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Investigation of the Catalytic Liquid System Ratio on the Strength Performance of Geopolymer Concrete

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Abstract
This study assessed the effects of the varying ratio of alkaline activators on the short-term mechanical property of slag-based geopolymer concrete (GPC) incorporated with corncob ash (CCA). Consequently, the study harnessed the waste products, eco-friendly and low-carbon footprint materials, ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) as binding agents in a bid to design and develop a sustainable product. Moreover, sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) gel were used as a catalytic liquid system (CLS) for the activation of the concrete products at the varying ratio of 1.5: 1, 2: 1, 2.5: 1 and 3: 1 for Na_2SiO_3 gel: NaOH solution respectively. Furthermore, GGBFS was replaced by CCA in 20, 40, 60, 80, and 100% volume using grade 30 MPa concrete (M 30) as a mix design proportion. The mix was activated with 14 molar concentrations of CLS. Subsequently, the concrete samples were cured under the ambient conditions and tested for compressive strength at 7, 28, 56 and 90 days. The experimental finding revealed that the optimum strength performance of slag-based GPC incorporated with CCA is achieved at a ratio of 2.5: 1 for Na_2SiO_3 gel: NaOH solution respectively when compared with 1.5: 1, 2: 1 and 3: 1 for the concrete. Therefore, the strength performance of GPC depends on the varying ratio of alkaline liquid and must be properly experimented to ascertain its best performance on the strength properties of GPC.

Keywords: Geopolymer concrete, corncob ash, ground granulated blast furnace slag, sodium silicate, sodium hydroxide, compressive strength

1. Introduction

In the construction industry, Portland cement is known as the second most utilized material as a basic ingredient of concrete and mortar production apart from water [1]. In spite of the considerable amount of literature on the benefits of Portland cement in the construction industry, studies have revealed that Portland cement emits a great potential of greenhouse gases such as carbon dioxide (CO_2), nitrous oxide, ozone, methane, chlorofluorocarbon, hydrofluorocarbon [1]. Moreover, the cement industry is one of the two largest emitters of CO_2, contributing up to 7% of global man-made emission of CO_2. However, there is a global interest in reducing CO_2 emission to the atmosphere particularly with the possibility of utilizing low-carbon and eco-friendly materials to attain the 2030 agenda for Sustainable Development, Goal 12, "*sustainable consumption and production pattern* [2]." Consequently, this drives the use of GGBFS and CCA as sustainable binders in the production of GPC. In contrast to Portland cement concrete (PCC), previous studies have established that the blending of both GGBFS and CCA in the production of concrete resulted in good workability and thermal insulation, excellent durability and higher mechanical properties [3-17]. GPC is a green concrete that is generating interest in the drive for sustainability. It is a product formed as a result of the polymerized reaction between the sustainable binding materials and the catalytic liquid system (CLS). CLS is used to denote the alkaline activator solution (AAS) in GPC. And one of the best methods to determine the quality of concrete is its compressive strength.

In 2012, *Sanni and Khadiranaikat* investigated the influence of severe environmental conditions on the strength performance of fly ash (FA)-based GPC using the combination of both Na_2SiO_3 gel and NaOH solution as AAS. The ratios of both Na_2SiO_3 gel to NaOH solution were selected as 2.5: 1 and 3.5: 1 respectively with designed molarity of 8 M and 12 M. The experimental finding indicated that the strength performance of GPC was maximum at a ratio 2.5:1 when compared with 3.5:1 [18]. In the same vein, *Shinde, Patankar and Sayyad* in 2017 explored the influence of fineness and AAS ratio on the mechanical properties of FA-based GPC at a varying ratio of Na_2SiO_3 gel to NaOH solution as 1: 1, 1.5: 1, 2: 1, 2.5: 1 and 3: 1 respectively. The designed molarity was 13 M. It was observed from the result that the AAS ratio of 1.5:1 exhibited the maximum strength when compared with other ratios [19].

Hence, this study proffers a way of determining the slump and the optimum strength performance of GGBFS-based GPC incorporated with CCA at varying ratio of CLS (Na_2SiO_3 gel and NaOH solution) under the ambient curing conditions. The designed concrete mix, M 30 was used as target strength because it is a concrete widely used for general purposes. The molarity of CLS was selected as 14 M because it exhibited the highest strength performance as revealed by the relevant studies [3], [4].

2. Materials and Methods

2.1 Materials

Corncob was sourced from Agbonle, Oyo State, Nigeria. It was sun-dried for 5 days to boost the burning process. Afterwards, it was burnt to ash to obtain corncob ash (CCA) under controlled temperature (600 ^{0}C) on a pilot scale gas furnace to reduce the emission of CO_2 to the atmosphere. Granulated blast furnace slag was obtained from the Federated Steel Mills, Ota, Nigeria. Thus, both CCA and GGBFS were obtained in accordance with the method stated by *Oyebisi et al.* in 2018 [3], [4]. Furthermore, their chemical compositions were analyzed and obtained inconsonant with the previous studies [3], [4].

Water used in the course of this study was sourced from the water and environmental laboratory of Civil Engineering Department, Covenant University, Ota, Nigeria and it was in accordance with the *British Standard* [20]. Sodium hydroxide pellets with 99% purity and gel of Na_2SiO_3 were both used as CLS and sourced from Lagos, Nigeria. Finally, both fine and coarse aggregates (12.5mm and 19mm) were sourced from Ota, Nigeria. And they were used in accordance with the procedure stipulated in the *British Standard EN* [21].

2.2 Mix Design of Concrete Proportion and Preparation of Alkaline Activators

The proportion of the concrete mix was designed in consonance with the *British Standard (BS)* [22]. Furthermore, the properties of the constituent materials, moisture contents, water absorptions and specific gravities were obtained and put into consideration during the mix design. The design mix proportions are indicated as 100% GGBFS + 0% CCA, 80% GGBFS + 20% CCA, 60% GGBFS + 40% CCA, 40% GGBFS + 60% CCA, 20% GGBFS + 80% CCA and 0% GGBFS + 100% CCA and denoted as G1, G2, G3, G4, G5 and G6 respectively. The CLS (Na_2SiO_3 gel and

NaOH solution) were prepared in accordance with the previous studies [3], [4] and in conformity with the chemistry laboratory procedure [23] (see Figure 1 a). The mix design quantities for M 30 at ratio Na_2SiO_3 gel: NaOH solution is presented in Tables 1, 2, 3 and 4 for 1.5: 1, 2: 1, 2.5: 1 and 3: 1 respectively.

Table 1: Mix design quantity for M 30 concrete at CLS ratio 1.5: 1

Mix ID	GGBFS (Kg/m^3)	CCA (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)	CLS/ binder
G1	390	0	675	1032	84	126	0.54
G2	312	78	675	1032	84	126	0.54
G3	234	156	675	1032	84	126	0.54
G4	156	234	675	1032	84	126	0.54
G5	78	312	675	1032	84	126	0.54
G6	0	390	675	1032	84	126	0.54

Table 2: Mix design quantity for M 30 concrete at CLS ratio 2: 1

Mix ID	GGBFS (Kg/m^3)	CCA (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)	CLS/ binder
G1	390	0	675	1032	70	140	0.54
G2	312	78	675	1032	70	140	0.54
G3	234	156	675	1032	70	140	0.54
G4	156	234	675	1032	70	140	0.54
G5	78	312	675	1032	70	140	0.54
G6	0	390	675	1032	70	140	0.54

Table 3: Mix design quantity for M 30 concrete at CLS ratio 2.5: 1

Mix ID	GGBFS (Kg/m^3)	CCA (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)	CLS/ binder
G1	390	0	675	1032	60	150	0.54
G2	312	78	675	1032	60	150	0.54
G3	234	156	675	1032	60	150	0.54
G4	156	234	675	1032	60	150	0.54
G5	78	312	675	1032	60	150	0.54
G6	0	390	675	1032	60	150	0.54

Table 4: Mix design quantity for M 30 concrete at CLS ratio 3: 1

Mix ID	GGBFS (Kg/m^3)	CCA (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)	CLS/ binder
G1	390	0	675	1032	52.5	157.5	0.54
G2	312	78	675	1032	52.5	157.5	0.54
G3	234	156	675	1032	52.5	157.5	0.54
G4	156	234	675	1032	52.5	157.5	0.54
G5	78	312	675	1032	52.5	157.5	0.54
G6	0	390	675	1032	52.5	157.5	0.54

2.3 Mixing, Casting and Curing

The mixing of concrete ingredients and casting of fresh concrete were performed based on the specified procedures stipulated by the *BS* [24] (see Figure 1 b). Thereafter, the concrete specimens were removed from the moulds after 72 hours rest period (to allow full polymerization without hindrances) and cured under the ambient conditions (25-28 ºC temperature and 60-65% relative humidity) (see Figure 1c).

2.4 Experimental Tests

The slump of the fresh concrete and the compressive strength of the hardened concrete specimens were conducted in consonance with the specifications of the *BS* [25-26] respectively (see Figure 1 d).

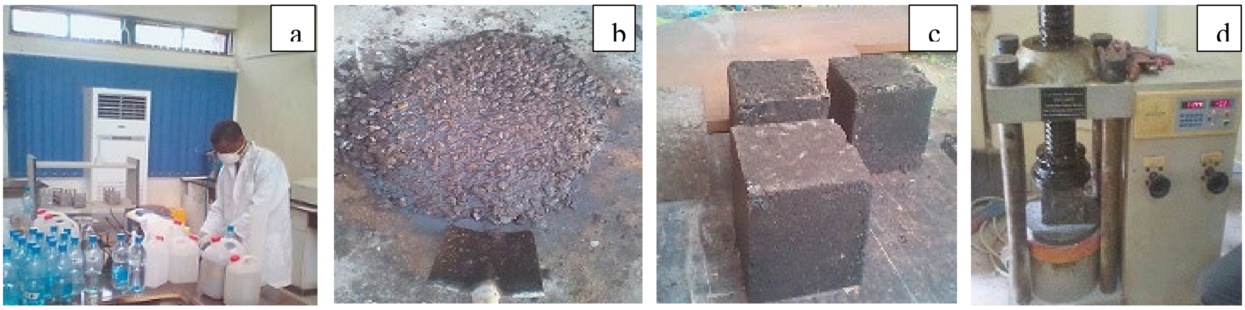

Figure 1: Production process of GPC (a) preparation of CLS (b) mixing process (c) concrete cubes under ambient curing conditions (d) strength test

3. Results and Discussions

3.1 Chemical compositions of Binders

Table 5 presents the results of the chemical compositions of the binders analyzed by the XRF. From the table, it is obviously shown that both GGBFS and CCA met the required specifications of the *American Concrete Institute* [27] and the *American Society for Testing and Materials* [28] respectively. Hence, it can be deduced that both GGBFS and the CCA used are suitable materials for the production of GPC.

Table 5: Chemical compositions of binders

Oxide Composition (%)	Binder		Standard Specification	
	GGBFS	CCA	ACI 233R for GGBFS	ASTM C 618 for CCA
CaO	36.52	18.23	32-40	-
SiO_2	35.77	59.50	32-45	$SiO_2 + Al_2O_3$
Al_2O_3	14.11	8.78	7-16	$+ Fe_2O_3 \geq$
Fe_2O_3	0.92	9.13	0.1-1.5	70%
SO_3	1.08	1.25	0.7-2.2	4% max
MgO	9.45	1.23	5-15	4% max
Na_2O	0.30	0.65	-	0.70 min
M.C	0.52	1.25	-	3% max
LOI	0.32	0.49	-	10% max

M.C is the moisture content and LOI is the loss of ignition

3.2 Slump of the fresh concrete

The result of the slump values for the fresh concrete activated at a varying ratio of CLS is illustrated in Figure 2. The result revealed that slump increased with increasing CCA content at all levels of CLS ratios. The reason for this may be attributed to the increase in internal porosity and specific surface area of CCA when compared with GGBFS [29]. It also supports the findings of *Oyebisi et al.,* in 2018 [7], [8] that the slump of fresh concrete increased with the increase in CCA quantity. Moreover, it was noticed from the result that the slump values reduced at the increase in CLS ratio up to 2.5: 1, but at 3:1, it increased again and maintained the similar trend with 2: 1. The reason may be as a result of higher NaOH solution in 1.5: 1 and 2: 1 CLS causing excessive OH^- and undesirable settings in the mix, thereby, slowing down the rate of setting time and increase the slump value [29]. However, CLS ratio of 3:1 may be ascribed to the higher viscous mix due to excessive Na_2SiO_3 gel in the mix, resulting in a slow rate of setting time and increase the workability properties of the fresh concrete [30]. Comparing the CLS ratios, there is an average increase of 18.22%, 14.74% and 9.95% in slump values of 1.5: 1, 2: 1 and 3: 1 respectively to 2.5: 1. Thus, it can be deduced that the slump values of the fresh concrete produced with M 30 design mix proportions fulfilled the *BS EN*'s specifications of 50 to 150 mm for slump as a medium to the high degree of workability [25]. And this can be used in normal reinforced concrete work without vibration and heavily reinforced sections with vibration.

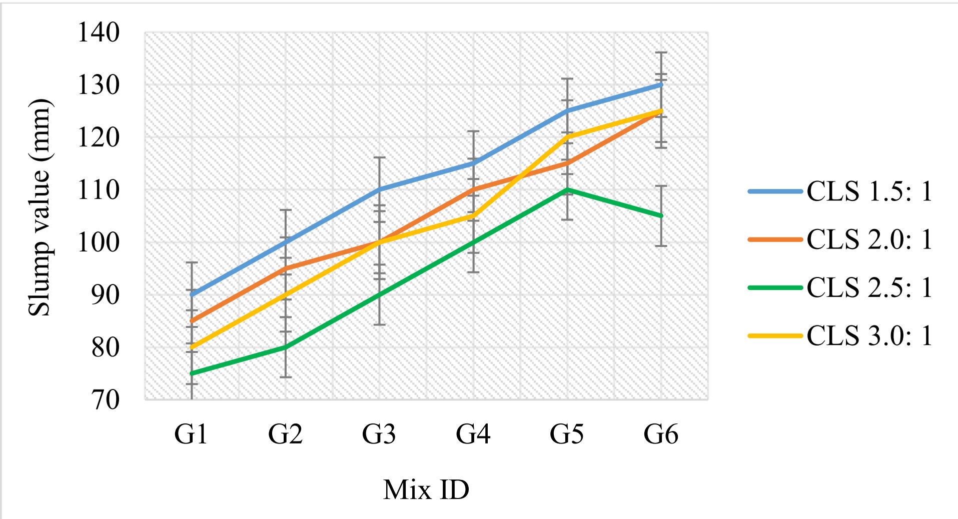

Figure 2: Slump value for the fresh concrete mix

3.3 Compressive strength of the hardened concrete

Figure 3 to Figure 6 indicate the compressive strengths of GPC at 7, 28, 56 and 90 days curing with respect to varying CLS ratio. The results show that the compressive strength of the hardened concrete increased with increasing ratio of CLS in all types of concrete and curing ages, but at CLS 3:1, the strength was compromised and attained the similar pattern of strength with that of CLS 2:1. This connotes that the strength performance of GPC does not depend on the higher ratio of CLS and that is why CLS 2.5: 1 exhibited higher compressive strength when compared with CLS 3: 1. The increase in strength from 1.5: 1 up to 2.5: 1 may be attributed to the moderation of activated potential of CLS as fortifying agent to initiate the geopolymeric reaction, improve the alkalinity and crystallinity, compress the microstructure of geopolymer matrix, reduce the void and enhance the overall strength of the GPC [30-31]. However, the compromise in strength performance of CLS 3: 1 may be as a result of the higher content of Na_2SiO_3 gel in the mix which produces higher viscous mix and results in a slow rate of setting time, creates voids in the mix and affects the overall strength performance of the hardened concrete [30]. Moreover, the results indicate that CLS 2.5:1 manifests the highest strength performance when compared with CLS 1.5: 1, CLS 2: 1 and CLS 3: 1. On the other hand, all concrete mix types met the target strength of M 30 at 28-day curing except G5 and G6 at all CLS ratios. This may be attributed to the higher content of CCA in the mix.

Economically, the cost of NaOH pellets is 5 times higher than the cost of Na_2SiO_3 gel [9]. Thus, it can be established that CLS ratio 2.5: 1 of G1, G2, G3 and G4 can be used in the structural application while G5 and G6 may be applied in non-load bearing purposes.

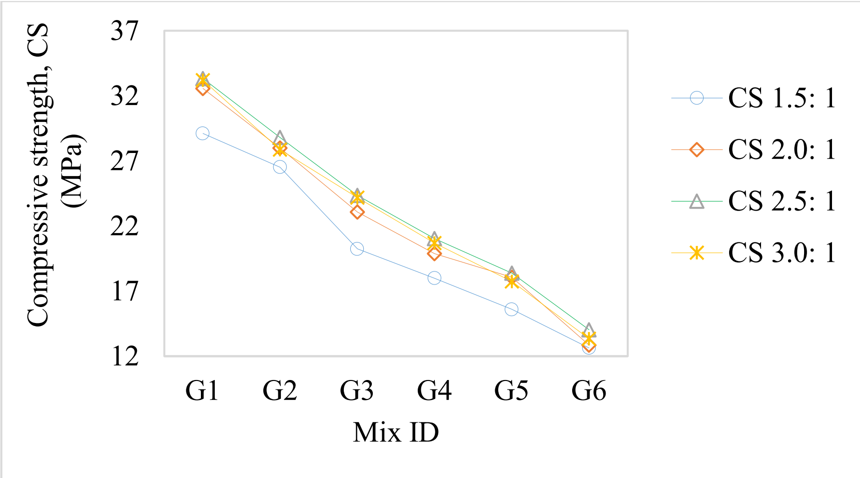

Figure 3: Chart of CS against CLS at 7-day curing

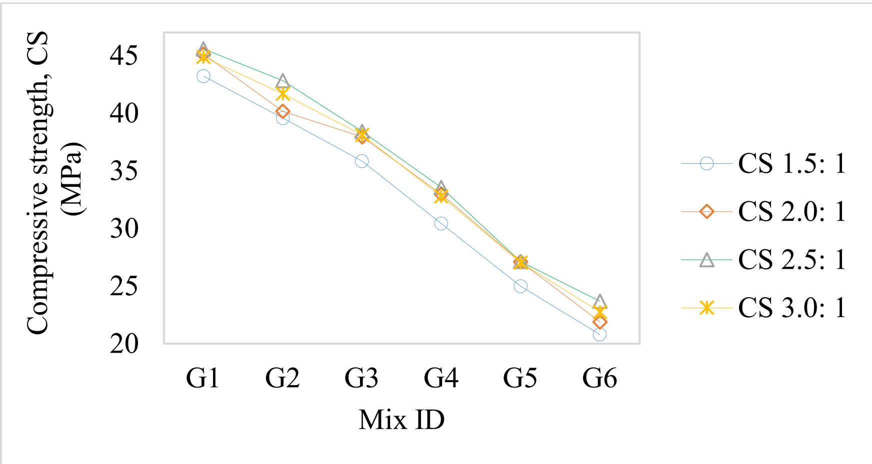

Figure 4: Chart of CS against CLS at 28-day curing

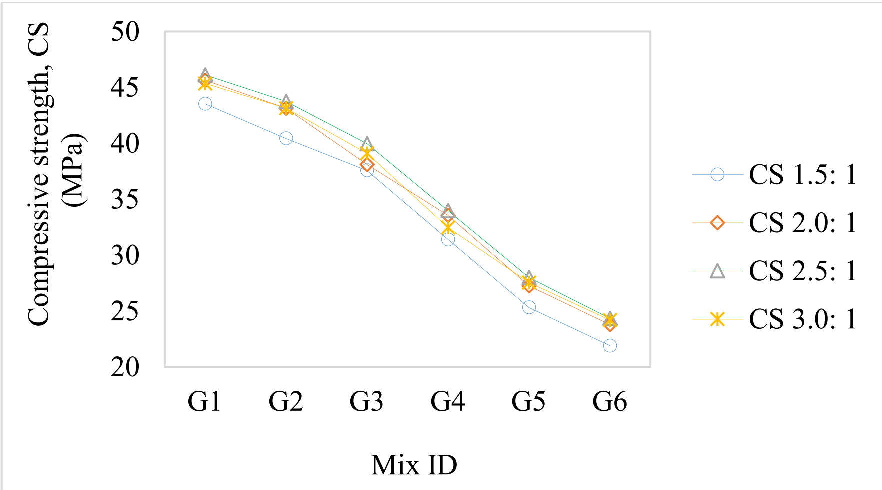

Figure 5: Chart of CS against CLS at 56-day curing

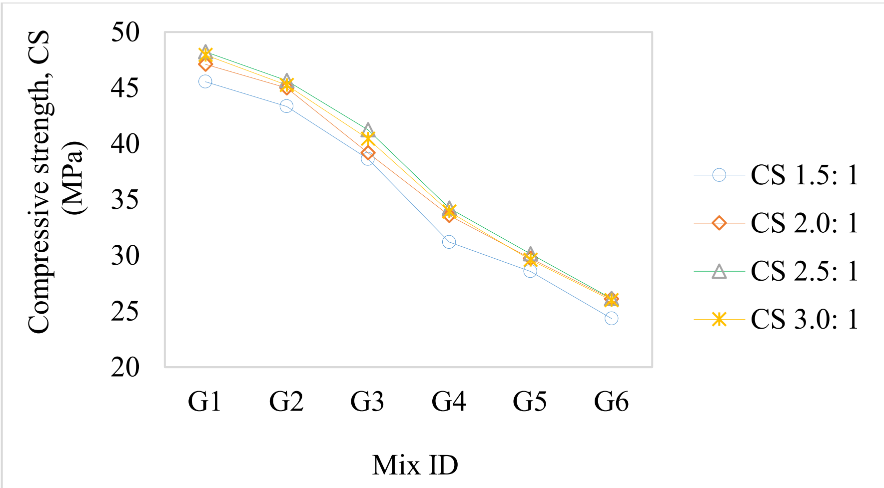

Figure 6: Chart of CS against CLS at 90-day curing

4. Conclusions

Consequent upon the findings from this study, it can be concluded that the CLS ratio influences the strength performance of GPC. The highest strength performance was exhibited at CLS 2.5: 1. And it is recommended that CLS 2.5: 1 at 40 % CCA and 60% GGBFS maximum replacement level be utilized in general construction as a structural concrete while the mix replacement level above be used in non-load bearing concrete. Thus, it is noteworthy to state that this study utilized the local contents and sustainable materials in the production of GPC by assessing the strength performance of the product at a varying ratio of CLS. It also explored the chemistry of materials for sustainability, sustainable production, and sustainable buildings and cities. The Civil and Structural Engineers should, therefore, examine the ratio of CLS before any design or construction/building is made to ascertain the best performances in terms of workability and strength.

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