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Research Paper

Experimental Study and Investigation of Compressive Strengths of Bentonite Geopolymer Concrete

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Abstract
This work presents the experimental study and investigation of the compressive strengths of Bentonite Geopolymer Concrete (BGC). The materials used in this research were bentonite, water, cement, superplasticizer, sodium reagents (alkaline activators), river sand and granite chippings. The concrete was tested for compressive strength and durability in magnesium sulphate solution. The bentonite geopolymer concrete (BGC) and controlled ordinary Portland cement concrete (i.e. normal concrete), each of dimension, 150 x 150 x 150mm were produced using the following mix proportions: 1:2:4. 1:1$^1/_2$:3, 1:3:6 and 1:1:2. The concrete were cured for 7, 14 and 28 days respectively. The normal concrete cubes were cured in curing tank containing distilled water while BGC cubes were subjected to ambient curing. The compressive strengths of both BGC cubes and normal concrete cubes were tested for compression in the universal testing machine. The results showed that compressive strengths of BGC for all the mix ratios considered increased as the ambient curing ages increased. The maximum strengths of BGC occurred at 28-day curing. The maximum strengths of the concrete were found as 16.30 N/mm^2, 18.85 N/mm^2, 11.40 N/mm^2 and 23.10 N/mm^2 for 1:2:4, 1:1$^1/_2$:3, 1:3:6 and 1:1:2 mix ratios respectively. The static elastic modulus of the geopolymer concrete were computed and found to be within the acceptable limit recommended by BS 8110-2:1985. However, the compressive strengths of the controlled ordinary Portland cement concrete (i.e. normal concrete) were greater than the compressive strengths of BGC for the mix ratios considered. Furthermore, as the curing ages of BGC in the sulphate medium increased, the more resistant of BGC to sulphate attack. Also, as the quantities of bentonite used in the production of BGC increased, the more resistant of the concrete to sulphate attack. Consequently, 1:1:2 BGC has the least reduction in compressive strength in the sulphate medium, thus, more resistant to sulphate attack.

***Keywords**: Bentonite, Compressive Strength, Concrete, Magnesium sulphate, Durability, Sulphate attack*

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I. INTRODUCTION

Concrete is a basic building material known for its exceptional strength, durability, and versatility (Anyaogu & Ezeh, 2013). However, the conventional binding agent for concrete, cement poses significant environmental challenges. In response to these concerns, researchers have been exploring alternative binding materials, with geopolymer concrete emerging as a promising solution (Davidovits, 2015). Majority of construction works uses concrete. Today, apart from water, concrete is the most consumed material, with three tons per year used for every person on earth. It is made from a mixture of cement, fine and coarse aggregates and water.

Cement can be considered as the 'glue' that binds aggregates together to form concrete. Therefore, concrete is basically a mixture of aggregates and paste. The aggregates being sand and Granite or crushed stone; the paste being water and Portland cement. Portland cement is not a brand name, it is the generic term for the type of cement used in virtually in all concrete works. Cement constitutes 10 to 15 percent of the concrete mix by volume and, through aprocess of hydration, cement and water harden and bind the aggregates into a rocklike mass. This hardening process will continue for years implying that concrete will get stronger as it gets older. Cement is manufactured through a closely controlled chemical combination of calcium, silicon, aluminum, iron and other ingredients. Common materials used to manufacture cement include limestone, shells, and chalk or marble combined with shale, clay, slate, blast furnace slag, silica sand, and iron ore. These ingredients, when heated at high temperatures form a rock-like substance that is ground into the fine powder called cement. Cement production takes place all around the world, however, there is a concentration of production in certain regions of the world

(Ian Tiseo, 2024). The total cement production in 2020 was estimated to be 4.1 billion metric tons. The top five cement producing countries (China, India, Vietnam, United States and Indonesia) account for approximately 68.2% of global cement production in 2020, with China alone accounting for over 60% of the total global production (4.2 billion metric tons in 2021, according to National Bureau of Statistics of China). At such an alarming rate of increase in the production of cement, it is only a matter of time before limestone becomes a scarce commodity (Ian Tiseo, 2024).

Global emissions from the manufacture of cement stood at 1.6 billion metric tons of carbon dioxide (CO_2) in 2022. Emissions from cement production have increased massively since the1960s, and have more than doubled since the turn of the century. More than four billion metrictons of cement are currently produced worldwide each year (Ian Tiseo, 2024). With such highlevels of CO_2 production and the limited supply of raw materials, there is need for alternative technology to be developed such as geopolymer concrete.

Geopolymer concrete is an innovative construction material that offers several advantages over traditional Portland cement-based concrete. It utilizes silica and alumina-rich waste materials which offers a compelling advantage by potentially reducing CO_2 emissions by up to 80% compared to ordinary Portland cement (OPC) while remaining economically feasible (Xu & VanDeventer, 2002). This revolutionary formulation not only reduces the environmental impact associated with the production of traditional cement but also enhances the mechanical and durability properties of the resulting concrete. A solution of sodium hydroxide and sodium silicate or water is used to activate sodium aluminosilicates such as fly ash, granulated blast furnace slag, metakaolin, and volcanic ash to form geopolymer concrete (GPC)

As a result of the high expenses and health risks connected with the disposal of agricultural and industrial wastes such as fly ash, rice husk ash and GGBS in recent years, recycling and reusing of these wastes has become an immensely complicated issue to be addressed. Although their use in cement manufacturing has helped to improve the system performance over the past several decades, the growing demand for the production of cement on ahuge scale has piqued the interest of researchers who are concerned about the influence of carbon dioxide, CO_2 emissions on global warming. According to the Environmental Protection Agency (EPA), this represents around 5–8% of overall CO_2 emissions into the atmosphere. In construction, reducing CO_2 emission is projected as an objective, for these, the proposed solution is using pozzolanic additions, such as slag, silica fume and fly ash to replace cement because they enhance the rheological, strength, durability and transfer properties (Sharma & Khan, 2018). These improvements are explained and attributed to the pozzolanic activity of these materials because if Portlandite is present, it leads to additional calcium silicate hydrates (C-S-H).

It is now the primary focus of geopolymer research and development to create alternative cement manufacturing techniques and cost-effective construction materials. Because geopolymer materials have a lower calcination temperature than conventional procedures, they emit significantly less CO_2 than conventional processes.

Geopolymers are a member of the family of inorganic polymers, and are a chain structures formed on a backbone of Al and Si ions. The chemical composition of this geopolymer material is similar to natural zeolitic materials, but they have amorphous microstructure instead of crystalline (Palomo et al, 1999; Xu & van Deventer, 2002). The polymerisation process involves a substantially fast chemical reaction under highly alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Davidovits, 2015). Geopolymer can take one of the three basic forms: (i) Poly(sialate), which has [-Si-O-Al-O-] as the repeating unit, (ii) Poly(sialate-siloxo), which has [-Si-O-Al-O-Si-O-] as the repeating unit and (iii) Poly(sialate-disiloxo), which has [-Si-O-Al-O-Si-O-Si-O-] as the repeating unit. Where Sialate is an abbreviation of silicon-oxo-aluminate (Davidovits, 2015).

It is important to note that any material that contains mostly Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material for the manufacture of geopolymer. Several minerals and industrial by-product materials have been investigated in the past. The investigation showed that typical geopolymer materials include the following: metakaolin or calcined kaolin, fly ash, combination of fly ash and metakaolin, and combination of granulated blast furnace slag and metakaolin (Davidovits, 2015; Barbosa et al, 2000).

The most common alkaline activator used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate (Davidovits, 2015; Palomo et al. 1999; Barbosa et al. 2000; Xu & van Deventer, 2002; Swanepoel & Strydom, 2002; Xu & van Deventer 2002). Palomo et al (1999) concluded that the type of activator plays an important role in the polymerisation processes. Reactions occur at a high rate when the alkaline activator contains soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides. Xu and van Deventer (2002) confirmed that the addition of sodium silicate solution to the sodium hydroxide solution as the alkaline activator enhanced the reaction between the source material and the solution. Furthermore, after a study of the geopolymerisation of sixteen natural Al-Si minerals, they found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution.

The most common industrial waste used in the production of geopolymer concrete (GPC) at commercial level is fly ash. However, the major sources of fly ash are carbon-emitting which may not be sustainable in near future. Therefore, there is need to source for non-carbon emitting pozzolanic material in production of GPC. Such material could be bentonite. Bentonite is a primarily expandable montmorillonite clay. Montmorillonite is a 2:1 type of clay family, and its unit layer structure consists of one Al^{3+}octahedral sheets. It had plenty of applications in various fields. The major applications include the utilization of bentonite are as drilling fluids, foundry bonds, pelletizing iron ore, cat litter and absorbents, adhesives, bleaching earths, ceramics, etc. (Alkaya and Esener, 2011).

Nigeria as a nation is blessed with abundant bentonite resources which if well harnessed, it can be effectively used in geopolymer /supplementary cementation. Every region in Nigeria has been reported to have a substantial deposit of bentonite clays. The proven reserve of bentonite in Nigeria has been modestly estimated to be above 700 million metric tons (Omole et al. 2013; Bilal et al., 2015). Globally, it occurs abundantly in India and Pakistan. Despite of its availability, its use in concrete was limited as thickener agent, but not as either Supplementary cementations materials or geopolymer concrete materials. However, due to its rheological functionality, bentonite has been mainly used as thixotropic materials. On the other hand, its limited use as a substitute for cement in concrete production can be due to its poor pozzolanic reactivity when compared to other clay materials, such as metakaolin and fly ash (Rackel, 2011). It is well established that clays with kaolinite contents greater than 45% have the best pozzolanic reactivity. Past researches had shown that bentonite has varying physical and chemical properties depending on the source of collection.

Researches have also shown that bentonite contains an appropriate amount of oxides (SiO_2+Al_2O_3+Fe_2O_3), hence can be classified as pozzolans (Pelisser et.al, 2018), its structure is too stable to be soluble and reactive. Bentonite is an aluminosilicate mineral available in volumes exceeding several million tonnes in many parts of the world. It is obtained by thermal transformation of kaolinite, which is mined in many parts of the world. Calcination of kaolinite at temperature between 550-900°C to dehydrate and amorphized its crystalline structure (Taher, 2003). This can therefore result in sufficiently reactive aluminosilicate materials. It should be noted that the calcination temperature should be carefully controlled to avoid formation of inert phases such as mullite.

Most of the researches on Bentonite-cement concrete was performed in Pakistan due to its abundance. Due to its variations in physicochemical properties, the performance of Bentonite-cement concrete exhibits some uncertainties to the researchers. The average particle size of bentonite is nearly 4.32 μm (Reddy et.al, 2017). It contains SiO_2 in high percentages (Reddy et.al, 2017). The specific gravity (2.6–2.85) of bentonite is lower than that of other pozzolanic materials (Reddy et.al, 2017). Its colour could be greenish grey, browning green or light yellow. The colour used for this research is light yellow. Bentonite-cement concrete may perform less thermal resistance compared to other concretes made with pozzolanic materials like fly ash. It has loss of ignition (LOI) of range, 5–14 values (Shabab et.al, 2016; Reddy & Rao, 2019 and Afzal et.al, 2014). Bentonite-cement concrete generally exhibited longer setting times when compared with cement paste (Reddy et.al, 2017).

Memon et al. (2012), examined up to 21% bentonite substitution for cement in Bentonite cement blended concrete, reported that lower compressive strength exhibits at the age of 3, 7day, and a better result shown at 28, 56 days after curing, and reported that there were decrease in water absorption by increasing percentage of bentonite blending. Bentonite substitution achieve the low-cost concrete and improve the durability of the system by testing bentonite blended concrete against to hydrochloric acid and Sulfuric acid. He recommended utilization of super plasticizer needed to enhance workability. Junaid et.al (2013), showed that at 20% bentonite substitution, poor compressive strength results were reported when comparing with control mix but on the other hand, it showed very good resistance to sulphate attack. Karthikeyan et al (2015), reported that 30% substitution of bentonite results maximum split tensile strength to concrete.

Experimental investigation on bentonite-fly ash concrete mixes, reported that the concrete contains equal combination (50-50%) of bentonite and fly ash exhibits better results at the age of 90 days (Shabab et al.,2016). In 2017 experiments are performed as per standard procedure IS 5816, results that lower split tensile strength was observed in bentonite blended mixes (Reddy et al., 2017). Divyana (2015), laboratory results indicate a better splitting tensile strength by 20% bentonite replacement. Chandrakanth et al (2016), showed that 5% bentonite addition improves flexure strength of concrete. Sreeniva et al (2017), reported that 15% bentonite blended concrete shown great resistance against hydrochloric acid. Bentonite is used in self-healing cracks of cement paste associated with ground granulated blast furnace slag. The self-healing properties were evaluated with four parameters: crack width on the surface, crack depth, tensile strength recovery, and flexural recovery. The results show that bentonite improves the healing properties, in terms of surface crack width and crack depth (Ekaputri et al., 2018). A laboratory testing indicates the use of bentonite within the concrete can provide one of the best solutions to decrease the expansion due to alkali silica reaction through the protection of the concrete skeleton and provide a positive impact on the durability of the concrete (Tahiri et al.,2018). The objective of this study is the experimental study and investigation of compressive strength of bentonite geopolymer concrete.

II. MATERIALS AND METHODS

2.1 MATERIALS

The following materials were used in this research: Ordinary Portland Cement (OPC), Fine Aggregates, Coarse aggregates, Alkaline activator, Superplasticizer, Bentonite and Water

i. **Ordinary Portland Cement (OPC)**: Dangote brand of OPC (42.5 grade), which conforms to the requirements of BS 12:1996 was used.

ii. **Fine Aggregate**: River sand used for this work was obtained from Otamiri, a river at Federal University of Technology, Owerri, Nigeria**.** The sand was spread and exposed to the atmosphere for 7 days to remove excess moisture which may affect the properties of the finished specimen. These aggregates passed through sieve no. 4 (4.75mm) and were predominantly retained on sieve no. 200 (75µm). The specific gravity and bulk density of the aggregate were 2.67 and 1602 kg/m^3. This conforms to specification of IS 2386:1963 and BS 1377-2(1990) for normal weight aggregate

iii. **Coarse Aggregate**: The coarse aggregates used in this work was granite chippings. It was bought from a stone/ quarry dealer in Owerri. The granite chippings were said to have been quarried by Crushed Rock Industries in Ishiagu along Enugu-Port Harcourt express way, Ebonyi State. The maximum size of the coarse aggregate was 20mm. Its specific gravity is 2.55 and compacted bulk density is 1571.52 kg/m^3 This conforms to specification of IS 2386:1999 and BS 1377-2(1990) for normal weight aggregate.

iv. **Alkaline activators**: A combination of alkaline silicate solution and alkaline hydroxide solution was chosen as the alkaline liquid. Sodium-based solutions were chosen because they were cheaper than Potassium-based solutions. The sodium hydroxide solids were of a laboratory grade in pellets form with 98% purity, obtained from local suppliers. The sodium hydroxide (NaOH) solution was prepared by dissolving the pellets (a small, rounded, compressed mass of a substance of sodium hydroxide) in water. The mass of sodium hydroxide solids in a solution varied depending on the concentration of the solution expressed in terms of molarity. Sodium silicates solution to sodium hydroxide solution ratio was taken as 2.5:1. The resultant solution was stored for 24 hours at room temperature to avoid exothermic action when added to source material before it was used for casting. In this research 8M of NaOH was prepared. Both NaOH pellets and 99% purity sodium silicate solution were obtained from a chemical shop in Owerri.

v. **Superplasticizer:** The superplasticizer used for research was CONPLAST SP430, it was obtained from a chemical shop in Enugu State. Superplasticizer is added to increase workability and setting times of the fresh concrete mixes.

vi. **Bentonite:** The bentonite used in this research was obtained from an onsite excavation operation in Bende, Abia state. This material was used for complete replacement of cement in the production of Bentonite Geopolymer Concrete (BGC). The bentonite was calcined in a kiln at a temperature of 750^{0}C. it was ground and sieved with a sieve size of $63\mu m$. Chemical analysis of the bentonite was performed in Department of Chemistry laboratory of Federal University of Technology. Owerri. The result is shown in Table 2

vii. **Water:** water is a significant ingredient in concrete mix. In this research, potable water was used. It was obtained from FUTO's water system. The pH value of the water was 7.

METHODS

i. Determination of mix ratio of bentonite geopolymer and normal concrete

Batching of materials was done by weight. Hence, each material was weighed using a scale before mixing. The controlled OPC concrete with all constituents and water-cement ratio of 0.55 were thoroughly mixed into a pan for 5 minutes and were cast into moulds of dimension 150 x 150 x 150 mm and were properly compacted. The concrete cubes were demoulded after 24 hours. The concrete cubes were thereafter cured in a curing tank containing a distilled water for 7, 14 and 28 days respectively.

The geopolymer concrete was prepared by hand mixing of its constituents. Firstly, Bentonite and aggregates were dry mixed in a pan for about three minutes. Then, the alkaline activator ($NaOH + Na_2SiO_3$) solution were added and mixed thoroughly with the dry mix of the bentonite and aggregate. Thereafter, the superplasticizer was premixed and added to the resultant mixture for another four minutes. These mixtures gave rise to fresh concrete. The fresh concrete mix is then immediately placed in the moulds of dimension 150 x 150 x 150 mm and given required compaction. The concrete cubes were allowed to set for 24 hours and demoulded, before keeping them under ambient temperature curing for 7, 14 and 28 days respectively. The concentration of sodium reagents used for the production of the geopolymer concrete was 8M. The alkaline solution to binder ratio for the geopolymer concrete is 0.3 with 1% of total mass of the mix being superplasticizer for the geopolymer concrete.

The following mix proportions were used to produce both bentonite geopolymer concrete and normal concrete: 1:2:4, 1:1$^{1}/_{2}$: 3, 1:3:6 and 1:1:2. The Mix Proportion by weight of Bentonite geopolymer Concrete and Normal Concrete are as shown in Tables 1.

Three (3) cubes were cast for each mix ratio and for each curing age. The curing ages of the concrete cubes were 7, 14 and 28 days. This gave a total of 72 cubes, such that 36 cubes were cast for normal concrete, 36 for bentonite geopolymer concrete.

Table 1: Mix Proportion by weight of Bentonite geopolymer Concrete and Normal Concrete

S/N	Mix Ratio	Alkaline activator	Super plasticizer	Type of concrete
NC1	1:2:4	-	-	NC
NC2	1:1$^{1}/_{2}$:3	-	-	NC
NC3	1:3:6	-	-	NC
NC4	1:1:2	-	-	NC
BC1	1:2:4	8M	1% of total mass	BGC
BC2	1:1$^{1}/_{2}$:3	8M	1% of total mass	BGC
BC3	1:3:6	8M	1% of total mass	BGC
BC4	1:1:2	8M	1% of total mass	BGC

NC = Normal Concrete BGC= Bentonite Geopolymer Concrete

ii. Compressive Strength test of both Normal Concrete and Bentonite Geopolymer Concrete

Normal concrete cubes were kept in the curing tank, while the geopolymer concretes developed were kept under ambient temperature curing for 7, 14 and 28 days respectively till the time of testing. The concrete cubes were weighed first using a 50kg capacity weighing balance, to ascertain the mass of each individual specimen. The mass values obtained were recorded. They were later used to calculate the density of each concrete cube. The concrete cube was placed in between two steel plates of 25mm thickness and wide enough as to cover the top and bottom of the cube in the Universal testing machine (UTM). Force was gradually applied through the platens of the testing machine until the concrete cube failed in compression. The value read off the UTM at failure of the cube represents its compressive load. The Compressive Strength of the concrete cube samples were determined using Equation (1).

$$\text{Compressive Strength, } \mathrm{f_c} = \frac{\text{Compressive Load, F}}{\text{Cross} - \text{sectional Area of concrete cube, A}} \qquad (1)$$

While the densities of the concrete cubes were obtained from Equation (2)

$$\text{Density, } \rho = \frac{m}{v} \qquad (2)$$

Where m is mass of the concrete cube (kg) and v is the volume of the cube (m^3). The results of the compressive strengths and densities of the concretes are shown in Table 3 – 5

iii. Test on effect of sulphate solution on compressive strength of Bentonite Geopolymer Concrete

External sulphate attack is a reaction between sulphate ions and hydration products of cement causing damages, is a real threat for concrete durability in an aggressive environment. Sulphates are naturally occurring minerals found in ground water, sea water, soils and waste waters. Sulphate attack on concrete may cause cracking, spalling, softening, expansion, loss of strength and other forms of damage. Common sulphates that are present in soil and ground water are the sulphates of sodium, potassium, calcium and magnesium. Magnesium sulphate has a more damaging effect than other sulphates because it leads to decomposition of the calcium silicate as well as of $Ca(OH)_2$ and of hydrated C_3A. This led to formation of hydrated magnesium silicate which had no binding properties (Neville and Brook, 2012). To test for the effect of sulphate environment on Bentonite Geopolymer Concrete (BGC), another 36 cubes of BGC produced using the adopted mix ratios were soaked in water containing 5% volume of Magnesium sulphate solution for 7, 14, 28 days after their 7, 14, 28 days ambient curing. The cubes were later subjected to compression test and their percentage reduction/gain in compressive strength were computed. The percentage reduction/gain in compressive strength, R_{CS} of the cubes were obtained from Equation (3)

$$R_{CS}\ (\%) = \left[\frac{C_C - C_S}{C_C}\right] * 100 \qquad (3)$$

Where

R_{CS} is percentage reduction/gain in compressive strength of concrete soaked in diluted sulfuric acid solution,

C_C is the average compressive strength of the concrete cubes not soak in dilute sulfuric acid solution, and

C_S is the average compressive strength of the concrete cubes soaked in dilute sulfuric solution

The result is shown Table 10 and Figure 3 respectively.

III. RESULTS AND DISCUSSION

3.1 RESULTS

a. Chemical analysis of Bentonite

The result of the chemical analysis of Bentonite used in this research is as shown in Table 2

Table 2: Chemical Analysis of Bentonite

Compound	**Composition (%)**
SiO_2	49.65
Al_2O_3	16.03
Fe_2O_3	8.44
MnO	0.49
CaO	8.02
Na_2O	3.54
MgO	3.70
K_2O	0.65
TiO_2	0.66
P_2O_5	0.37
SO_3	0.87
Loss of Ignition (LOI)	7.54

According to ASTM C618 (2019), major oxides for calcined pozzolan is (%SiO_2 + %Al_2O_3 + %Fe_2O_3) = 49.65 + 16.03 + 8.44 = 74.12% >70% and, glass content of the pozzolan is (% SiO_2 - % CaO) = 49.65 – 8.02 = 41.63% > 34%

b. Compressive strengths of Bentonite Geopolymer Concrete and Normal Concrete

The compressive strengths of the geopolymer concrete at different curing ages are as shown in Table 3 and Figure 1 respectively, while that of the normal concrete is as shown in Table 4. The densities of the geopolymer concrete and normal concrete are as shown in Tables 5 and 6. The percentage differences of the geopolymer concrete with respect to the normal concrete at 28-day curing is as shown in Table 7

Table 3: Compressive Strengths, fc_B (N/mm^2) at different curing ages of Bentonite Geopolymer Concrete

Mix No	Mix ratio	Curing Ages (days)		
		7d	14d	28d
BC1	1:2:4	15.67	15.80	16.30
BC2	$1:1^1/_2:3$	18.30	18.60	18.85
BC3	1:3:6	10.27	10.86	11.40
BC4	1:1:2	22.00	22.70	23.10

Table 4: Compressive Strengths, fc_N (N/mm^2) at different curing ages of Normal Concrete

Mix No	Mix ratio	Curing Ages (days)		
		7d	14d	28d
NC1	1:2:4	17.67	19.40	21.30
NC2	$1:1^1/_2:3$	20.32	21.33	22.78
NC3	1:3:6	10.18	10.88	12.40
NC4	1:1:2	25.02	25. 75	27.78

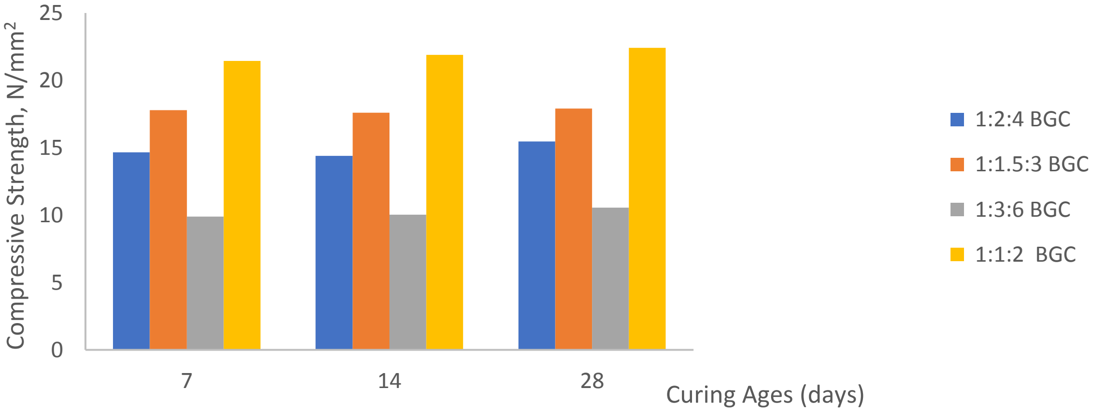


Figure 1: Variation of Compressive strength of Bentonite Geopolymer concrete (BGC) with curing ages

Table 5: Densities (kg/m^3) at different curing ages of Bentonite Geopolymer Concrete

Mix No	Mix ratio	Curing Ages (days)		
		7d	14d	28d
BC1	1:2:4	2020	2025	2028
BC2	1:1$^{1}/_{2}$:3	2054	2062	2075
BC3	1:3:6	2012.5	2016.8	2022
BC4	1:1:2	2068	2084	2102.3

Table 6: Densities (kg/m^3) at different curing ages of Normal Concrete

Mix No	Mix ratio	Curing Ages (days)		
		7d	14d	28d
NC1	1:2:4	2408	2410	2413
NC2	1:1$^{1}/_{2}$:3	2405	2411	2415
NC3	1:3:6	2401	2412	2417
NC4	1:1:2	2400	2409	2420

Table 7: Percentage Difference of the Compressive Strength of Bentonite Geopolymer Concrete with respect to Normal Concrete at 28-day curing

Mix ratio	Compressive Strength (N/mm^2)		
	fc_B	fc_N	Percentage Difference = $\left(\frac{fc_N - fc_B}{fc_N}\right)$ x 100
1:2:4	16.30	21.30	23.47
1:1$^{1}/_{2}$:3	18.85	22.78	17.25
1:3:6	11.40	12.40	8.06
1:1:2	23.10	27.78	16.85

Where fc_B = compressive strength of BGC fc_N = compressive strength of NC

Elastic Modulus of Bentonite Geopolymer Concrete

According to Neville and Brooks (2012), static elastic modulus of concrete with density between 1400kg/m^3 and 2320 kg/m^3, is obtained from Equation (4)

$$E_s = 1.7\rho^2 {f_c}^{0.33} \text{ x } 10^{-6} \qquad (4)$$

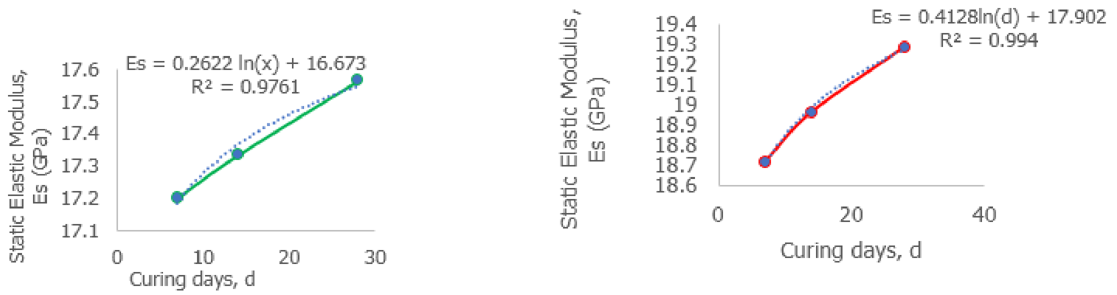
Where E_s is static elastic modulus (GPa), ρ is the concrete cube density(kg/m^3) and f_c is the compressive strength of the concrete (N/mm^2).

The static elastic modulus of the geopolymer concrete is as shown in Table 8.

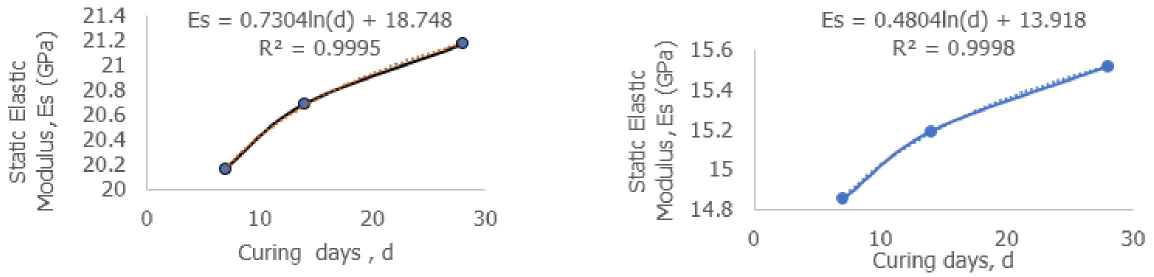
Table 8: Static Elastic Modulus of Bentonite Geopolymer Concrete

Mix ratio	Compressive strength at different Curing Ages in days, f_c (N/mm^2)			Densities at different Curing Ages in days, ρ (kg/m^3)			Static Elastic Modulus at different curing ages in days, $E_s = 1.7\rho^2 {f_c}^{0.33}$ x 10^{-6} (GPa)		
	7d	14d	28d	7d	14d	28d	7d	14d	28d
1:2:4	15.67	15.8	16.3	2020	2025	2028	17.20	17.33	17.56
1:1$^{1}/_{2}$:3	18.3	18.6	18.85	2054	2062	2075	18.72	18.97	19.29
1:3:6	10.27	10.86	11.4	2012.5	2016.8	2022	14.85	15.19	15.52
1:1:2	22.0	22.7	23.1	2068	2084	2102.3	20.16	20.69	21.18

The equations of the static elastic modulus with respect to curing ages for different mix ratios considered in this paper are as shown in Figures 2(a-d).



(a) 1:2:4 BGC (b) $1{:}1^1/_2{:}3$ BGC



(c) 1:1:2 BGC (d) 1:3:6 BGC

Figure 2: variation of static elastic modulus of BGC with the ambient curing ages

c. **Effect of sulphate solution on compressive strength of Bentonite Geopolymer Concrete**.
The compressive strengths and percentage reduction of compressive strength of Bentonite geopolymer concrete at different curing ages when soaked in magnesium sulphate solution are as shown in Tables 9 and 10, and Figure 3 respectively.

Table 9: Compressive Strengths (N/mm^2) at different curing ages of Bentonite Geopolymer Concrete soaked in magnesium sulphate solution

Mix No	Mix ratio	Curing Ages (days)		
		7d	14d	28d
BC1	1:2:4	15.18	15.38	15.88
BC2	$1{:}1^1/_2{:}3$	17.76	18.13	18.47
BC3	1:3:6	9.92	10.55	11.09
BC4	1:1:2	21.38	22.22	22.85

Table 10: Reduction in Compressive Strength, R_{CS} of Bentonite Geopolymer Concrete (BGC) at different curing ages when soaked in magnesium sulphate solution

Mix No	Mix ratio	Compressive strengths of BGC when not soaked magnesium sulphate solution, C_C (N/mm^2)			Compressive strengths of BGC when soaked in magnesium sulphate solution, C_S (N/mm^2)			Percentage Reduction in Compressive Strength, R_{CS} (%)		
		Curing Ages (days)			Curing Ages (days)			Curing Ages (days)		
		7d	14d	28d	7d	14d	28d	7d	14d	28d
BC1	1:2:4	15.67	15.80	16.30	15.18	15.38	15.88	3.12699426	2.65822785	2.57668712
BC2	$1{:}1^1/_2{:}3$	18.30	18.60	18.85	17.76	18.13	18.47	2.95081967	2.52688172	2.01591512
BC3	1:3:6	10.27	10.86	11.40	9.92	10.55	11.09	3.40798442	2.85451197	2.71929825
BC4	1:1:2	22.00	22.70	23.10	21.38	22.22	22.85	2.81818182	2.11453744	1.08225108

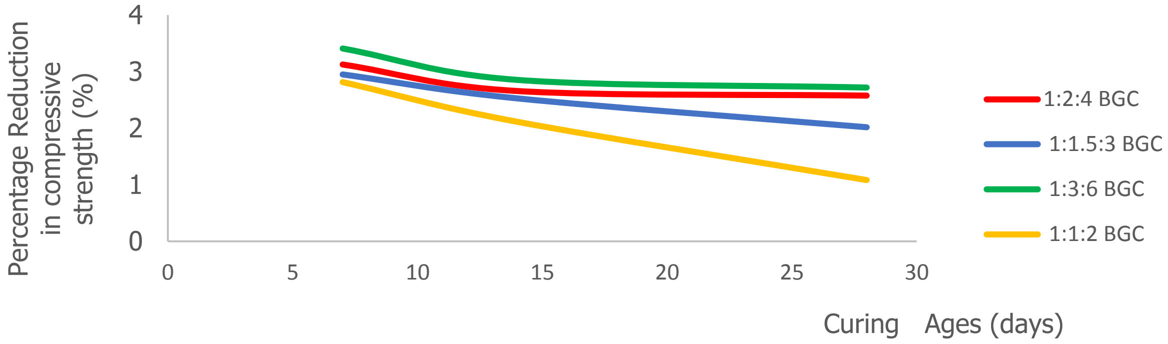


Figure 3: Percentage reduction in compressive strength of Bentonite Geopolymer Concrete (BGC) soaked in magnesium sulphate solution at different curing ages

3.2 DISCUSSION

a) The results in Table 2 of the study revealed that bentonite is a pozzolan according to the American ASTM C 618 classification, with the sum of major elements $Al_2O_3 + SiO_2 + Fe_2O_3 > 70\%$, and the difference of major elements ($SiO_2 – CaO$) > 34.

b) The results in Table 3 and Figure 1 showed that compressive strengths of BGC for all the mix ratios considered increased as the ambient curing ages increased. The maximum strengths of the concrete occurred at 28-day curing. The maximum strengths of BGC were found as 16.30 N/mm^2, 18.85 N/mm^2, 11.40 N/mm^2 and 23.10 N/mm^2 for 1:2:4, 1:1$^1/_2$:3, 1:3:6 and 1:1:2 mix ratios respectively. However, the comparison in Table 7 showed that the compressive strengths of the controlled ordinary Portland cement concrete (i.e. normal concrete) were greater than the compressive strengths of BGC for the different mix ratios considered in the research. The feeble strengths of BGC may be due to low content of CaO in the pozzolan.

c) The compressive strengths of concrete depend on the curing age of the concrete, while the static elastic modulus of concrete depends on its compressive strength. Consequently, the static elastic modulus,Es of concrete depends on its curing age, d. From Figures 2(a-d), the static elastic modulus of BGC for different mix ratios considered in this research are as follows

i. $Es = 0.2622\ln(d) + 16.673$ for 1:2:4 BGC (5a)
ii. $Es = 0.4128\ln(d) + 17.902$ for 1:1$^1/_2$:3 BGC (5b)
iii. $Es = 0.7304\ln(d) + 18.748$ for 1:1:2 BGC (5c)
iv. $Es = 0.4804\ln(d) + 13.918$ for 1:3:6 BGC (5d)

In Table 8, the values of static elastic modulus of all the mix ratios considered for BGC at 28-day curing ages are within acceptable limit recommended by BS 8110-2: 1985

d) The results in Tables 9 and 10, and Figure 2 showed that as the curing ages of the concrete in the sulphate medium increases, the more resistant of BGC to sulphate attack. Also, as the quantities of bentonite increases in the production of BGC, the more resistant of the concrete to sulphate attack. Consequently, 1:1:2 BGC has the least reduction in compressive strength in the sulphate solution medium, thus more resistant to sulphate attack.

IV. CONCLUSION

The experimental investigation of compressive strengths of Bentonite Geoplymer concrete has shown that the concrete can be used in construction of eco-friendly structures, but it can only be empolyed on non-load structural elements due to its low compressive strengths. Again, it has a good resistant to sulphate attack, thus it can be used in areas where the soil and ground water is slightly acidic or contain resonable sulphates.

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