INCORPORATION OF HIGH-VOLUME FLY ASH TO PRODUCE STRUCTURAL LIGHTWEIGHT CONCRETE

by

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DEDICATION

I would like to dedicate this work to my parents, siblings, wife, and my grandmother, who recently passed away. I am forever grateful for the endless support and love I receive from them. I am also grateful to them all for inspiring and motivating me through this journey as a first-generation student. May God bless you all.

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ABSTRACT

Concrete industry is one of the main industries using large proportion and volume of our natural resources. Ordinary Portland Cement is an important source for the emission of carbon dioxide into the atmosphere because of burning fuel and raw materials' decomposition during the production process of cement. Due to the increasing demand in concrete, one of the most effective and reliable ways to reduce the negative impact on the environment in the concrete industry is through the use of waste and by-product materials such as aggregates and ordinary portland cement replacement in concrete.

The prospect of producing structural lightweight concrete using large volume of waste materials and by-products is investigated in this current study. The lightweight material used as coarse aggregate comprised of expanded shale and expanded clay. While the waste and by-product material comprised of a high volume (50% and 70%) of type C and type F fly ash, as replacement for cement by volume. The mechanical properties such as compressive strength, split-tensile strength, flexural strength, modulus of elasticity and drying shrinkage for up to 28 and 56 days are investigated as well as slump and unit weight for fresh density. The durability properties such as abrasion resistance, water absorption, resistance to chloride ion penetration and freeze and thaw resistance are also investigated. All lightweight concrete containing 50% fly ash class C and F replacement showed adequate strength in the mechanical properties. While lightweight concrete with 70% fly ash both class C and F exhibited strength lost compared to other concrete samples. Test results showed that the early ages of drying shrinkage of ordinary Portland

cement and fly ash are similar but with the growth rate of drying shrinkage in OPC, it is expected for concrete incorporated with fly ash to exhibit good resistance to drying shrinkage. Test results also indicated that, concrete incorporated with fly ash showed good resistance to chloride ion penetration and there was no significant difference in abrasion for either OPC or fly ash incorporated concretes. There was significant difference in water absorption of the concrete containing fly ash. However, concretes with fly ash performed poorly and could not resist exposure to freeze and thaw mechanism especially concretes incorporated with 70% fly ash F.

I. INTRODUCTION

Background

Concrete is only second to water as the most commonly used material in the world, therefore crucial to stress that it is without doubt the most versatile, most important and hugely used building material (Meyer, 2005). Concrete is the basis of present-day development, providing shelter to billions, providing structure for education, healthcare, transport, energy and serving as defense mechanism during natural disasters (Gharehbaghi, 2015). Approximately, over 10 billion tons of concretes are produced each year, which requires wide and expansive amounts of natural resources to produce cement and aggregates (Meyer, 2009). Unfortunately, the demand for concrete will continue to increase as economic and global development increases. It is reported that the demand for concrete will increase by the year 2050 from 10 billion tons to approximately 18 billion tons annually (Li et al., 2009).

Portland Cement production is extremely energy-intensive, with the industry only third to China and USA in global carbon dioxide emission with up 2.8 billion tons (Habert, 2014). Moreover, the production of one ton of Portland cement is estimated to emit one ton of carbon dioxide in the atmosphere (Meyer, 2006). Carbon dioxide is a greenhouse gas that substantially accords to global warming with 7% alone coming from the cement industry (Benhelal et al., 2013; Nomeli & Riaz, 2015). Lee & Wang, (2016) have proposed methods to calculate the total amount of carbon dioxide emitted in the atmosphere during concrete production. This proposed method considers materials such as cement, aggregates, admixtures, superplasticizers, and water used in the production and transportation of concrete. It reports that a total of about 287 kg of carbon dioxide is emitted during the production of 1 m^3 concrete with cement; 390 kg, water; 150 kg, coarse and fine aggregates of 970 kg and 890 kg, respectively.

Sustainable development has become a household term for recent group of researchers that aim to reduce the negative impact of concrete globally (Meyer, 2006). Scientists and researchers are striving to find common ground and strike the balance between socio-economic development and preservation of the environment. Thus, improving infrastructure and quality of life without disadvantageously and negatively affecting our environment (Alabi & Mahachi, 2021; Lippiatt & Ahmad, 2004; Meyer, 2006). Researchers in the concrete industry are cautious about this concern hence, increasing its compliance with the demand of sustainable development (Lippiatt & Ahmad, 2004). Even though, the energy consumption of Portland cement is comparably less to steel, due to the high demand of cement, large quantity production of OPC makes it extremely energy intensive and produces the most carbon dioxide generated, it is essential to replace OPC with other materials, especially, those that are by-products from industrial processes with supplementary cementitious properties such as fly ash and ground granulated blast furnace slag (Shafigh et al., 2016). Increasing the reliance on these supplementary cementitious materials and recycled materials will help curb the demand on natural resources, cost, and energy efficient, and general ecological and environmental benefit (Arezoumandi & Volz, 2013).

High-Volume Fly Ash (HVFA) concrete has been gaining grounds among researchers as a cost-effective, resource efficient, durable, and a viable alternative for different kinds of ordinary Portland cement concrete applications (Nomeli & Riaz, 2015; Szecsy, 2006). Concretes containing more than 50 percent of fly ash are regarded as a high-volume fly ash (HVFA). Since fly ash is a by-product, large quantities are available in every part of the world at low and affordable costs. Hence, the application of high-volume fly ash offers the best possible option in reducing the rising demand on OPC (Naik, 2008; Nomeli & Riaz, 2015; Szecsy, 2006). Approximately 75 million tons of fly ash are produced in the USA annually, and 65 percent are processed into useful applications (Dwivedi & Jain, 2014). Also, in the USA, Leadership in Energy and Environmental Design (LEED) points are awarded for any concrete mixture that contains more than 40 percent fly ash. Research has shown that, the use of fly ash at 50 percent or more have wide range of benefits such as improving workability and decreasing internal temperature (Burden, 2006) (Ashley, 2008). However, (Hemalatha & Ramaswamy, 2017) reports that there is inconsistencies in the properties of high-volume fly ash and this subsequently leads to poor development of early day age strength of the concrete.

Structural lightweight aggregates concretes are adaptable and flexible building materials which are about 20 to 40% less dense to normal weight concrete (Kockal & Ozturan, 2011b). Its reduced density helps to decrease dead loads, reduced foundation cost, consequently, reducing the sizes of columns, footings, and load bearing elements. It also is advantageous from conserving energy because it produces more wall elements for better insulation properties (Shafigh et al., 2014).

When combined, structural lightweight high-volume fly ash concretes have wide range and so many desirable properties which includes sufficient strengths. Even though HVFA has different wide ranges of benefit, its durability properties are the most desirable (Hamoush, 2011). Its better performance in durability properties is associated with its low content of calcium hydroxide as compared to OPC. HVFA is less susceptible to cracks because it has decreased shrinkage when compared to OPC. Also, its good thermal shrinkage and cracking properties stem from the decreased heat of hydration at early ages. It is essential to also, note that HVFA is less susceptible to freeze/thaw damage due to its permeability properties (Bilodeau & Malhotra, 2000; Langley et al., 1989).

Aim and Objective

With all the benefit that comes with high-volume fly ash, only 35 percent is allowed to be used as replacement for OPC in the industry. Hence, this research aims to produce structural lightweight high-volume (50 and 70 percent) fly ash concrete without doing much damage to the strength. Some of the objectives of this studies are as follows:

1. Reducing the emission of carbon dioxide during
2. Increasing the use of waste materials and byproducts
3. Producing an economical and environmentally friendly concrete
4. Reducing the density of concrete hence, making it easy to transport
5. Reducing time and cost of labor during construction
6. Reducing the demand on energy during construction
7. Improving thermal and sound insulation properties
8. Improving workability and ultimate strength

Originality Statement

While there have been studies on other lightweight aggregates, this research uses 2 lightweight aggregates (Expanded Clay and Shale) as total replacement for reference coarse aggregate (limestone). Also, there is the addition of other durability properties such as water absorption and resistance to chloride permeability which are yet to be studied under this circumstance. Hence, this study aims to bridge the gap in research by producing structural lightweight concrete incorporating high-volume fly ash while studying other engineering properties yet to be studied in this regard.

Flowchart of Research

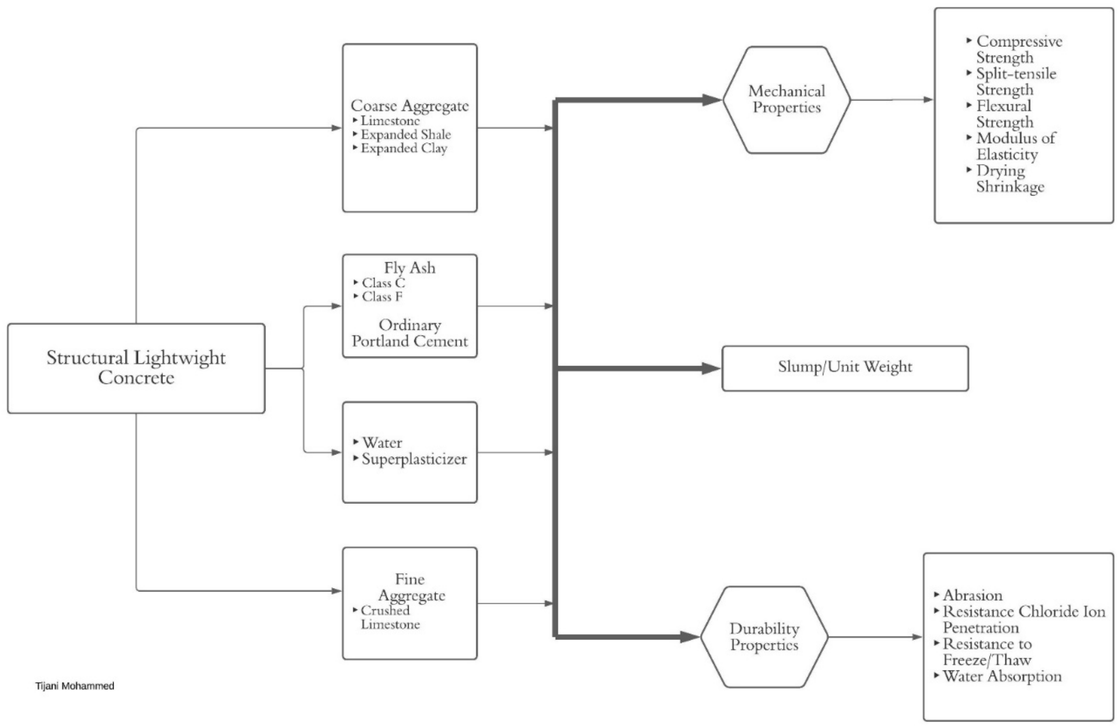

Figure 1: Illustration of Flowchart of Research

II. LITERATURE REVIEW

Bilodeau et al., (1998) studied the mechanical and durability properties of structural lightweight concrete incorporating high-volume of fly ash. This research investigated the application of using high-volume fly ash concrete with 58% replacement of class C and F by mass. The lightweight aggregates used are not specified in this research. Also, it investigated mechanical properties such as compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, abrasion resistance, drying shrinkage, and creep. The durability properties studied in this paper are air-void parameters, water permeability, resistance to freezing and thawing cycling, resistance to chloride-ion penetration, and the depth of carbonation. It is reported that the incorporation of fly ash in lightweight concrete provides later day strength to the concrete. The development of strength in lightweight incorporated with fly ash is slower compared to that of normal concrete. The mechanical properties of the lightweight concrete incorporated with high-volume fly ash are similar in later ages to the reference normal concrete. The study also reported that structural lightweight high-volume fly ash concrete produces adequate compressive strength >35MPa after 28-day of age.

Shafigh et al., (2016) also studied the engineering properties of lightweight concrete containing limestone powder and high-volume fly ash. This study focused on incorporating high-volume fly ash in lightweight concrete with the inclusion of limestone powder. A water/cement ratio of 0.30 is used for the reference concrete and a 0.32 for fly ash incorporated concrete. Replacement of ordinary Portland cement with high-volume fly ash (by mass of total cementitious material) in Oil Palm Shell lightweight concrete significantly reduces the density of the concrete produced. It also reports that the compressive strength of OPS concrete with high-volume fly ash at 28-day age is significantly higher compared to the OPS concrete without fly ash. Other engineering property tests such as water absorption suggests that lightweight concrete with 50% fly ash has almost similar properties to lightweight concrete without fly ash. The drying shrinkage between lightweight concrete and concrete with 50% fly ash have no significant difference. But lightweight concrete with 70% fly ash shows significant increase in drying shrinkage for 3 months.

Sirotin et al., (2013) studied the effect of fly ash on the durability of lightweight concrete. This study aimed at presenting a method that allows to manufacture durable lightweight concrete which consists of a matrix including a hardened paste of cementitious materials and a normal weight and a lightweight mixture that forms the structure of the concrete. It is concluded that the durability of lightweight concrete consisting of both lightweight and normal weight aggregates could be significantly improved by high volumes of fly ash as an additive to ordinary Portland cement.

Tanyildizi & Coskun, (2008) studied the effect of high temperature on compressive and splitting tensile strength of lightweight concrete containing fly ash ASTM Type I Portland cement was used with 0% to 30% replacement with Fly ash class F. Specimens were heated to temperatures of 200, 400 and 800^{0}C, respectively, to test the compressive and splitting tensile strength of lightweight concrete. It is reported that samples with 30% fly ash replacement obtained the most and highest compressive and splitting tensile strengths.

Kockal & Ozturan, (2011a) studied the effects of aggregate properties such as strength, porosity, water absorption, bulk density and specific gravity on the strength and durability of lightweight fly ash aggregate concrete (LWAC). The influence of properties of aggregates such as Sintered lightweight fly ash aggregate, Cold bonded lightweight fly ash aggregate and normal weight aggregate on mechanical and durability properties of concrete were tested. Rapid freezing and thawing, water permeability, accelerated corrosion, rapid chloride permeability, compressive strength, splitting tensile strength and modulus of elasticity were the tested. It is concluded that lightweight concretes obtained lower splitting tensile and compressive strengths and modulus of elasticity than normal weight concrete. Fly ash aggregate lightweight concrete being air-entrained is greatly resistant when exposed to freezing and thaw cycle.

Patel et al., (2019) also researched the durability and microstructural characteristics of lightweight concrete prepared by using fly ash. The main objective of this experiment was to study the durability and microstructural characteristics of lightweight concrete prepared by using fly ash. Cenosphere and Sintered fly ash aggregate as replacements of natural fine and coarse aggregate, respectively. Using Cenosphere and Sintered fly ash aggregate, in various combinations i.e., 0%, 50%, 75% and 100% for each, sixteen concrete mixes were produced. Properties of concrete tested were compressive strength, resistance to sulphate, acid, and chloride attack of concrete. Further, the scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses for these concrete mixes are performed in support of the above strength and durability behaviors. This study concluded that chloride resistance of concrete containing fly ash improves and could be associated to the finer particles of fly ash.

III. MATRIX FOR EXPERIMENTAL RESEARCH

Table 1: Matrix for Experimental Research

Test	Size(mm)	Specimens	# Of test days	Volume (m^3)	Total Volume (m^3)	Test Days	ASTM Standard Method
MECHANICAL PROPERTIES							
Compressive Strength	100.6*203.2	3	4	0.001642	0.019765	7,14,28,58	ASTM C39
Split-tensile Strength	100.6*203.2	3	1	0.001642	0.004927	28	ASTM C496
Flexural Strength/ Modulus of Rupture	152.4*152.4*508	3	1	0.011808	0.035396	28	ASTM C78
Drying Shrinkage	76.2*76.2*279.4	3	1	0.001614	0.004870	3,7,14,28,58	ASTM C157
Static Modulus of Elasticity/ Poisson's Ratio	100.6*203.2	0	1	0.001642	0.000000	28	ASTM C469
Density of Fresh Concrete/ Slump	76.2*76.2*279.4	0	1	0.001614	0.000000	1	ASTM C138
				TOTAL	**0.064959**		
DURABILITY PROPERTIES							
Abrasion	100.6*203.2	3	1	0.001642	0.004927	28	ASTM C944

Chloride Ion Penetration	100.6*203.2	3	1	0.001642	0.004927	7,14,28,56	ASTM C1202
Freezing and Thawing	76.2*101.6*406.4	3	1	0.003143	0.009430	-	ASTM C666
Water Absorption	100.6*203.2	1	1	0.001642	0.001642	28	ASTM C1585
				TOTAL	**0.025797**		

IV. MATERIALS

Ordinary Portland Cement

Ordinary Portland cement used is from a source in USA and it is in accordance with ASTM type I. The chemical composition of the OPC used is provided in Table 2.

Fly Ash

Two types of fly ashes are used in this research, and they are obtained from local plant in Texas. Fly ash class F is in accordance with ASTM class F fly ash specification with CaO content less than 18%. Class C fly ash is also within the ASTM limit with CaO content greater than 18%. Table 2 shows the chemical compositions of both Class C and F fly ash.

Fine Aggregate

The fine aggregate used in this study is crushed limestone. The physical property of this aggregate is shown in table 3.

Coarse Aggregate

Three different coarse aggregates are used in this study. Two lightweight aggregates, Expanded Shale and Clay obtained locally in Texas. These aggregates have maximum size of 9.5 mm, and they are used as received from supplier as they are in accordance with ASTM C 330 for structural lightweight purpose. Limestone rock is also used as a coarse aggregate for reference to the two lightweight aggregates. The physical properties of these aggregates are provided in table 3.

Table 2: Composition of Ordinary Portland Cement and Fly Ash from Source			
Components (%)	Cement	Fly Ash C	Fly Ash F
SiO_2	20.8	33.99	50.12
Fe_2O_3	3.8	5.70	4.61
AI_2O_3	5.2	20.50	18.24
CaO	64.3	26.99	16.38
MgO	1.2	4.29	3.80
SO_3	2.0	2.09	0.82
K_2O	0.4	0.40	1.30
Na_2O	0.1	1.66	1.00
Loss ignition	1.3	0.60	0.30

Table 3: Physical Properties of Coarse Aggregates				
Physical Properties	Crushed Limestone Sand	Limestone Rock	Expanded Shale	Expanded Clay
Specific gravity (SSD)	2.77	2.57	1.78	1.60
Absorption Rate (%)	2.89	2.00	17.00	14.50

Table 4: Physical Properties of Cementitious Materials			
Physical Properties	Cement	Fly Ash C	Fly Ash F
Specific gravity (SSD)	2.50	3.13	3.13
Blaine's fineness (kg/m^2)	370	380	380

V. MIX PROPORTIONS

In batch 1, five concretes are mixed with OPC + NA as reference containing limestone rock as coarse aggregate and OPC. Other mixes in batch 1 vary from each other based on the two types of fly ash (C and F) and the high-volume replacement of OPC (50 and 70%). Similarly, Batch 2 and 3 follow the same procedure as in batch 1, with each batch bearing a different kind of coarse aggregates, expanded shale in batch 2 and expanded clay in batch 3. The reference mix (OPC + Shale) in batch 2 contains expanded shale and OPC, with all other mixes in the batch 2 differing in type of fly ash and volume replacement of OPC. Also, reference for batch 3 consists of expanded clay and OPC. Mixes 50% F + Clay, 70% F + Clay, 50% C + Clay and 70% C + Clay in batch 3 only differing in the class of fly ash and volume replacement of Ordinary Portland cement. Furthermore, all other aggregates such as coarse and fine aggregates are all batched and mixed in their saturated surface dry conditions (SSD). All values in the table are provided in per meter cube.

Table 5: Theoretical Mix Proportions

Mix ID Name	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Crushed Limestone Sand (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	W/binder (Cement + Fly Ash)
BATCH 1							
OPC + NA	390	0	1073	715	156	1.26	0.40
50% F + NA	195	156	1073	715	140	1.14	0.40
70% F + NA	117	218	1073	715	134	1.08	0.40
50% C + NA	195	156	1073	715	140	1.14	0.40
70% C + NA	117	218	1073	715	134	1.08	0.40
BATCH 2							
OPC + SHALE	390	0	745	715	156	1.26	0.40
50% F + SHALE	195	156	745	715	140	1.14	0.40
70% F + SHALE	117	218	745	715	134	1.08	0.40
50% C + SHALE	195	156	745	715	140	1.14	0.40
70% C + SHALE	117	218	745	715	134	1.08	0.40
BATCH 3							
OPC + CLAY	390	0	667	715	156	1.26	0.40
50% F + CLAY	195	156	667	715	140	1.14	0.40
70% F + CLAY	117	218	667	715	134	1.08	0.40
50% C + CLAY	195	156	667	715	140	1.14	0.40
70% C + CLAY	117	218	667	715	134	1.08	0.40

VI. TEST PROCEDURE

Process of Concrete Mixing

All mixtures are done in a concrete mixer with a capacity of 0.11 m^3. Both coarse and fine aggregates are kept in saturated surface dry (SSD) conditions before each mix.

Firstly, the coarse aggregate is added to the mixer and allowed to mix for a minute. Then the fine aggregate (sand) is added and allowed to mix together for two minutes. Half of the calculated amount of water to be used is added to the mixture and allowed to mix in the mixer drum for at least 3 minutes. The total amount of cementitious material is then added. OPC is added first immediately followed by fly ash. This can mix for 3 minutes and then the rest of the water is added to the mixture. Meanwhile, in mixtures where superplasticizers are used, the superplasticizer is mixed with the water remaining before adding to the mixture. Slump test is then performed to determine the workability of the concrete mix. Then the fresh unit weight density test is done to determine the weight of the fresh concrete.

Preparation, Casting, Consolidation, and Curing

In mechanical property test, concrete samples are cast in a cylinder of 100x200 mm for compressive strength, split-tensile strength, and modulus of elasticity. 3 specimens are cast for each test. 2 beams of 150x150x500 mm are used to cast for flexural strength. And 3 beams of 75x75x275 mm are used to cast for drying shrinkage test. In durability property test, a 100x200 mm cylinder is used to cast specimens for abrasion, chloride permeability, and water absorption tests. Three cylinders are cast for each test beside water absorption test. Meanwhile, a 75x100x400 mm beam is used to cast specimens for freeze and thaw test. And a 75x75x275 mm is used to cast specimens for alkali-silica rection tests.

All concrete samples are compacted using a vibrating table. After molding, all samples are covered with water-saturated burlaps and plastic sheets. These samples are left in casting room for 24 hours. All Samples are then demolded after 24 hours of casting and then transferred into a moist-curing room of temperature 23 ± 3ºC and 100% relative humidity until testing day is due. Meanwhile, after 7 days of curing, drying shrinkage samples are taken and are stored in a drying room with temperature 23 ± 2ºC and 50 ± 4% relative humidity.

In mechanical property testing, for the purpose of reporting accurate results, 3 samples are used in each test, hence, all results reported in this research are the average of these 3 samples excluding flexural strength which has an average of 2 samples.

In durability test, chloride permeability test sample is immersed in a lime saturated water for 21 days at 38 ± 2ºC after 7 days of curing. Freeze and thaw samples are immediately placed in the freeze and thaw chamber/apparatus after 7 days of curing for cycle to begin.

VII. TEST METHODS

Unit weight and Slump

Density of fresh concrete and slump is determined in accordance with ASTM C138. These do not have test days but rather determined during mixing of concrete.

Mechanical Test

Compressive strength

The compressive strength of the sample is determined in accordance with ASTM C39. The strengths at ages 7,14,28 and 56 are determined. Cylindrical samples used in this test are kept in curing room until test day. Samples are taken out of the curing room on testing day and water on the surface is wiped out. Then, sample is placed vertically on the compression test equipment. Pads caps are placed on both sides of the cylindrical samples so that uniform load application and distribution could be facilitated. Then without shock, load is applied continuously and uniformly at a constant rate of 0.24 ±0.03 MPa/s The maximum load at breaking point is recorded and then compressive strength of the sample is calculated. Three samples are determined at each age and the average is presented in this study.

Split-tensile strength

This test is performed in accordance with ASTM C496. Three samples are used to determine this test on 28-day of age. Water on the surface of samples is wiped out after taking out of the curing room. Lines are drawn diametrically on the two ends of the specimen to make sure that they are on the same axial place. The specimen is then weighed.

The compression testing machine is set to the range needed for the test. Afterwards, a strip of plywood is placed on both the lower and upper of the specimen. Sample is aligned so that they are the same as the lines drawn diametrically. Load is then continuously applied without shock at a rate within the range 0.7 to 1.4 MPa/min. Breaking load is then recorded and split tensile is subsequently, calculated. The average of these 3 samples is also presented in this study.

Flexural strength

ASTM C78 is used to carry this test. Sample is placed in the apparatus as described in the standard. Then a load of 3 and 6% of the estimated ultimate load is applied. The gap between the sample and the supports is checked to make sure it is not more than 0.10 mm. The load indicator is tared to zero before the equipment or before the test is started. Load is applied continuously without shock until failure at a constant rate. The maximum load at the breaking point is then recorded and flexural strength is calculated. The average of 2 samples are determined at the age of 28-day.

Drying Shrinkage

Drying shrinkage test is done with reference from ASTM C157. The three samples cast for this test are stored in an air-dry room of temperature 23 ± 2°C and 50 ± 4% relative humidity and measurements are taken on 3,7,14,28, and 56 days of age. A comparator is used in measuring the length change. Subsequent measurements are compared to the initial measurement to determine volumetric contraction.

Modulus of Elasticity

This is determined using ASTM C469. Samples have not been cast for this test but rather a cylindrical sample is used to perform this on 28-day of age after determining the equivalent 28-day compressive strength. A strain measuring equipment called compressometer is attached the to the sample as described in the standard. Sample is placed on a lower platen then the axis is aligned with the center of the thrust that bears the block and then the block is slowly brought to bear the load on the sample. This allows for uniform seating of the sample. Uniform Load is then applied to the sample at a constant rate of 0.24MPa/sec until at 40% of the ultimate load. During loading, the strain values at 50 millionths and the equivalent load at 40% are recorded. This process is repeated three more times and then the average is taken.

Durability Test

Resistance to Abrasion

Three cylindrical samples are cast for abrasion test and stored in curing room until 28-day of age for testing. This is determined in accordance with ASTM C944. The average of the 3 samples is reported in this study. The mass of the sample is recorded to the nearest 0.1g. Sample is then tightened to the abrasion device and the surface to be tested is aligned normally to the shaft. Rotating cutter is then attached to the device and then its slowly lowered until contact is made with sample. Abrasion is then started at a normal or double load for 2 minutes after sample is in contact with rotating cutter device. Sample is removed and cleaned with a soft brush after every 2 minutes of abrasion and then the mass is recorded to the nearest 0.1g.

Resistance to Chloride Ion Penetration

Chloride permeability is determined in accordance with ASTM C1202. The average of 3 samples cast is determined after sample is immersed in a lime saturated water for 21 days at 38 ± 2°C after 7 days of curing. The cylindrical sample is placed in between the two single cell reservoirs with NaCl and NaOH solutions in each of the reservoirs. The reservoirs are connected to a direct current supply and 60V voltage is applied to the sample at both the ends for 6 hours. The measurement of the current going through the sample at different time period. LCD is then determined.

Resistance to Freezing and Thawing

Three sample beams are cast for freeze and thaw and its test is determined according to ASTM C666. This has no specific test day, but data is taken after each cycle the sample goes through. Samples are placed in the freeze and thaw chamber where the internal temperature of the specimens is lowered from 4 to -18 °C and back to 4 °C between 2 and 5 hours. This cycling is repeated for numerous cycles unless failure occurs earlier. Measurements taken are used to determine the freeze and thaw during the periodic cycle.

Water Absorption

A 50-mm piece is taken from the cylinder and then this sample is placed into a chamber with temperature of 50 °C and 80% relative humidity for 3 days. Samples are then moved to sealed container containing water and fully submerged for a minimum of fifteen days. Both the outside and top of the piece of sample is coated with epoxy before being placed in water. The change in mass of the piece sample is then measured over a period of time.

VIII. TEST RESULTS AND DISCUSSION

Unit weight and Slump

The unit weight data obtained in batch one of the mixtures showed higher unit weight compared to other mixtures in other batches. This is basically due to the materials used in batch one. In batch one, OPC + NA to 5, the coarse aggregate used was limestone rock. Because this is a normal coarse aggregate used in traditional concrete, it exhibited a unit weight closed to the range of normal concrete. OPC + NA showed the highest unit weight of 2326 kg/m3, as a normal coarse aggregate, fine aggregate and type I cement were used. As Ordinary Portland cement were replaced with high-volume fly ash, the unit weight of the concrete mixture began to reduce.

The unit weight of batch two, OPC + Shale to 10 also, follows similar suit. The unit weight in this batch is noticeably lower than that of batch one. This is significantly due to the difference in the coarse aggregates used. Lightweight aggregate (shale) is used as a substitute for the normal coarse aggregate (limestone). The reference concrete (OPC + Shale) had a unit weight of 1988 kg/m3 which is reasonably higher than other mixes in the batch when replaced with high-volume fly ash.

Similarly, due to use of different lightweight aggregate (clay), the reference concrete for batch three had a unit weight of 1911 kg/m3. Subsequent unit weight in this batch reduced due to the replacement of ordinary Portland cement with high-volume fly ash.

High-volume fly ash concrete mixtures exhibited higher slump in all mixes. This is probably due to the amount of high-volume fly ash. It is important to note that, there was no segregation witnessed in these mixtures due to a reasonable slump value. The use of lightweight aggregates compensated reaching even higher slump and slump flow. Due to higher absorption rate of lightweight concrete, superplasticizers were added to the mixtures in batch two and three to enhance the workability and flow of the concrete mixtures. There were some variations in the slump and the dosage of the superplasticizers for different mixtures of the same batches. This is generally due to the adjustment made with the replacement of normal coarse aggregates with lightweight aggregates. Table 6 shows the results obtained for slump and unit weight of the concrete samples.

Table 6: Results for slump and unit weight

Mix ID	Slump (mm)	Unit Weight (Kg/m^3)
BATCH ONE		
OPC + NA	103	2326
50% F + NA	107	2259
70% F + NA	131	2243
50% C + NA	110	2259
70% C + NA	129	2235
BATCH TWO		
OPC + Shale	165	1988
50% F + Shale	163	1892
70% F + Shale	167	1907
50% C + Shale	166	1893
70% C + Shale	171	1899
BATCH THREE		
OPC + Clay	167	1911
50% F + Clay	182	1827
70% F + Clay	191	1810
50% C + Clay	177	1871
70% C + Clay	181	1833

Mechanical Properties

Compressive Strength

Figures 2, 3, and 4 show the data on the compressive strength of concrete. In Batch One, the 7-day compressive strength indicates that OPC + NA and 50% C + NA have similar strength 40.12 and 45.04 MPa respectively, in the initial stage. The 56-day compressive strength of 50 percent fly ash class C was noticeably higher strength than the normal concrete. Simultaneously, 70% C + NA with 70 percent fly ash class C also shows significantly high strength similar to the normal concrete after 56-days of curing as can be seen in figure 8.

Figure 3 shows that, in Batch two, the reference mix shows similar strength to 50% C + Shale and 70% C + Shale respectively (32.20, 39.09 and 30.21 MPa). The reference mix shows reasonable strength after 56-days of curing. The concrete sample with fly ash class C shows reasonable strength growth on the 28-day but strength rarely changed on the 56-day. However, fly ash class F (50 and 70 percent) shows steady strength growth up until 56-day of age. In Batch three, the reference concrete and concrete with 50 percent class C fly ash show similar strength at the initial stages and subsequently, both OPC + Clay and 50% C + Clay had steady strength growth of 47.39 and 50.10 MPa respectively, after 56-day of age as presented in figure 10.

In general, a compressive strength ranging from 42-55 MPa was achieved for 28-day in all the reference mixes and the mixes containing 50 percent fly ash class C. However, a compressive strength ranging from 25-44 MPa after 28-day was achieved in all mixes containing 50 and 70 percent class F fly ash. While comparing the different coarse aggregates used in this research, it can be seen that there is a significant difference in the strength achieved regardless of the replacement of fly ash. This can be associated to the fact that; normal coarse aggregate usually tends to have higher compressive strength than lightweight coarse aggregate because of its density. Figure 11 shows about 14.25% and 9.27% strength loss when comparing the normal aggregate and the two lightweight aggregates in OPC. In 50%F, there is a significant strength reduction of about 65% when normal aggregate is replaced with one of the lightweight aggregates (clay). While in 50%C, there is about 29.8% and 15.2% strength reduction after 28-day of age. Meanwhile, strength reduction in 70%C was about 13.5% and 38.9% when replaced with the two lightweight aggregates (shale and clay) respectively.

Supplementary cementitious materials such as fly ash containing pozzolanic contents need calcium hydroxide in order for pozzolanic reaction to take place so that additional calcium silicate hydrate could be produced. Hence, the presence of calcium hydroxide is significant in Portland-pozzolan cement pastes. In a research such as this with concrete containing high-volume content of pozzolanic materials because of the reduction of ordinary portland cement in the concrete mixture, there is no adequate calcium hydroxide for its usage through the pozzolanic reactions. Hence, the reduction in the development of compressive strength in the high-volume fly ash concrete mixes specifically in concrete mixes such ash 70% F + NA, 70% C + NA, 70% F + Shale, 70% C + Shale, 70% F + Clay, 70% C + Clay.

According to (*318-19 Building Code Requirements for Structural Concrete and Commentary*, 2019), the compressive strength of concrete for structural purposes could not be less than 35 MPa after 28 days of curing. It can be seen that in this current research, concrete mixes 50% F + Shale, 70% F + Shale, 70% F + Clay and 70% C + Clay could not meet this requirement.

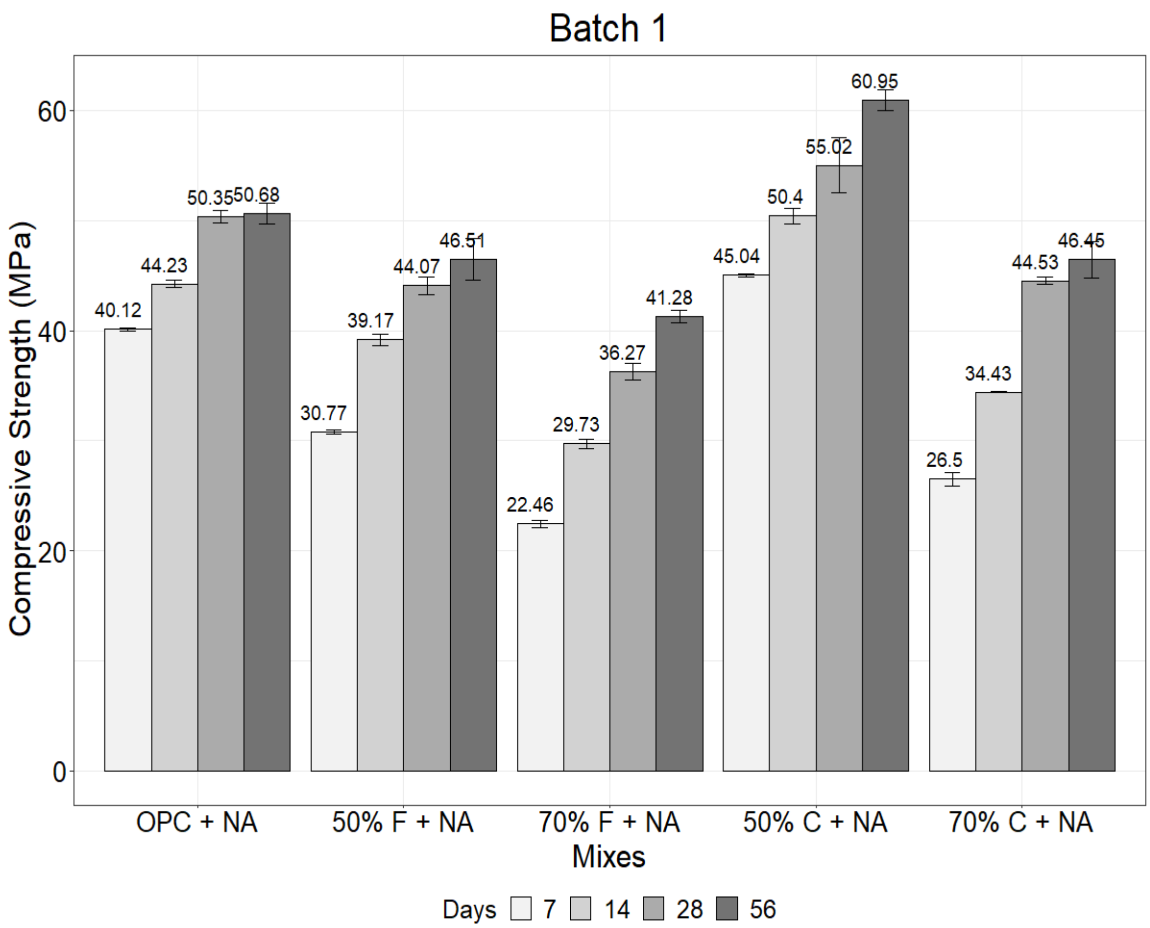

Figure 2: Compressive strength of mixes in batch 1.

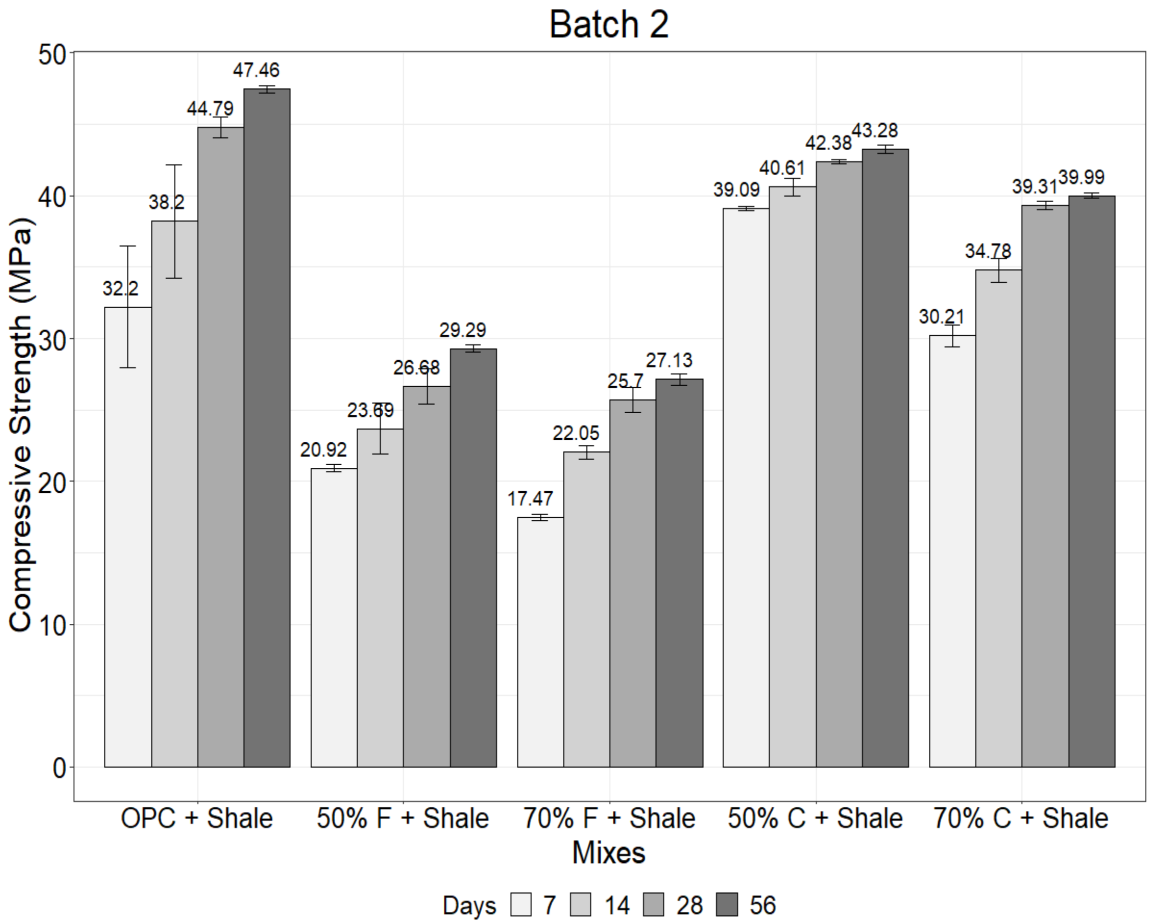

Figure 3: Compressive strength of mixes in batch 2

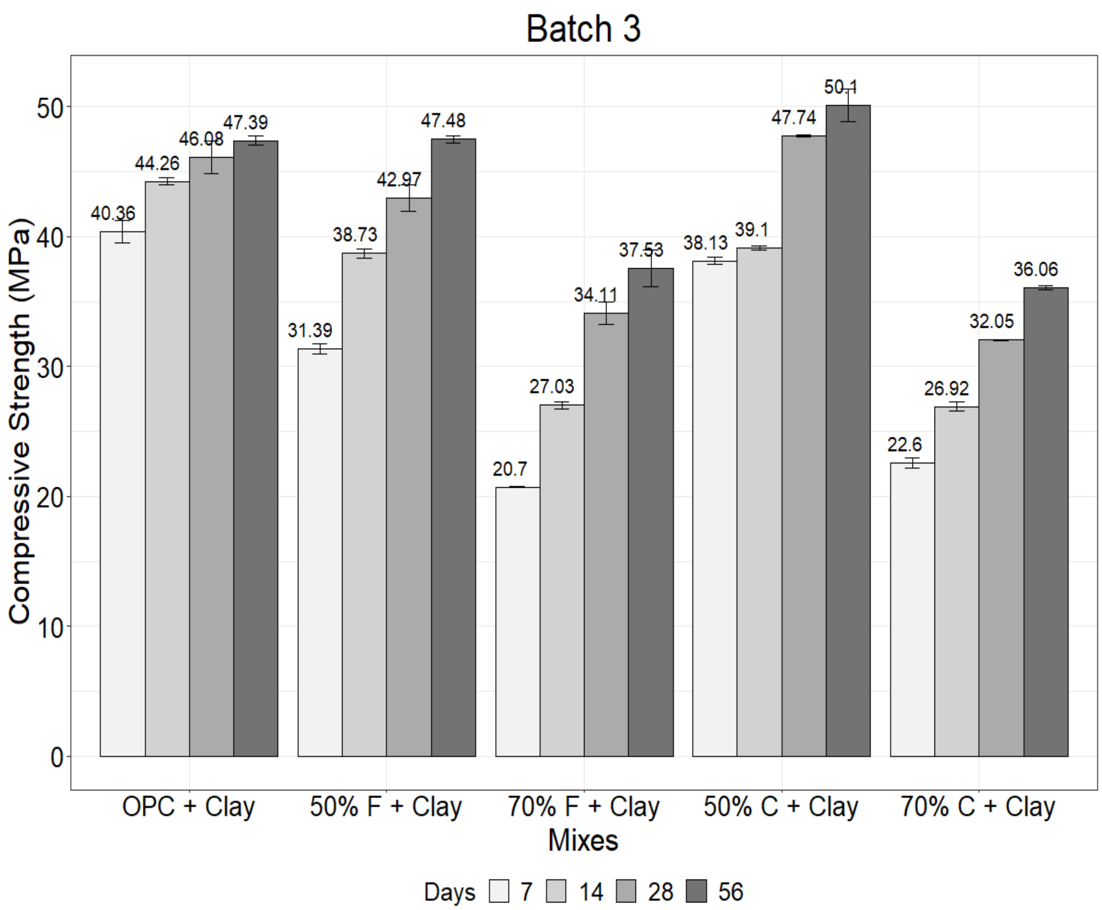

Figure 4: Compressive strength of mixes in batch 3

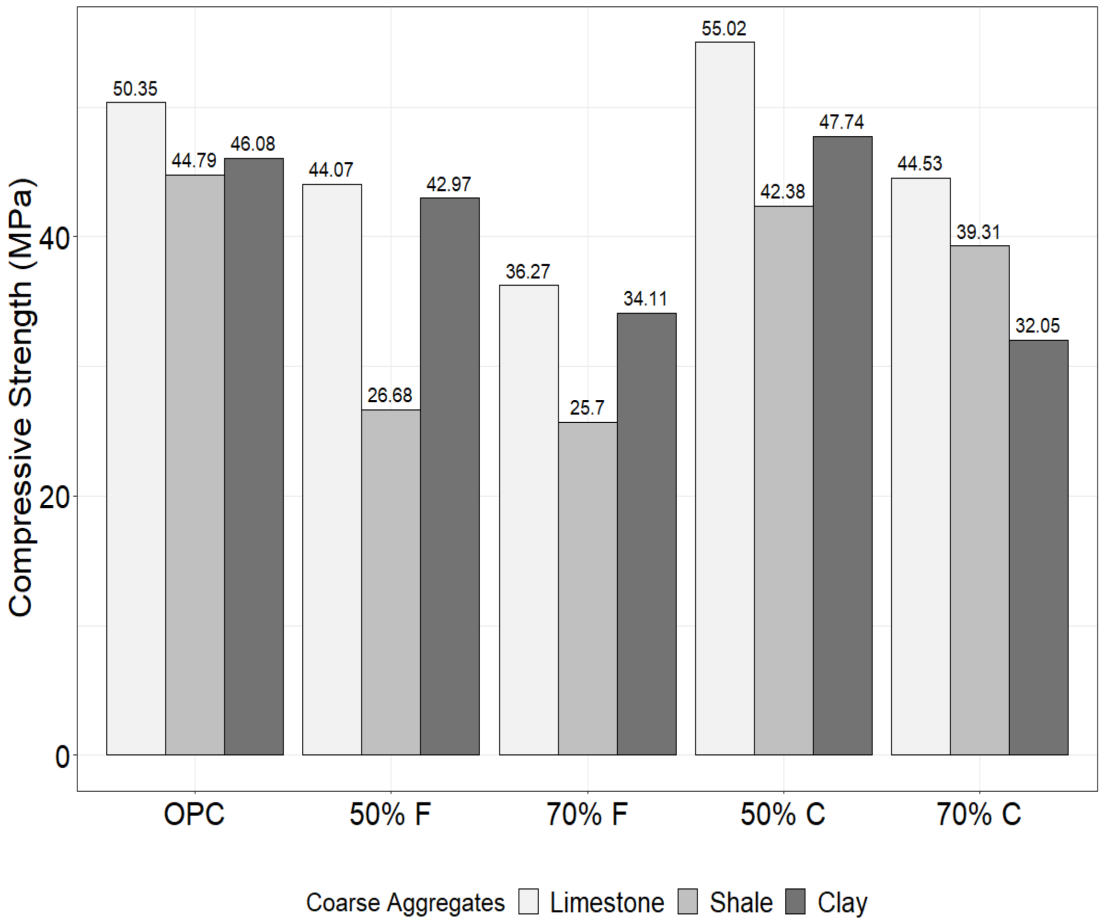

Figure 5: 28-day compressive strength comparison of normal and lightweight aggregates

Split-tensile Strength

The splitting tensile strength of the reference concrete and the high-volume concrete show similar strength at 28 days. In batch one, it is noticeable that the split-tensile strength of the reference concrete at 28 days is 3.40 MPa while mixes with high-volume class C fly ash have slightly higher strength. In batch two, the reference concrete mix has the highest splitting tensile strength at 3.70 MPa compared to 2.95 and 3.46 MPa for 50% F + Shale and 70% F + Shale, respectively. Similar could be said of batch 3, where 50% + Clay has slightly higher strength compared to the reference concrete, OPC + Clay. Figures 6, 7, and 8 below show the data for splitting tensile strength.

While comparing the splitting-tensile strength in terms of the coarse aggregate replacement as illustrated in figure 9, it can be seen that the normal coarse aggregate had the highest split-tensile strength even though concrete samples with lightweight aggregates also showed good and enough strength. The lowest strength among all these aggregates could be seen in the 70 percent high-volume fly ash class F replacement with ordinary Portland cement.

The loss in strength and the curb in the development of concrete samples in the splitting tensile strength could be associated with the binder paste and the different types of aggregates used in this research. Hence, at 70% fly ash replacement in both shale and clay, the splitting tensile strength of the concrete samples reduce.

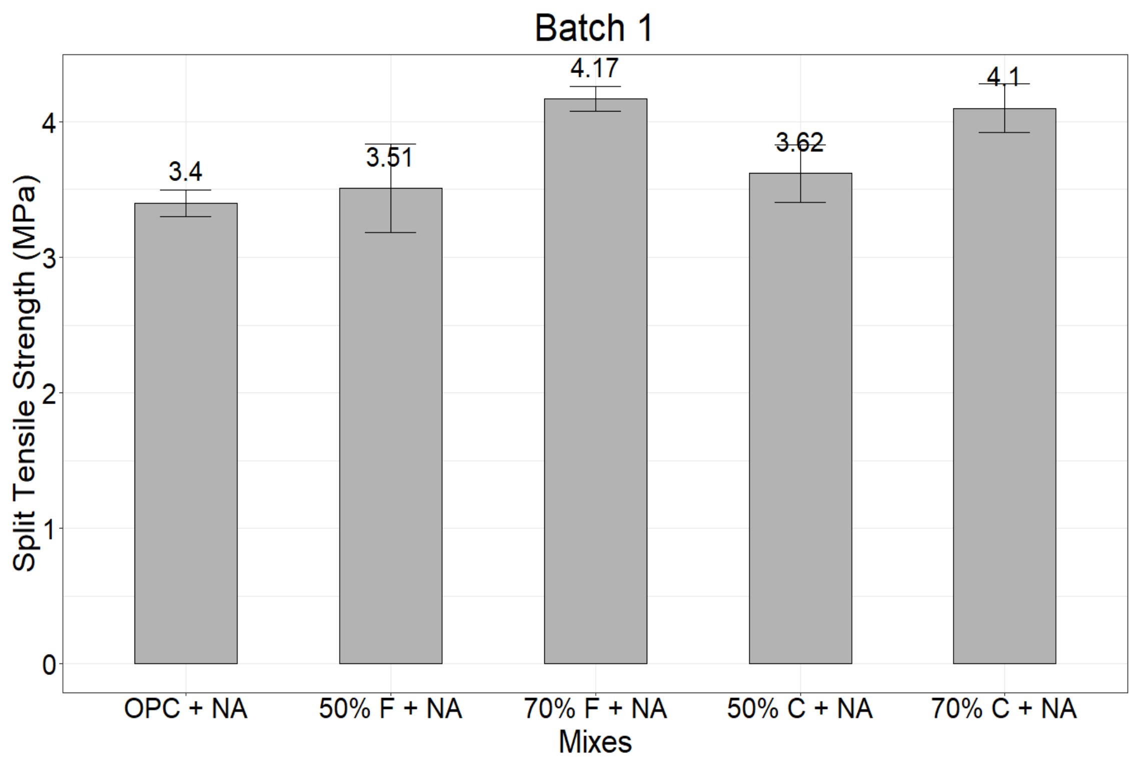

Figure 6: 28-day split-tensile strength for mixes in batch 1

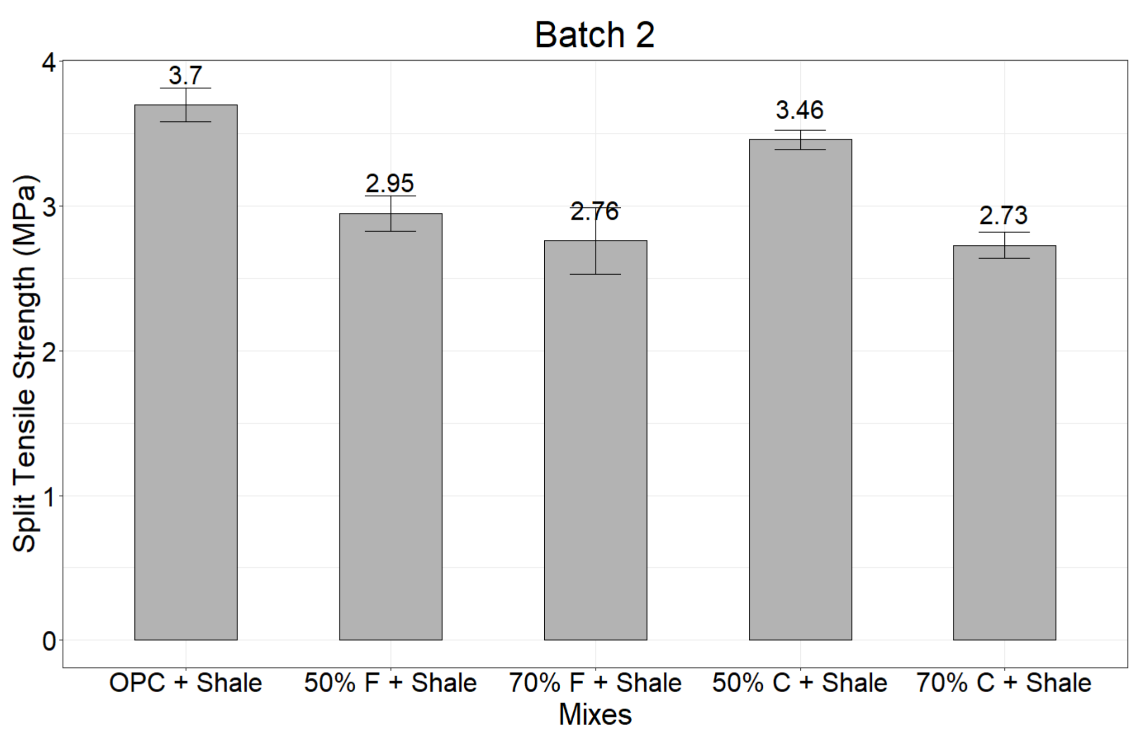

Figure 7: 28-day split-tensile strength for mixes in batch 2

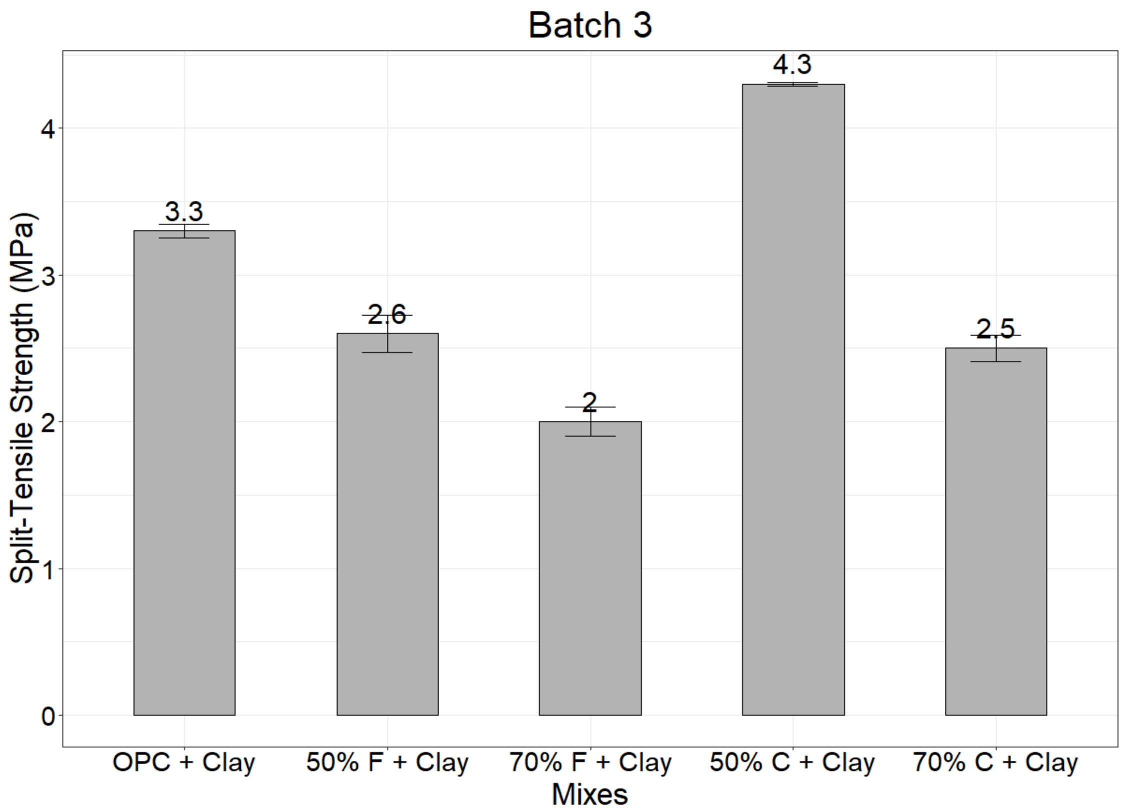

Figure 8: 28-day split-tensile strength for mixes in batch 3

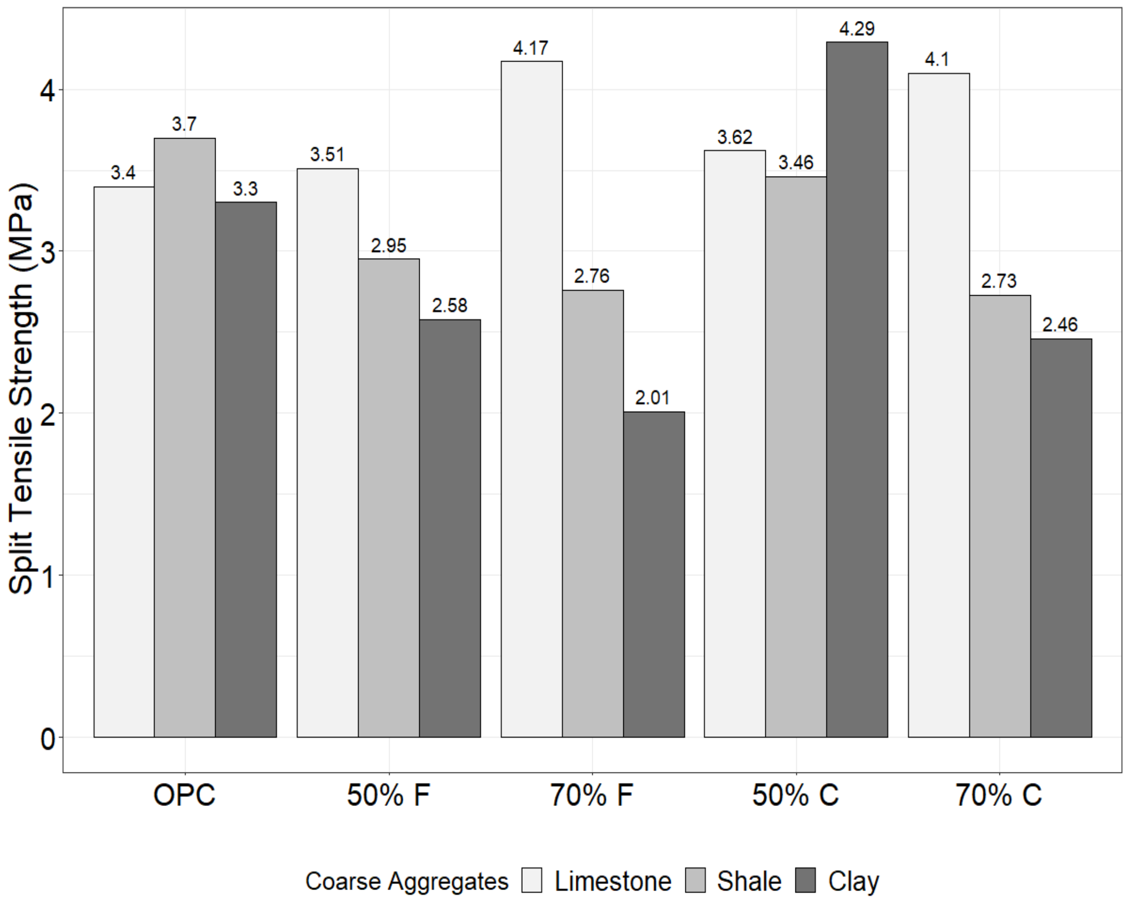

Figure 9: 28-day split-tensile strength comparison of normal and lightweight aggregates

Flexural Strength

The flexural strength of the high-volume concrete mixes in batch one ranges from 4.97 to 5.89 MPa. The reference concrete is higher in this regard with a 6.98 MPa at 28 days. Both classes of fly ash exhibit good performance in terms of flexural strength. Meanwhile, in batch two, high-volume fly ash concrete mixes have similar ranges compared to that of batch one, ranging from 4.07 to 4.98 MPa relative to 4.70 MPa for the reference concrete. The same could be said for batch three where all the strengths range from 4.27 to 4.92 MPa. These are illustrated in figures 10, 11, and 12.

However, in figure 13, the illustration of the 28-day flexural strength indicates that, the flexural strength of concrete produced with normal aggregate showed the most strength compared to those manufactured with lightweight aggregate. But concretes made with lightweight aggregates also showed good strength. There is a significant strength loss when ordinary Portland cement is replaced with high-volume fly ash especially in the case 70 percent replacement with class F fly ash.

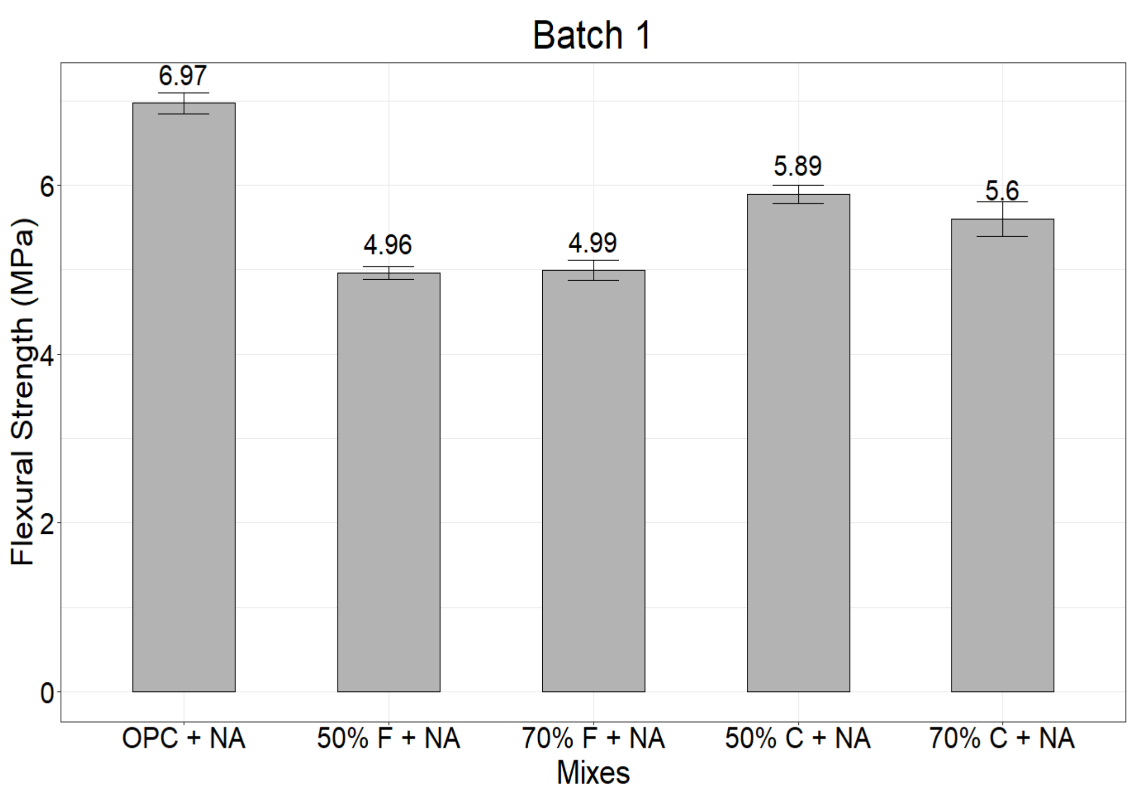

Figure 10: 28-day flexural strength for mixes in batch 1

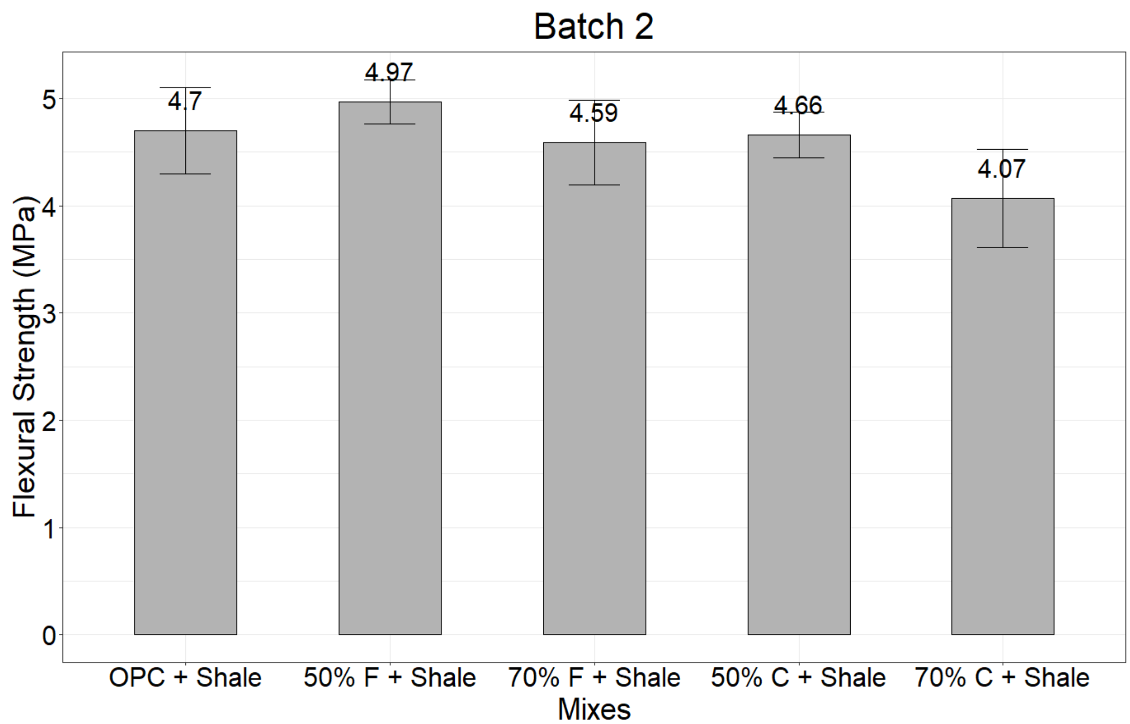

Figure 11: 28-day flexural strength for mixes in batch 2

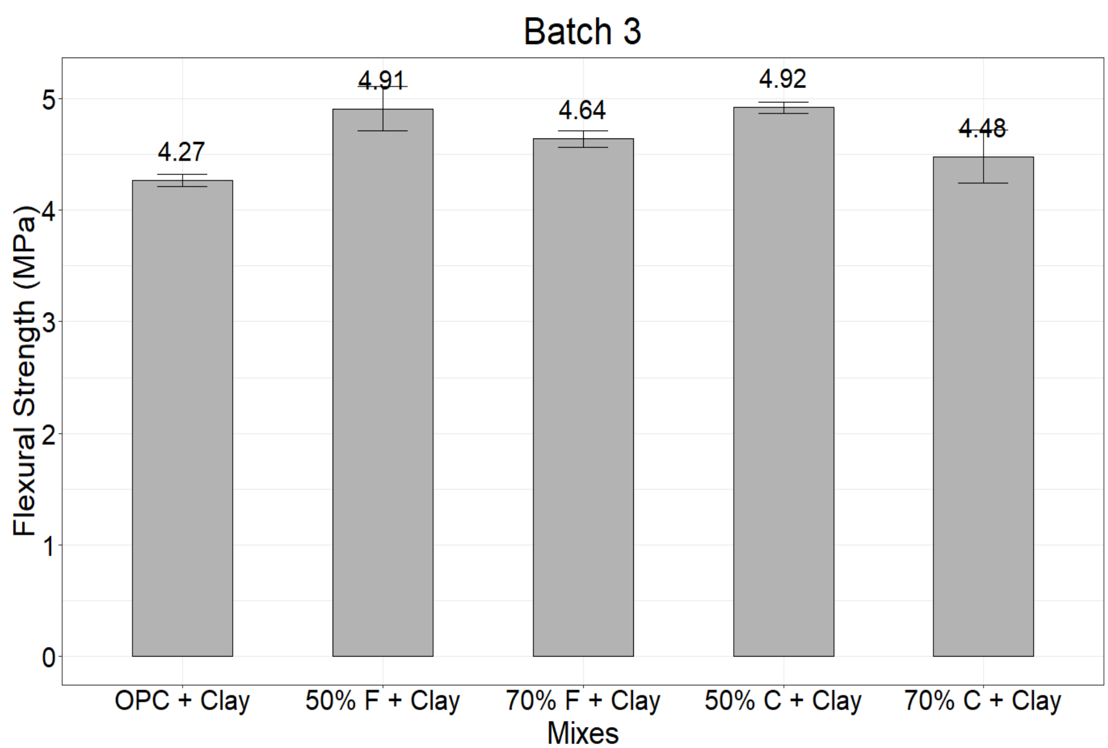

Figure 12: 28-day flexural strength for mixes in batch 3

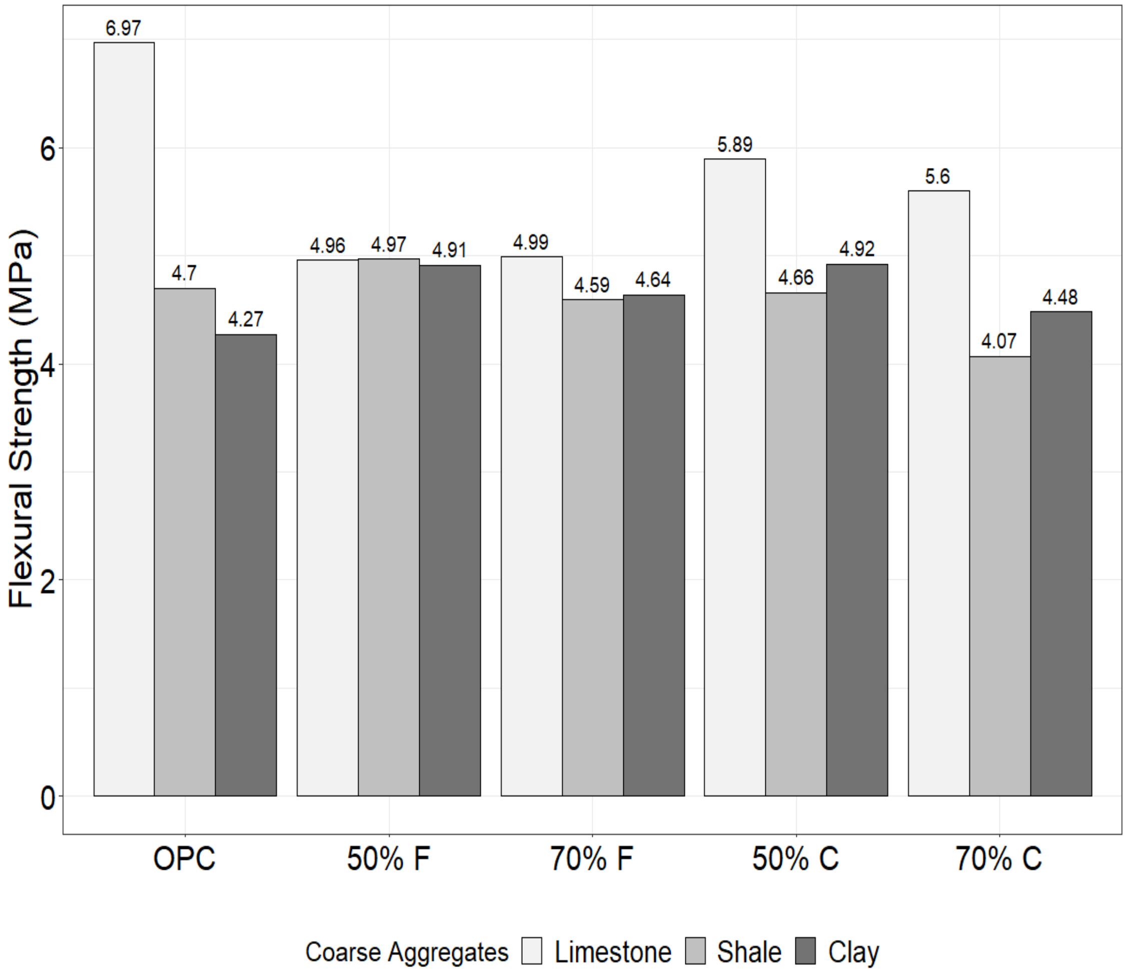

Figure 13: 28-day flexural strength comparison of normal and lightweight aggregates

Young's Modulus of Elasticity

The young's modulus of elasticity of the reference mixes ranges from 31.19 to 33.56 GPa while the young's modulus of elasticity for the high-volume fly ash concrete mixes ranges from 23.32 to 34.49 GPa at 28 days. The noticeable lower modulus of elasticity values under 30 GPa are probably due to the relative compressive strengths at the same age of curing. Generally, the young's modulus of elasticity for all the reference concrete and the high-volume fly ash concrete mixes are similar. Hence, it is possible to imply that, the differences are probably due to the differences in their respective compressive strengths. Figures 14, 15, and 16 illustrate the respective young's modulus of elasticity in batches 1, 2, and 3, respectively.

Additionally, figure 17 illustrates the modulus of elasticity in terms of the aggregates. It is noticeable that both lightweight aggregates had good performance as well as the normal aggregate. The only significant decrease in modulus of elasticity is seen in 70 percent high-volume fly ash replacement with ordinary Portland cement.

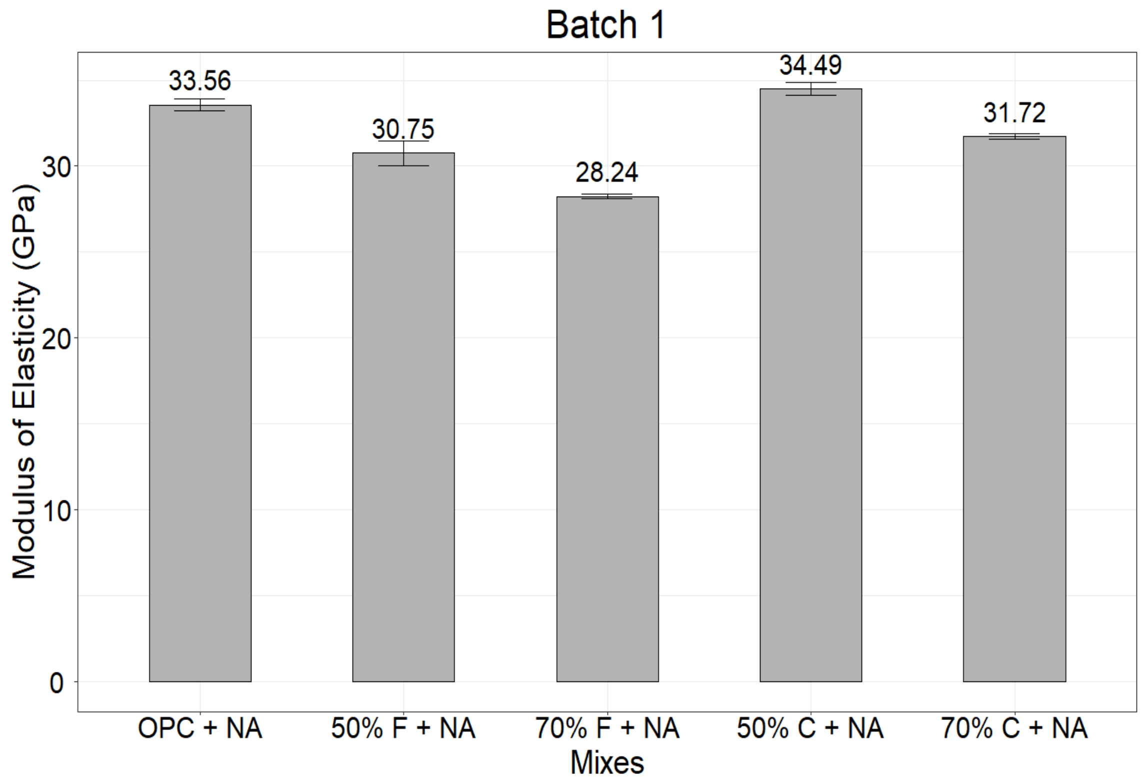

Figure 14: 28-day Modulus of elasticity mixes in batch 1

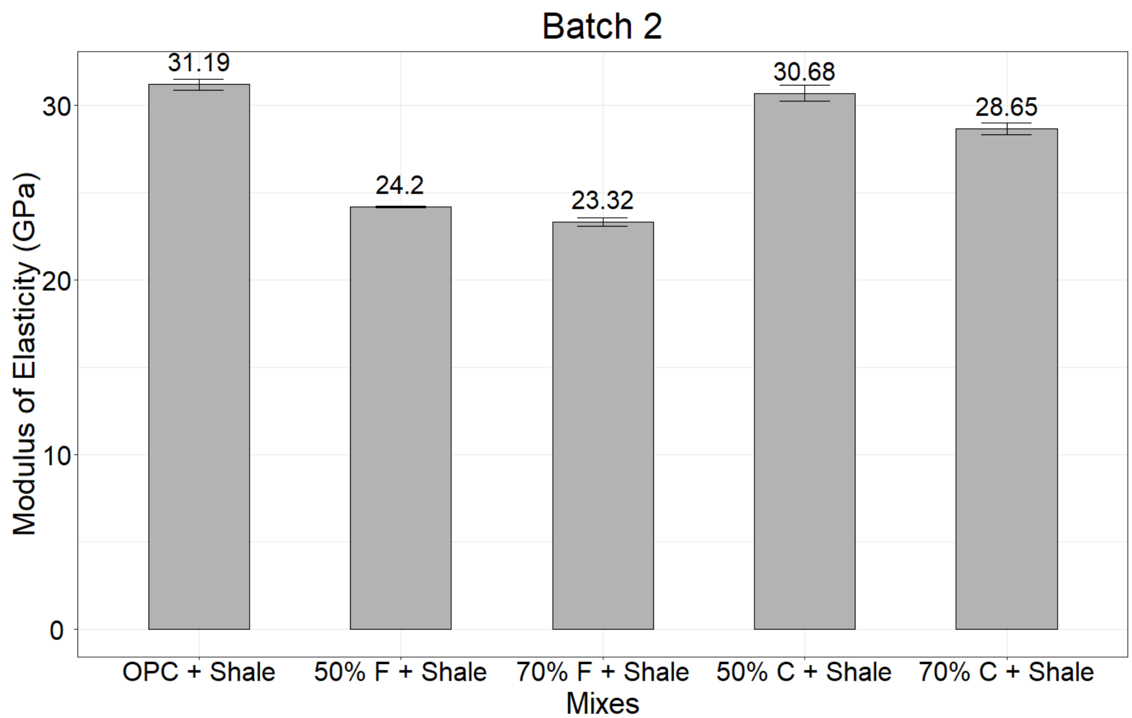

Figure 15: 28-day Modulus of elasticity mixes in batch 2

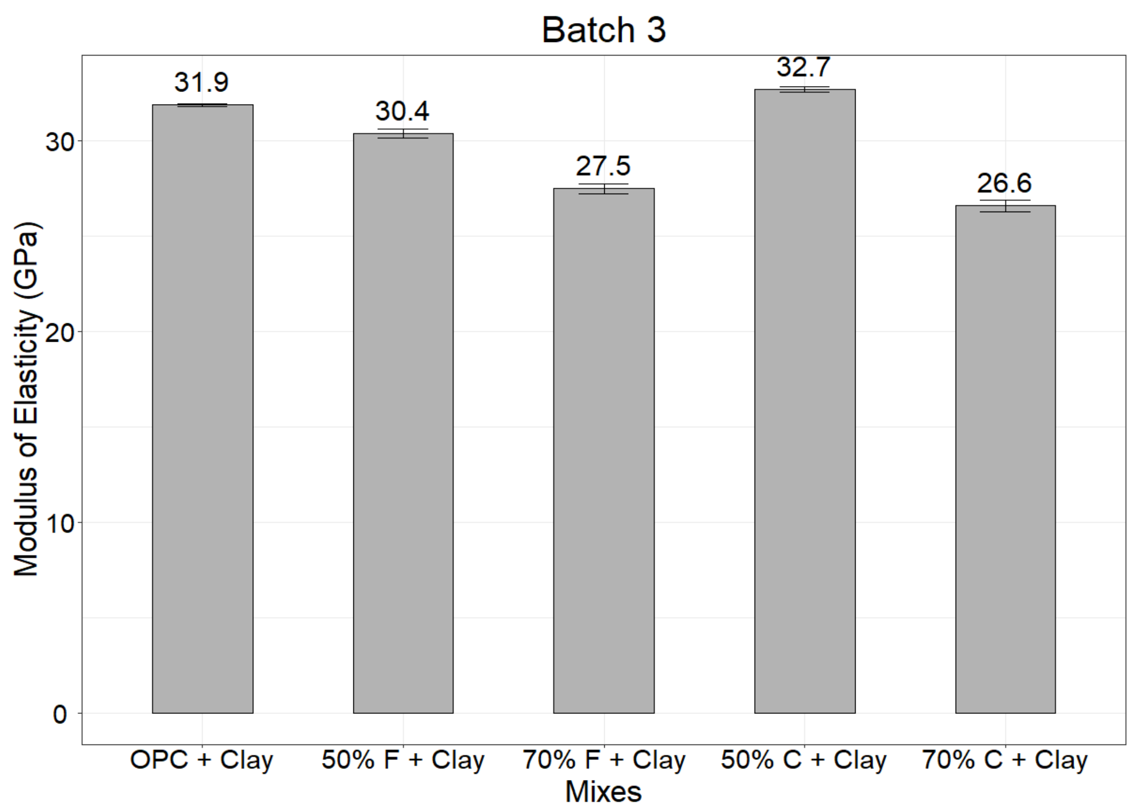

Figure 16: 28-day Modulus of elasticity mixes in batch 3

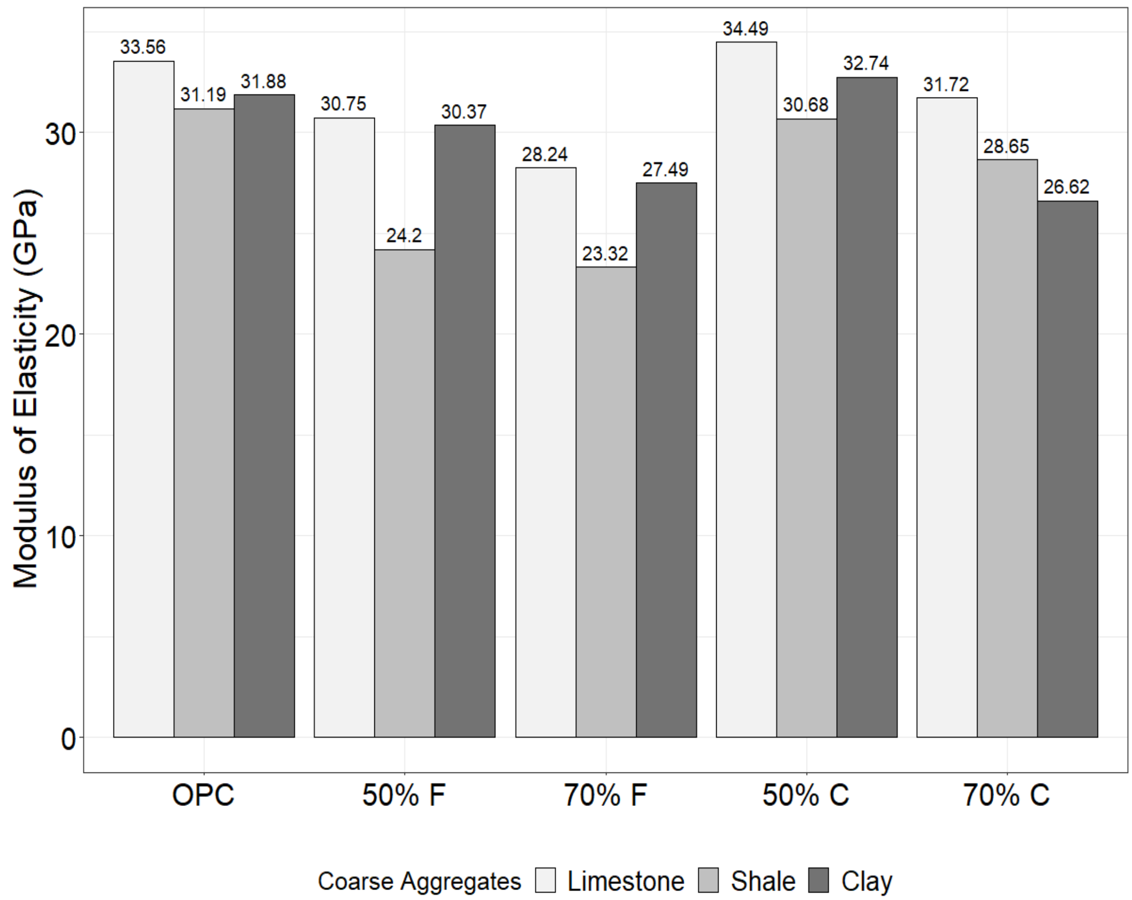

Figure 17: 28-day Modulus of elasticity comparison of normal and lightweight aggregates

Drying Shrinkage

Restrained concrete cracks when the stresses made by drying shrinkage surpass the tensile strength of the concrete. These cracks formed behave as an avenue for gases like carbon dioxide, oxygen and nitrate including aggressive water such as chloride and sulphate. Consequently, effect the future serviceability of the concrete samples. Therefore, the drying shrinkage of concrete is very essential and directly related to the sustainability of the structure of concrete.

Figures 18, 19, and 20 below show the development of drying shrinkage for mixes in batches one, two and three for up to about 56 days. For all concrete mixes, it has been indicated that, drying shrinkage remarkably increases over the first 56-day of age, especially in the case of 70% replacement of fly ash class F. From the development of drying shrinkage to up to about 56-day of age, it is expected that there will be additional development for the concrete mixes in future. This could be attributed to the fact that in lightweight high-volume fly ash concrete, the water absorbed by the lightweight aggregate which contributed to the curing of the concrete samples after being exposed to moist curing condition for 7 days, which would have compensated for the water loss when the concrete is exposed to dry environment.

Generally, it could be seen that there is no remarkable difference between the drying shrinkage of the reference mixes in all the batches and the mixes with 50% replacement of both classes of fly ash. It is reported that the use of fly ash in normal and accurate proportions does not remarkably influence the strain of drying shrinkage of concrete structure (Joshi & Lohita, 1997). (Shafigh et al., 2013) suggested that the drying shrinkage of concrete mixes having 10% fly ash, with the same amount of binder to water ratio is indistinguishable at all ages. However, mixes with 70% class F fly ash have remarkably higher development in drying shrinkage compared to the references in all batches.

It is also significant to note that water binder ratio plays an important role during the development drying shrinkage. In this case, since all concrete mixes are produced using the same water binder ratio, it is hard to invest the effect of water binder ratio. But it can be implied that the development of drying shrinkage containing 70% class F fly ash in batches two and three is highly significant. This could be associated to the use of lightweight aggregates which absorbs more water compared to normal aggregates. Besides the difference in the aggregates used and the amount of high-volume fly ash replacement, there is no definite reason to associate to the development of drying shrinkage.

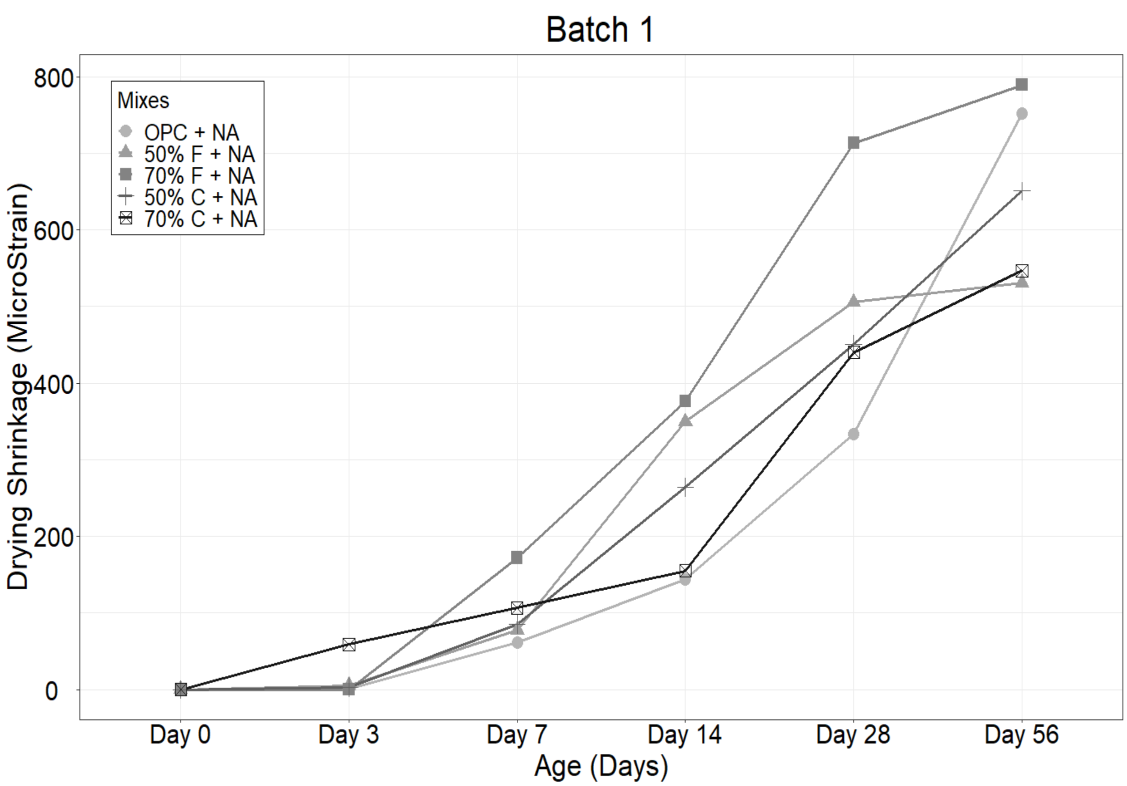

Figure 18: Development of drying shrinkage for mixes in batch 1

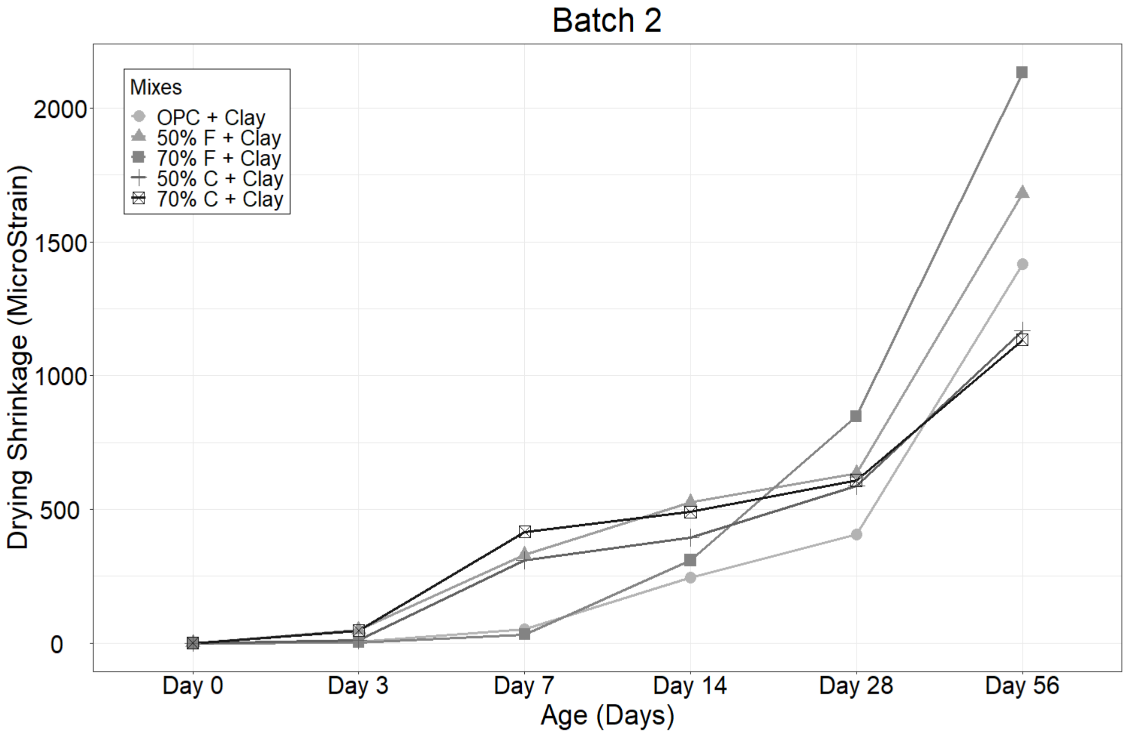

Figure 19: Development of drying shrinkage for mixes in batch 2

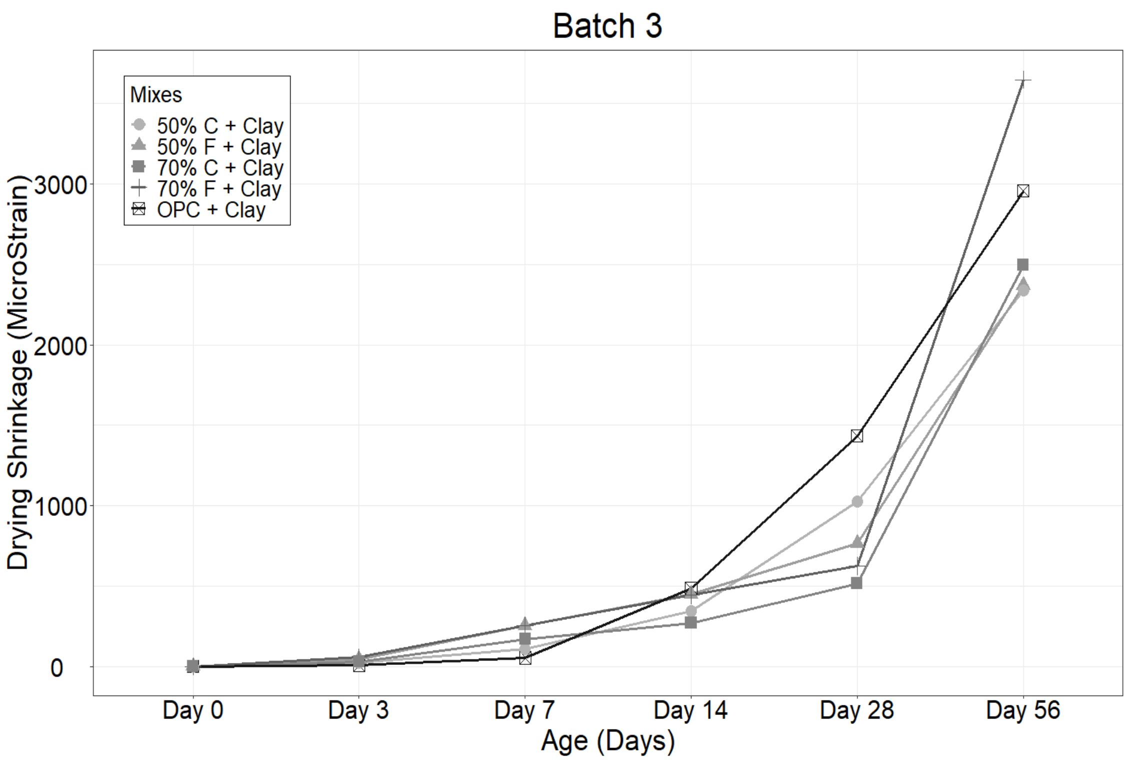

Figure 20: Development of drying shrinkage for mixes in batch 3

Durability Properties

Resistance to Abrasion

It is noticeable that all concrete mixtures exhibited good abrasion resistance. It is important to note that abrasion was carried out under normal rate at 9.979 kgf. The main factors that influence the abrasion resistance are the types of aggregates and the compressive strength of the concrete. Moreover, it is important to note that both lightweight and normal coarse aggregates showed good abrasion resistance. Generally, in this experiment, it could be implied that there is no clear relationship between the factors affecting abrasion and the abrasion test results obtained. Figures 21, 22, and 23 illustrates abrasion resistance to concrete in batches 1, 2, and 3, respectively.

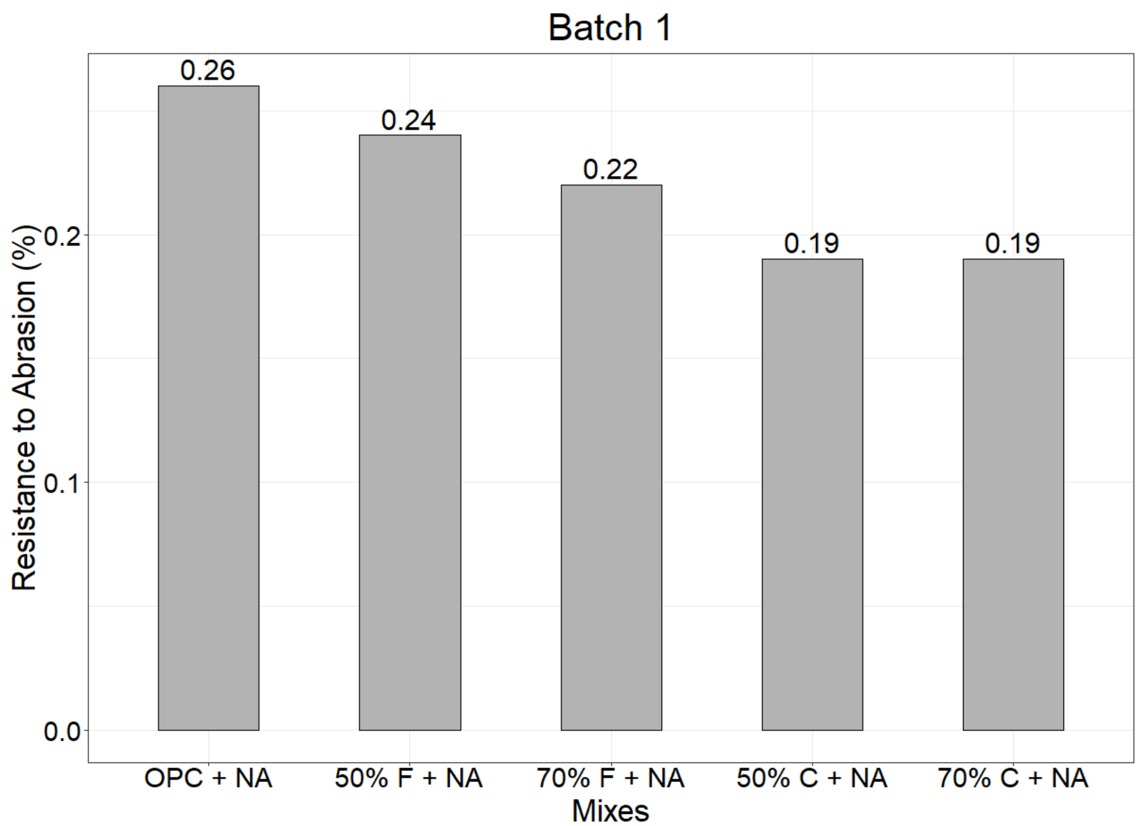

Figure 21: Abrasion resistance for mixes in batch 1

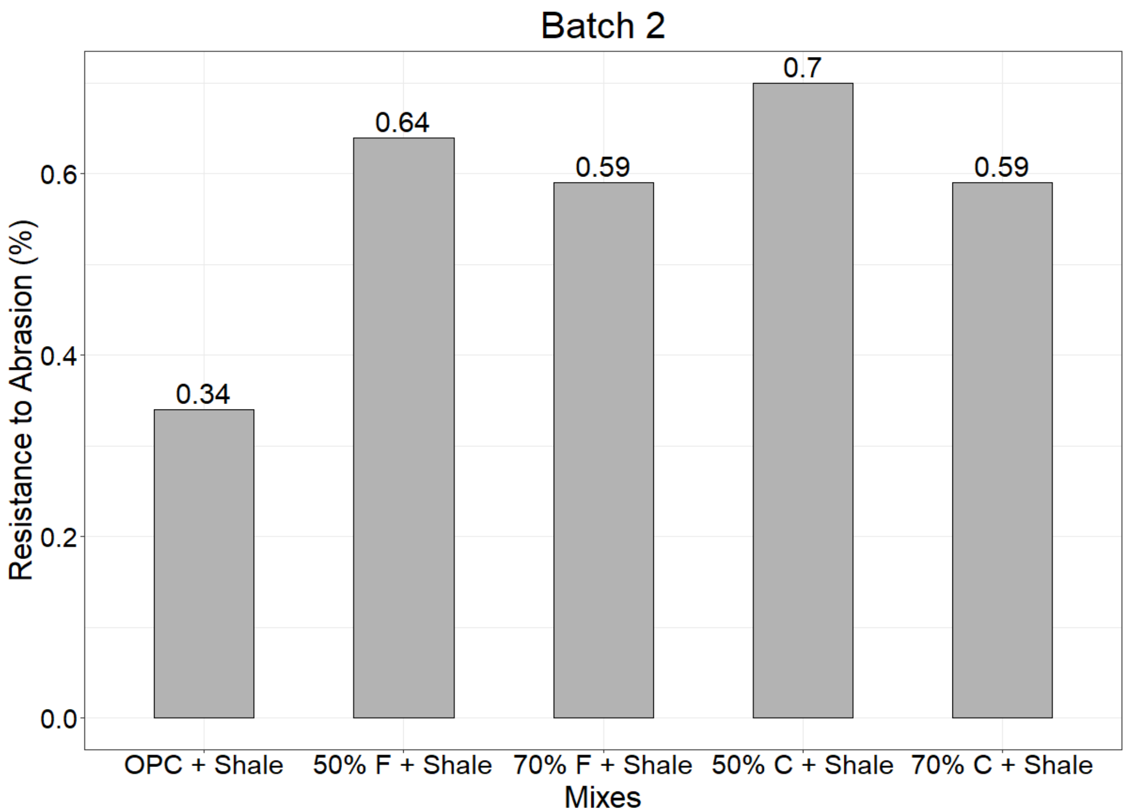

Figure 22: Abrasion resistance for mixes in batch 2

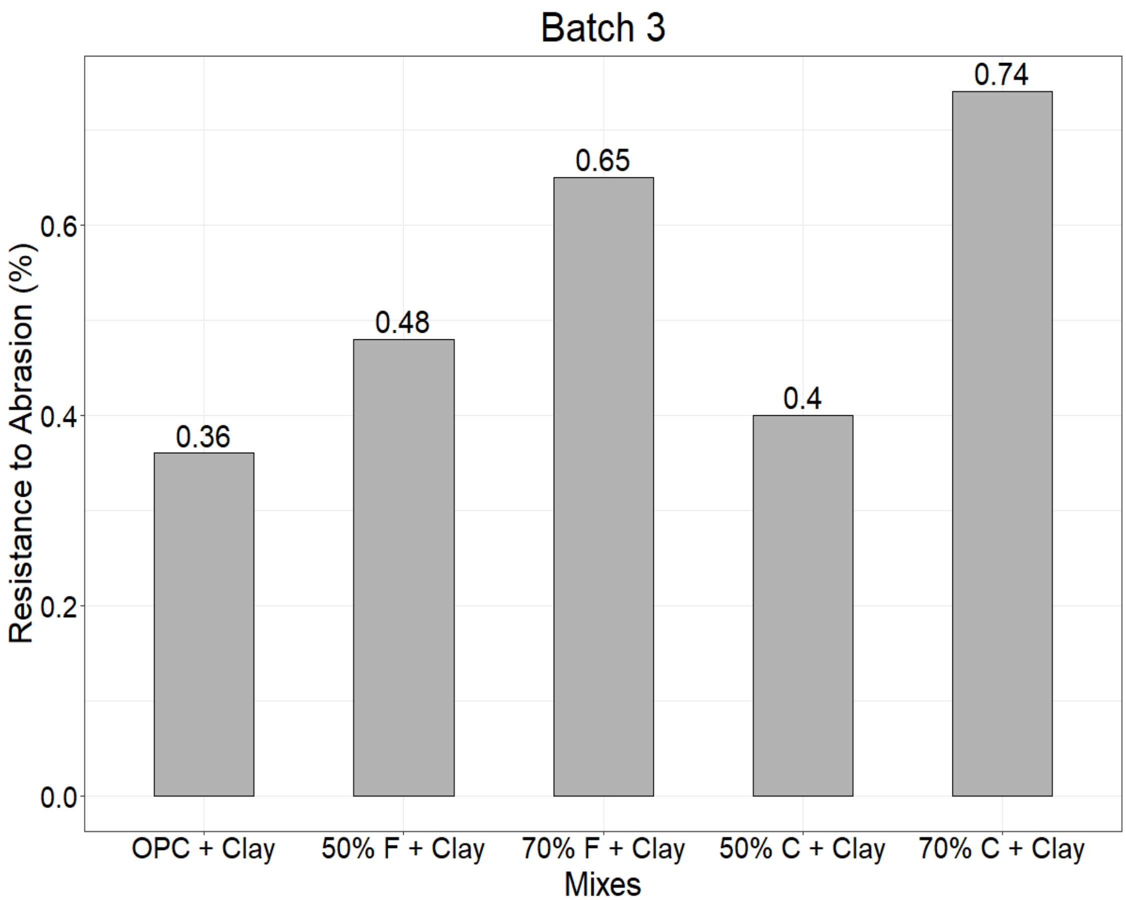

Figure 23: Abrasion resistance for mixes in batch 3

Resistance to Chloride Ion Penetration

The resistance to chloride ion penetration is an essential aspect that requires a better understanding in structural concretes. Generally, it is understood that the addition of supplementary cementitious materials and mineral admixtures importantly improves chloride ion penetration through chloride binding and pore fillings. The data in the table 8 below indicates that all concretes including high-volume fly ash lightweight concretes investigated showed high resistance to the chloride-ion penetration. The results of the concrete containing high-volume fly ash showed significantly higher resistance to chloride ion penetration. These results are also, in accordance with other previous studies done by researchers on normal-weight high-volume fly ash concrete (Bilodeau et al., 1994; Bilodeau & Malhotral, 1992; Thomas, 2007; Sivasundaram, 1991).

It is important to note that, even though normal-weight concretes with high-volume fly ash showed good resistance to chloride ion penetration, lightweight high-volume concretes exhibited the most resistance towards chloride ion penetration. Table 7 also, illustrates the extent of electric charges passed through the concrete samples in batches 1, 2, and 3, respectively. Consequently, predicting the resistance to chloride ion penetration in the concrete. Table 7 shows the chloride ion penetrability based on charged passed according to (C09 Committee, n.d.),

Table 7: Chloride ion penetrability based on charged passed ASTM C1202

Charge Passed	Chloride Ion Penetration
>4000	High
2000 to 4000	Medium
1000 to 2000	Low

100 to 1000	Very low
<100	Negligible

Table 8: Results for Electric charge and chloride ion penetration

Mix Number	Mix ID	Total Electric Charge Passed (Coulombs)	Chloride Ion Penetration
BATCH ONE			
1	NA + OPC	2032.67	Moderate
2	50% F + NA	1328.67	Low
3	70% F + NA	2743.00	Moderate
4	50% C + NA	1427.67	Low
5	70% C + NA	1934.67	Low
BATCH TWO			
6	Shale + OPC	1688.00	Low
7	50% F + Shale	1218.33	Low
8	70% F + Shale	1517.00	Low
9	50% C + Shale	1118.00	Low
10	70% C + Shale	1126.00	Low
BATCH THREE			
11	Clay + OPC	1517.33	Low
12	50% F + Clay	1048.00	Low
13	70% F + Clay	1490.33	Low
14	50% C + Clay	773.00	Very Low
15	70% C + Clay	1421.00	Low

Water Absorption

Neville & Brooks, (1987) suggests one of the techniques to evaluate the durability of a concrete sample is by observing the characteristics of its absorption. Neville & Brooks, (1987) also states that even though water absorption evaluates the durability of concrete, it is not a good benchmark to measure the standard and quality of concrete. However, according to (Teo et al., (2008)), the absorption of most concrete samples is below 10% by mass. Water absorption for all the concrete samples is shown in table 9 below. It can be noticed that all concrete samples after 28-day age exhibited less than 10% water absorption by mass. There is a significant increase in the difference in the absorption rate of normal concrete and the lightweight concrete. It is also noticeable that concrete samples with high-volume fly ash have higher absorption rate in all the batches. However, according to (Sun et al., (2019)), at later age, the absorption rate for concrete with high-volume fly ash will subsidize due to the fact that pozzolanic reaction of fly ash will highly progress and then consume greater amounts of CH. Subsequently, producing additional secondary C-S-H gels which will then result in denser and more compact microstructure. Hence, reducing the amount of the absorption rate of water in high-volume fly ash concrete.

Also, (Teo et al., 2008) studied the measurement of water absorption of lightweight concrete with 510 kg/m3 of ordinary Portland cement, cured in water for 7 days. It was observed that the water absorption of lightweight high-volume fly ash concrete decreases as the age of the concrete increases. This happens due to the improvement of the quality of shell surrounding Portland cement paste over a period. Subsequently, it expected that the water absorption rate of 70% F +NA, 70% C +NA, 70% F +Shale, 70% C +Shale, 70% F +Clay, and 70% C +Clay.

Table 9: Results for water absorption

Mix ID	Water Absorption			
	Initial mass (g)	Final mass (g)	Mass Change (g)	Percent Change
BATCH ONE				
NA + OPC	844.40	859.93	15.53	1.84
50% F + NA	944.20	958.87	14.67	1.55
70% F + NA	943.47	964.73	21.27	2.25
50% C + NA	1023.23	1033.53	10.30	1.01
70% C + NA	905.23	927.33	22.10	2.44
BATCH TWO				
OPC + Shale	712.07	731.30	19.23	2.70
50% F + Shale	691.77	716.07	24.30	3.51
70% F + Shale	652.00	696.30	44.30	6.79
50% C + Shale	653.93	703.60	49.67	7.60
70% C + Shale	679.03	733.97	54.93	8.09
BATCH THREE				
OPC + Clay	751.30	755.97	4.67	0.62
50% F + Clay	724.43	742.13	17.70	2.44
70% F + Clay	727.23	769.03	41.80	5.75
50% C + Clay	699.17	731.63	32.47	4.64
70% C + Clay	659.17	714.37	55.20	8.37

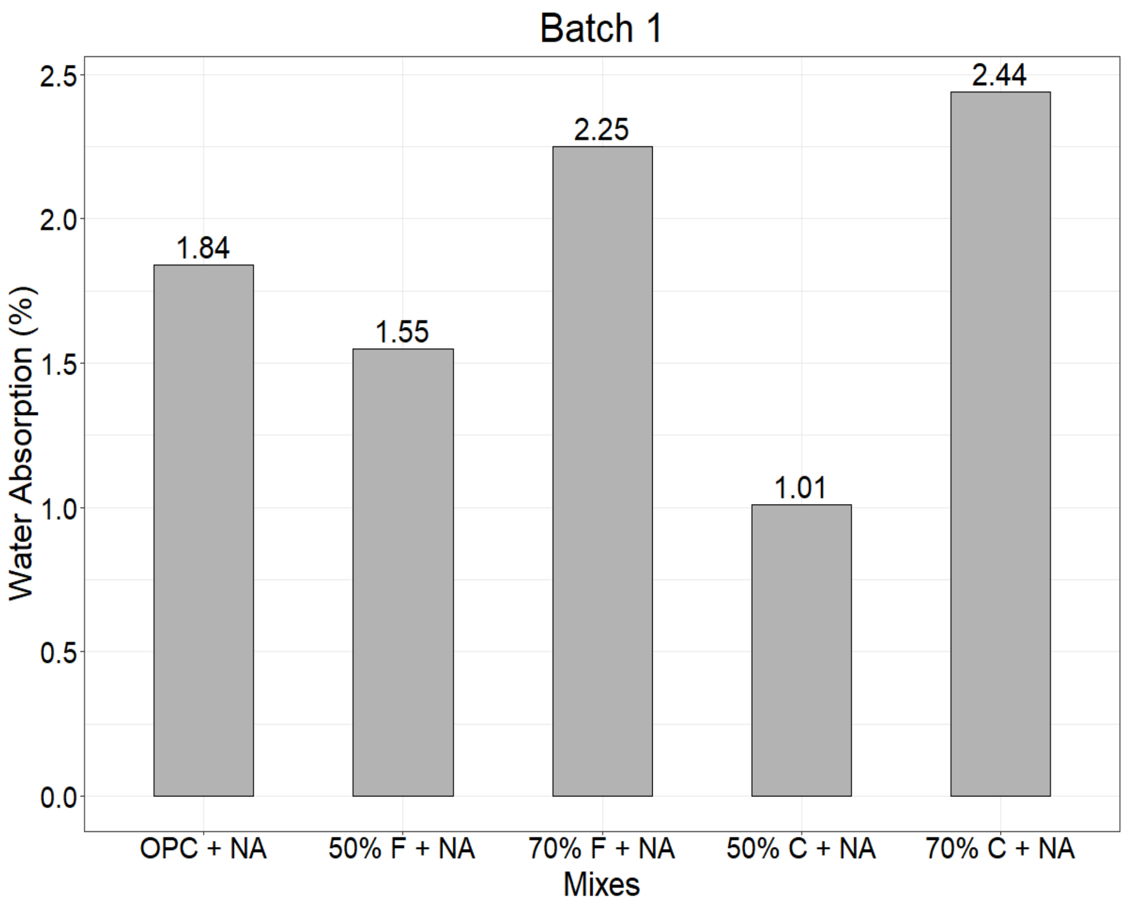

Figure 24: water absorption for mixes in batch 1

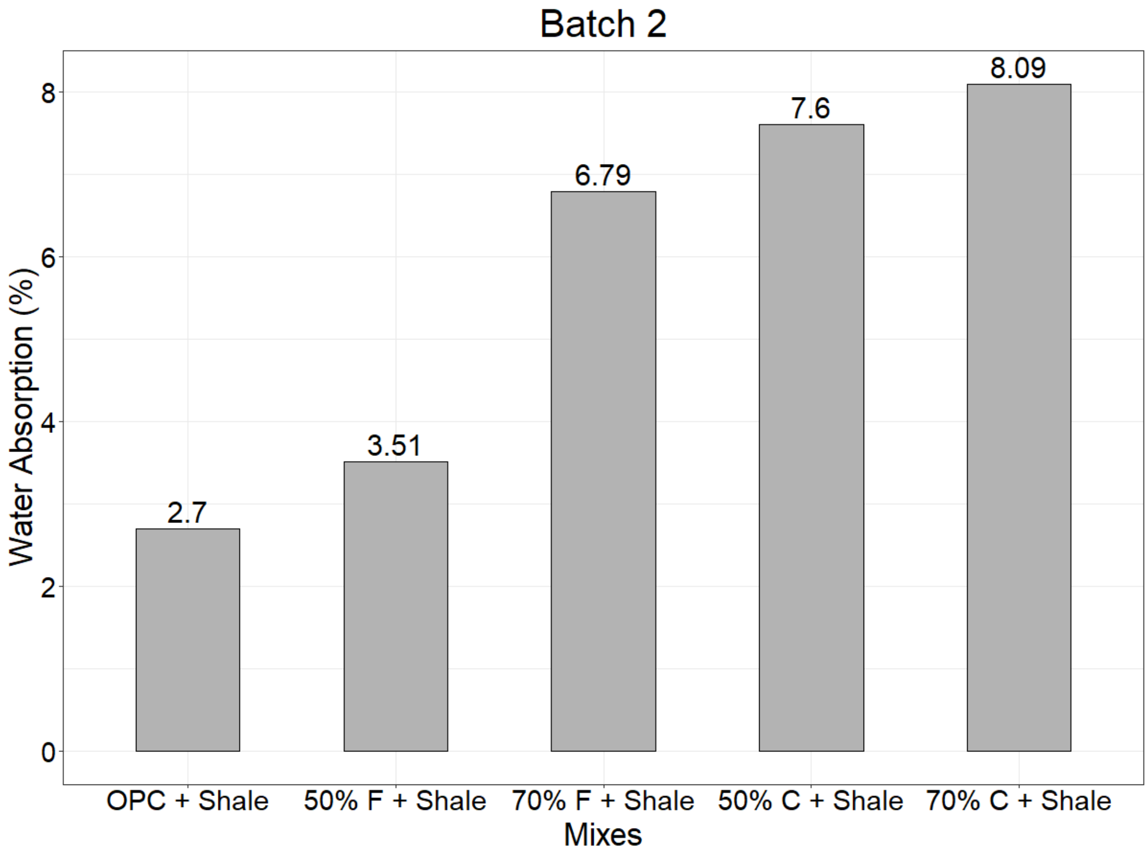

Figure 25: Water absorption for mixes in batch 2

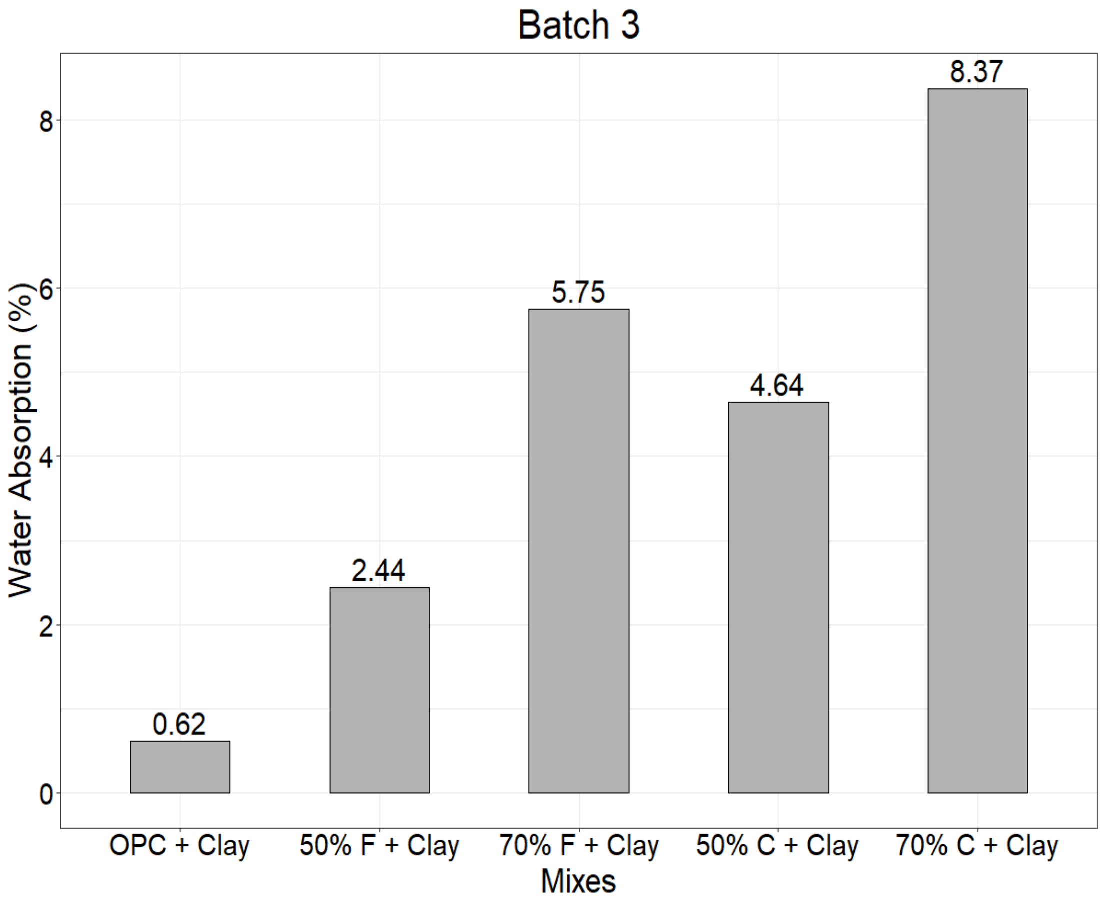

Figure 26: Water absorption for mixes in batch 3

Resistance to Freezing and Thawing

The rapid freezing and thawing test procedure is important to determine concrete samples' frost resistance by comparing its durability performance. Even though the properties of lightweight aggregate concrete are enhanced by the improvement in the method of manufacturing and processing. However, the resistance of lightweight concrete to freezing and thawing is still unclear.

The durability of all concrete samples subjected to repeated cycles to freezing and thawing is determined from weight, resonant frequency, and dynamic modulus of elasticity. Table 10 below shows the results of the percent mass and relative frequency test carried out. It is noticed that the refence concrete prism in batch one exhibited the most resistance to freezing and thawing by reaching a higher durability factor and having the most dynamic modulus of elasticity. Concrete prisms containing high-volume fly ash also, exhibited high resistance to freeze and thaw. This could be due to leaching because of increase amount of calcium hydroxide in the concrete creates voids which accelerate freezing and thawing. The fact that fly ash combines with calcium hydroxide thereby producing more cementitious materials subsequently reduces the calcium hydroxide amount that could be leached from the concrete. However, the lightweight concretes showed the lowest resistance freezing and thaw compared to concrete prisms made of normal-weight aggregates which is in accordance with other studies carried out by other researchers (Mao & Ayuta, 2008). It was noticed that concretes made with lightweight aggregates and high-volume fly ash at 70% replacement easily absorbs water and then subsequently suffers a higher damage during freezing and thawing. (Kockal & Ozturan, 2011a) states that concrete samples greater than 85 percent durability factor can exhibit good resistance to freezing and thawing. As indicated in figures 27, 28, and 29, concretes with 50 percent high-volume fly ash showed good resistance to freeze and thaw. A durable concrete sample exposed to rapid freezing and thawing cycle should have a relative dynamic modulus of elasticity greater than or equal to 60% of the initial value after completing 300 cycles. Figures 27, 28, and 29 indicate that the relative dynamic modulus of elasticity of most of the concrete samples demonstrated more than 70% of relative dynamic modulus of elasticity except mixes 70% F + Clay and 70% C + Clay.

The results of weighing concrete samples showed that most concrete samples lost small quantities of mass during the freeze thaw cycle. Hence, these concretes were able to maintain and keep their integrity. Table 10 illustrates the percent change of freeze and thaw mass and relative frequency.

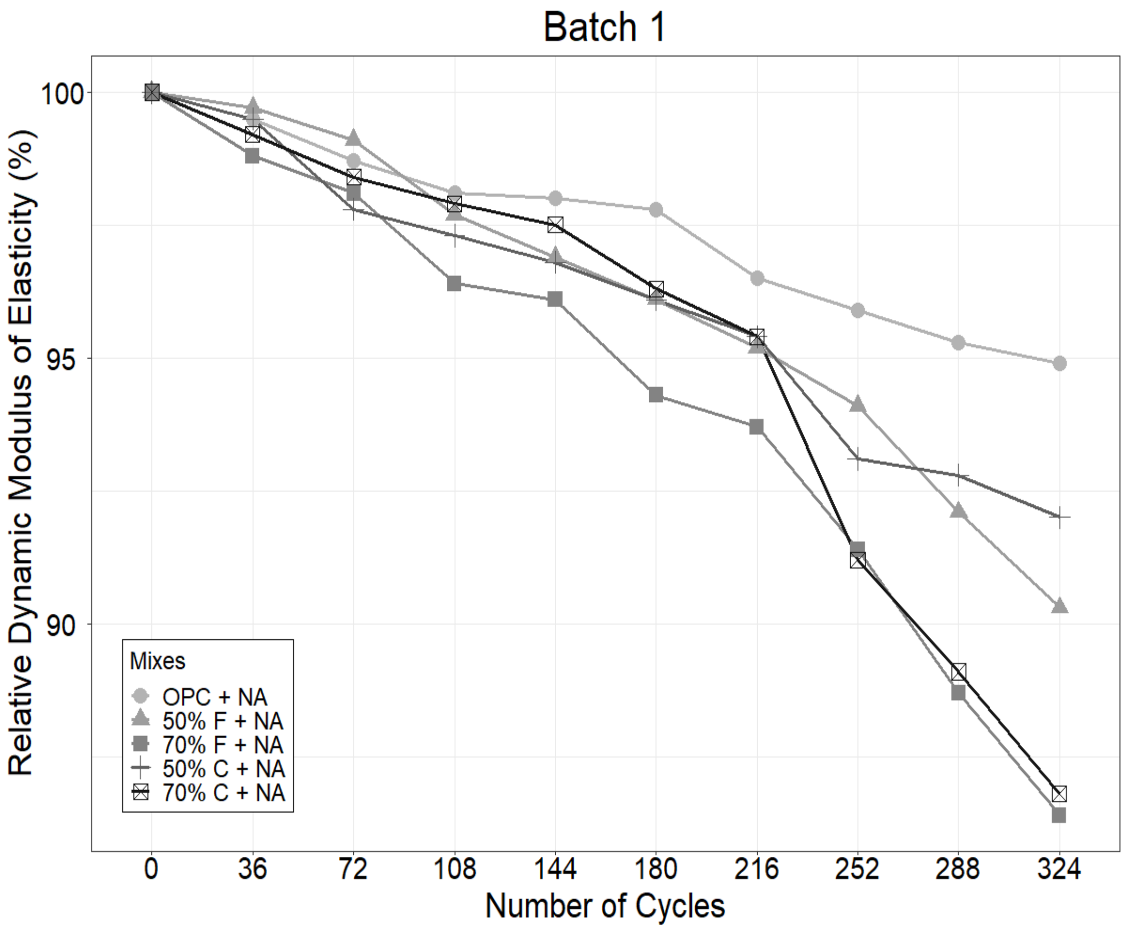

Figure 27: Percent change in relative dynamic modulus of elasticity in batch one

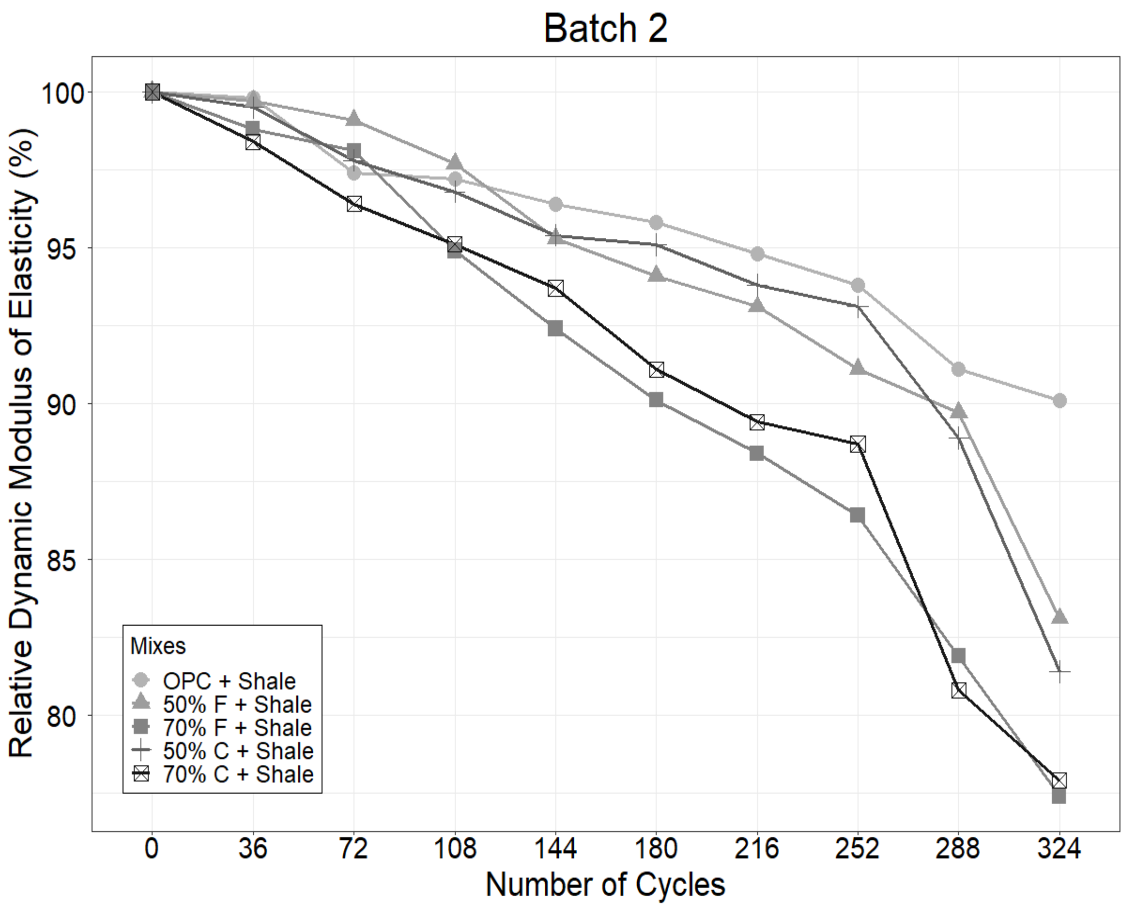

Figure 28: Percent change in relative dynamic modulus of elasticity in batch two

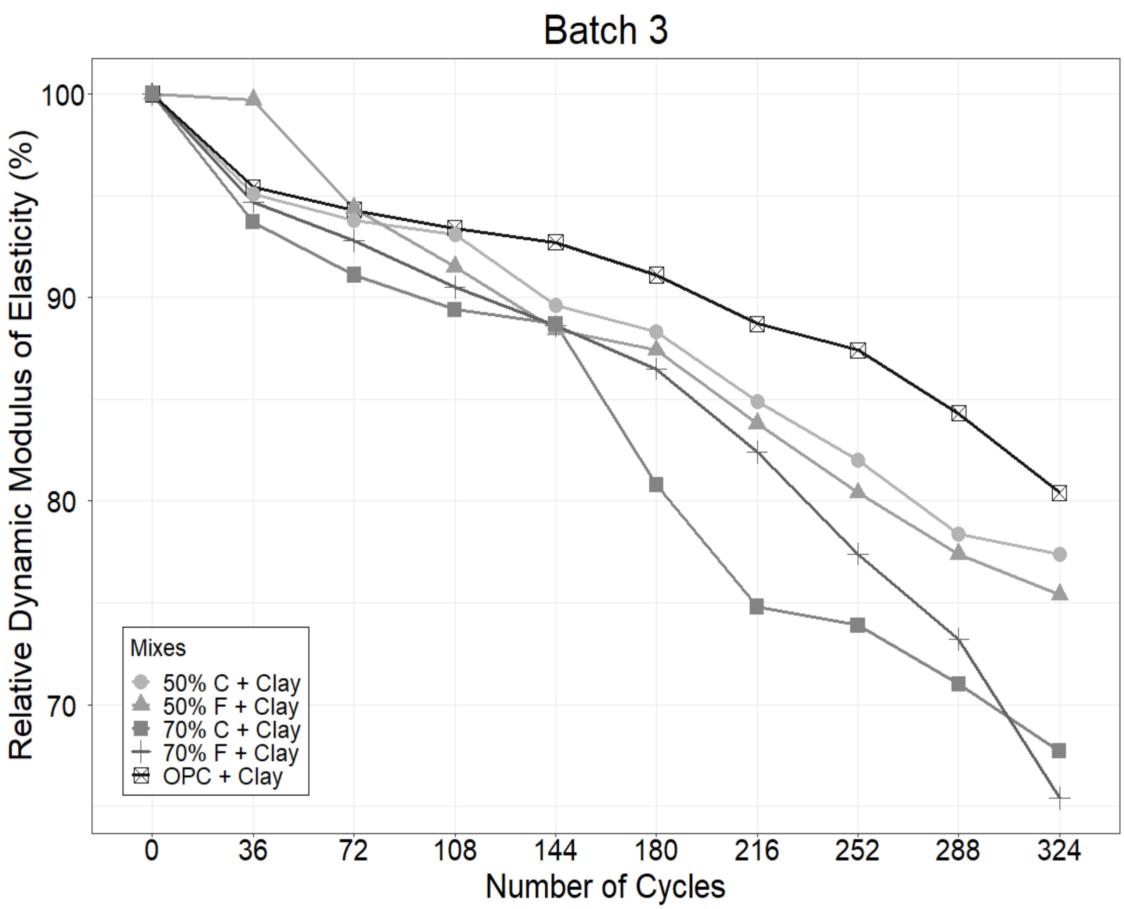

Figure 29: Percent change in relative dynamic modulus of elasticity in batch three

Table 10: Percent change of Freeze and Thaw weight and relative frequency		
Mix ID	Percent change at the end of freezing and thawing	
	Mass	Relative Frequency
BATCH ONE		
OPC +NA	0.27	0.02
50% F + NA	0.29	0.18
70% F + NA	0.39	0.44
50% C + NA	0.32	0.24
70% C + NA	0.41	0.72
BATCH TWO		
OPC + Shale	0.35	0.11
50% F + Shale	0.98	0.32
70% F + Shale	1.75	0.98
50% C + Shale	0.88	0.41
70% C + Shale	1.44	0.86
BATCH THREE		
OPC + Clay	0.38	0.10
50% F + Clay	1.12	0.74
70% F + Clay	1.98	1.26
50% C + Clay	1.24	0.84
70% C + Clay	2.18	1.88

IX. CONCLUSION

It is found that the replacement of high-volume fly ash (by volume) with ordinary Portland cement is indeed a suitable and effective in producing structural lightweight concrete for structural applications. This is significant and useful especially in those countries that utilize nothing to less amount of fly ash. Significantly, structural lightweight concrete in addition to high-volume fly ash will be beneficial to developing and under-developed countries in improving their infrastructures. This is important because, it greatly reduces the cost of overall construction and the disposal of waste and by-product. Therefore, the utilization of waste materials is extremely rewarding in the industry of construction.

- Structural lightweight high-volume fly ash (50%) concrete could be produced with satisfactory unit weight less than 1850 kg/m^3 and adequate compressive strength greater than or equal to 35 MPa at 28 days of age.
- 70% high-volume fly ash F and C have about 25% to 45% strength reduction at 28 days compared to ACI specified strength of concrete for structural applications.
- Drying shrinkage in structural lightweight high-volume concrete increases about 35% to 65% at 56 days of age compared to conventional concrete incorporated with high-volume (50%) fly ash.
- The utilization of lightweight aggregates could possibly be attributed to the increase in water absorption of the concrete due to the high absorption rate of the aggregate even though fly ash is also indicated higher permeability.
- Structural lightweight high-volume fly ash concretes performed poorly and could not resist freeze and thaw. It could be associated to the fact that both lightweight

aggregate and fly ash absorbed more water and become susceptible to early cracking in the samples of the concrete.

X. FUTURE WORK

- Study of drying shrinkage for later ages including 3, 6, 9 and 12 months in the concrete mixes above as it showed shrinkage could still take place at later ages.
- Study of the air void system of the structural lightweight high-volume concrete under optical microscope, XRD and SEM.
- Study of the thermal conductivity and heat transfer of the structural lightweight high-volume concrete samples.

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