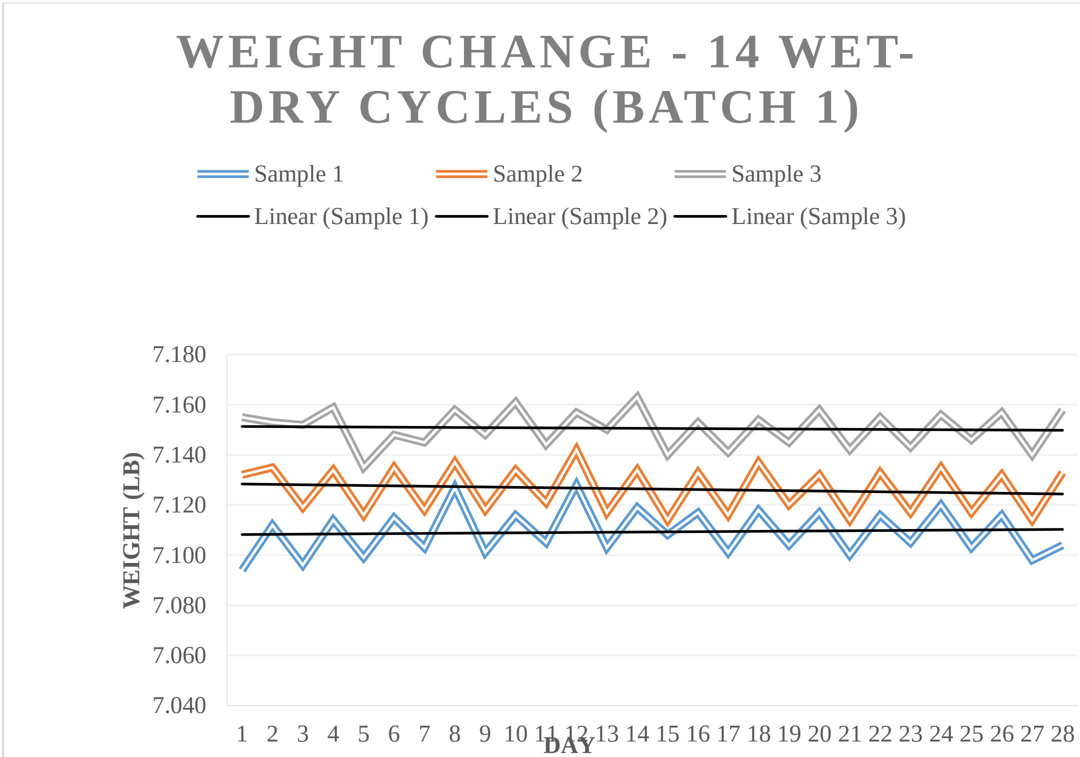
B1	42 DAYS		
	Sample 1	**Sample 2**	**Sample 3**
out	7.062	7.172	7.129
in	7.059	7.156	7.135
out	7.065	7.173	7.130
in	7.057	7.153	7.138
out	7.071	7.173	7.131
in	7.056	7.158	7.136
out	7.074	7.172	7.130
in	7.058	7.149	7.140
out	7.078	7.170	7.131
in	7.057	7.153	7.143
out	7.075	7.176	7.132
in	7.050	7.154	7.140
out	7.072	7.178	7.129
in	7.053	7.151	7.142
out	7.073	7.175	7.132
in	7.057	7.152	7.140
out	7.075	7.174	7.130
in	7.056	7.154	7.143
out	7.074	7.178	7.129
in	7.055	7.153	7.139
out	7.076	7.173	7.132
in	7.052	7.160	7.144
out	7.074	7.173	7.131
in	7.054	7.143	7.138
out	7.072	7.175	7.136
in	7.056	7.154	7.143
out	7.076	7.174	7.132
in	7.052	7.157	7.139
out	7.075	7.176	7.130
in	7.053	7.160	7.142
out	7.070	7.174	7.133
in	7.056	7.158	7.146
out	7.075	7.176	7.132
in	7.058	7.154	7.140
out	7.078	7.175	7.129
in	7.055	7.159	7.145
out	7.076	7.173	7.130
in	7.062	7.168	7.141
out	7.082	7.175	7.132
in	7.059	7.168	7.144
out	7.084	7.176	7.135
in	7.061	7.179	7.142

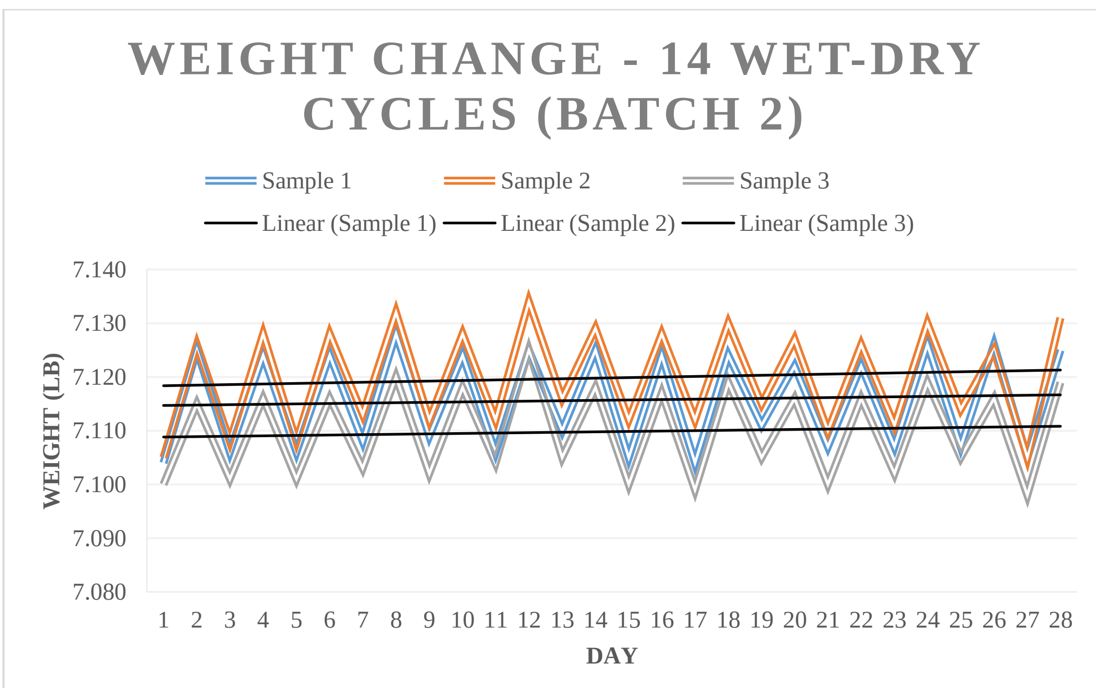
B2	42 DAYS		
	Sample 1	Sample 2	Sample 3
out	7.125	7.090	7.132
in	7.110	7.079	7.125
out	7.124	7.093	7.138
in	7.112	7.080	7.126
out	7.126	7.095	7.139
in	7.111	7.077	7.123
out	7.127	7.093	7.136
in	7.114	7.078	7.124
out	7.128	7.094	7.136
in	7.108	7.078	7.124
out	7.133	7.102	7.137
in	7.110	7.074	7.122
out	7.130	7.093	7.137
in	7.113	7.076	7.124
out	7.131	7.100	7.135
in	7.106	7.072	7.119
out	7.129	7.093	7.136
in	7.104	7.068	7.114
out	7.126	7.088	7.133
in	7.105	7.068	7.114
out	7.128	7.091	7.135
in	7.104	7.063	7.119
out	7.126	7.088	7.134
in	7.103	7.066	7.114
out	7.126	7.097	7.131
in	7.104	7.069	7.117
out	7.128	7.094	7.135
in	7.103	7.064	7.115
out	7.127	7.09	7.134
in	7.109	7.072	7.118
out	7.124	7.087	7.13
in	7.103	7.069	7.113
out	7.125	7.09	7.133
in	7.104	7.069	7.114
out	7.12	7.086	7.13
in	7.115	7.074	7.124
out	7.128	7.09	7.137
in	7.108	7.067	7.117
out	7.123	7.089	7.139
in	7.109	7.071	7.117
out	7.13	7.094	7.14
in	7.111	7.076	7.118

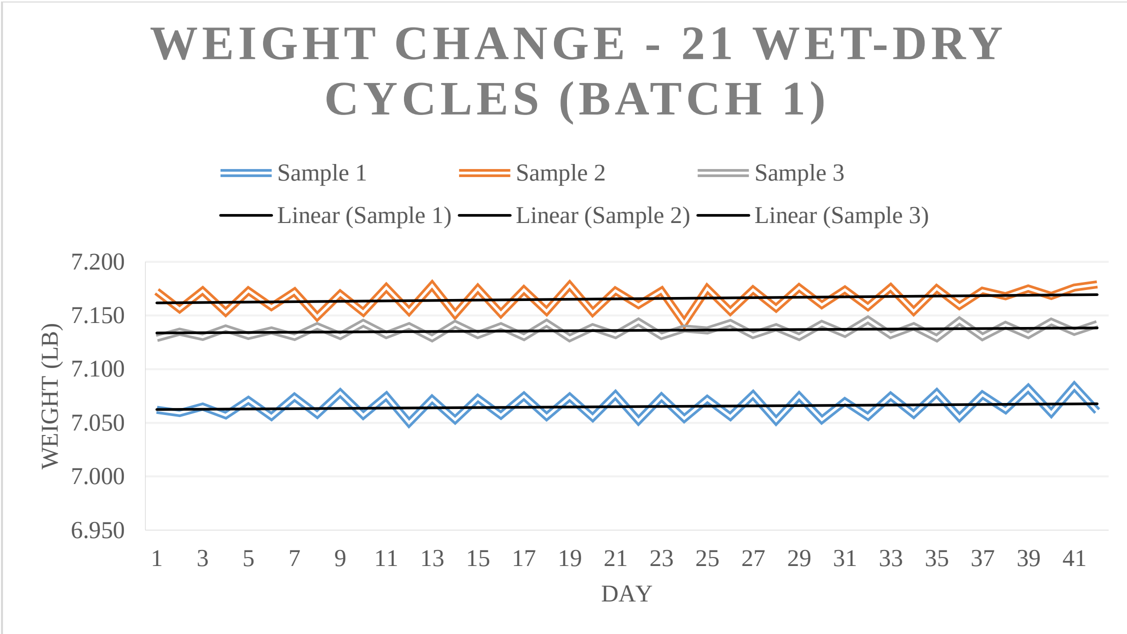
APPENDIX D: WEIGHT FLUCTUATION GRAPHS

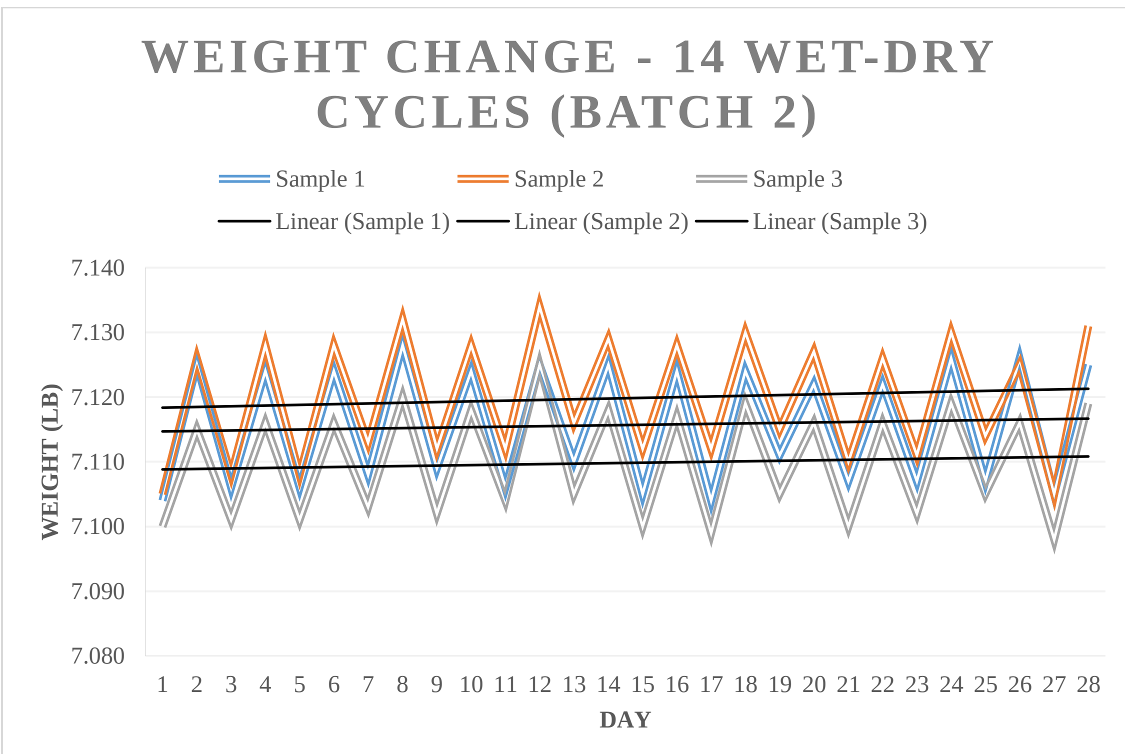





WEIGHT CHANGE - 14 WET-DRY CYCLES (BATCH 1)
Sample 1
Sample 2
Sample 3
Linear (Sample 1)
Linear (Sample 2)
Linear (Sample 3)
WEIGHT (LB)
7.180
7.160
7.140
7.120
7.100
7.080
7.060
7.040
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
DAY


WEIGHT CHANGE - 14 WET-DRY CYCLES (BATCH 2)
Sample 1
Sample 2
Sample 3
Linear (Sample 1)
Linear (Sample 2)
Linear (Sample 3)
WEIGHT (LB)
7.140
7.130
7.120
7.110
7.100
7.090
7.080
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
DAY


WEIGHT CHANGE - 21 WET-DRY CYCLES (BATCH 1)
Sample 1
Sample 2
Sample 3
Linear (Sample 1)
Linear (Sample 2)
Linear (Sample 3)
WEIGHT (LB)
7.200
7.150
7.100
7.050
7.000
6.950
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41
DAY


WEIGHT CHANGE - 14 WET-DRY CYCLES (BATCH 2)
Sample 1
Sample 2
Sample 3
Linear (Sample 1)
Linear (Sample 2)
Linear (Sample 3)
WEIGHT (LB)
7.140
7.130
7.120
7.110
7.100
7.090
7.080
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
DAY

APPENDIX E: CYLINDER INFORMATION LOG

TYPE OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	0		3000 PSI						
BATCH	1								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	47560	4.13	7.88	13.36	7.587	7.587	124.57	5	3558.80
CYLINDER 2	46630	4.03	8.00	12.77	7.337	7.337	124.12	3	3652.02
CYLINDER 3	47125	4.05	7.88	12.90	7.353	7.353	125.12	5	3654.45
COMPRESSION TEST	AVERAGE 3 (PSI)	**3621.75**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPE OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	0		3000 PSI						
BATCH	2								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	44136	4.00	7.81	12.54	7.3	7.3	128.75	2	3519.26
CYLINDER 2	45580	4.02	7.75	12.66	7.8	7.8	137.36	3	3600.08
CYLINDER 3	47331	4.03	7.88	12.74	8.3	8.3	142.92	3	3714.29
COMPRESSION TEST	AVERAGE 3 (PSI)	**3611.21**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPE OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	7		3000 PSI						
BATCH	1								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	42136	4.00	7.70	12.54	7.114	7.115	135.74	2	3359.78
CYLINDER 2	44999	4.02	7.85	12.69	7.132	7.142	136.17	3	3545.36
CYLINDER 3	47331	4.04	7.74	12.82	7.132	7.14	134.79	3	3692.26
COMPRESSION TEST	AVERAGE 3 (PSI)	**3532.47**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPY OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	7		3000 PSI						
BATCH	2								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	43952	4.07	7.71	13.01	7.11	7.11	132.82	2	3378.31
CYLINDER 2	44982	4.02	7.66	12.69	7.1	7.101	136.17	2	3544.02
CYLINDER 3	41834.1	4.04	7.70	12.82	7.106	7.107	134.79	3	3263.45
COMPRESSION TEST	AVERAGE 3 (PSI)	**3395.26**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPY OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	14		3000 PSI						
BATCH	1								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	40077	4.02	7.59	12.69	7.116	7.117	136.14	3	3157.56
CYLINDER 2	49166	4.01	7.60	12.62	7.096	7.101	136.93	2	3895.92
CYLINDER 3	40792	4.03	7.77	12.76	7.138	7.143	135.42	2	3196.78
COMPRESSION TEST	AVERAGE 3 (PSI)	**3416.75**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPY OF TEST	**COMPRESSION**		**MINIMUM**	**Notes:**					
# CYCLES	14		3000 PSI						
BATCH	2								
	LOAD (Lb)	**DIAMETER 1 (in)**	**LENGTH (in)**	**AREA (in_2)**	**BEGINNING WT (Lb)**	**FINAL WT (Lb)**	**DENISTY (LB/FT^3)**	**BREAK TYPE**	**STRENGTH (lb/in^2)**
CYLINDER 1	39915	4.03	7.78	12.76	7.108	7.109	135.47	3	3129.21
CYLINDER 2	38124	4.00	7.78	12.57	7.106	7.107	137.44	2	3032.29
CYLINDER 3	39743.6	4.01	7.76	12.66	7.111	7.093	136.54	3	3140.35
COMPRESSION TEST	AVERAGE 3 (PSI)	**3100.62**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPY OF TEST	COMPRESSION		MINIMUM	Notes:					
# CYCLES	21		3000 PSI						
BATCH	1								
	LOAD (Lb)	DIAMETER 1 (in)	LENGTH (in)	AREA (in$_2$)	BEGINNING WT (Lb)	FINAL WT (Lb)	DENISTY (LB/FT^3)	BREAK TYPE	STRENGTH (lb/in^2)
CYLINDER 1	41808	4.02	7.71	12.70		7.086	124.86	2	3291.98
CYLINDER 2	43203.8	4.02	7.63	12.68		7.1166	123.82	3	3408.46
CYLINDER 3	41931	4.01	7.56	12.65		7.092	131.52	4	3314.84
COMPRESSION TEST	AVERAGE 3 (PSI)	**3338.43**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

TYPY OF TEST	COMPRESSION		MINIMUM	Notes:					
# CYCLES	21		3000 PSI						
BATCH	2								
	LOAD (Lb)	DIAMETER 1 (in)	LENGTH (in)	AREA (in$_2$)	BEGINNING WT (Lb)	FINAL WT (Lb)	DENISTY (LB/FT^3)	BREAK TYPE	STRENGTH (lb/in^2)
CYLINDER 1	39195	4.01	7.79	12.64		7.111	124.86	3	3101.02
CYLINDER 2	38121	4.02	7.78	12.69		7.076	123.82	4	3003.83
CYLINDER 3	38436.75	4.00	7.44	12.57		7.118	131.52	2	3057.09
COMPRESSION TEST	AVERAGE 3 (PSI)	**3053.98**							
MATERIAL DESCRIPTION	Recycled Aggregate -Fly Ash Geopolymer								
TEST METHOD	Compressive Test								

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