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Rheology of slag-based geopolymer concrete using corncob ash as a pozzolanic material

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Abstract. This study examined the rheology of slag-based geopolymer concrete (GPC) incorporated with corncob ash (CCA). In an attempt to sustain an effective way of recycling our waste products and remedying land, water and air pollution, the study harnessed both ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) as sustainable binders. In addition, sodium hydroxide (NaOH) solution and sodium silicate gel (Na_2SiO_3) were used as alkaline liquid. Method of volume by batching was adopted where GGBFS was replaced by CCA in 0, 20, 40, 60, 80, and 100%. The paste normal consistency was used to prepare the specimens for both initial and final setting times of the fresh concrete. However, slump and compacting factor values on the freshly made concrete were determined on both grade 30 MPa and grade 40 MPa concretes using the activation of 12, 14 and 16 molar concentrations of NaOH pellets. The experimental results show that the initial and final setting times increased with increasing CCA content; while the slump, compacting factor tests also increased with increasing CCA content. On the other hand, the workability of GPC reduced with increasing grade of concrete and molarity of NaOH solution. The study finding is beneficial in that fresh concrete remains workable for longer periods, thus resulting in lesser joints. It is also advantageous especially in hot weather conditions.

Keywords: geopolymer concrete; corncob ash, ground granulated blast furnace slag; sodium silicate; sodium hydroxide

1. Introduction

Environmental preservation and sustainable infrastructure development are globally seen as a cogent step for future preservation. And in terms of sustainability, this step requires a balance in environmental, economic and societal factors; that is, it must be environmentally friendly, economical to afford and beneficial to human well-being respectively. However, it is very indispensable to seek another option to Portland limestone cement (PLC) utilization in the infrastructural development due to a large emission of carbon dioxide during its production to the atmosphere. Apart from water, PLC is termed as the most utilized construction material in the construction industry. Notwithstanding, its production significantly contributes higher carbon dioxide (CO_2) emission to the atmosphere when compared with sustainable construction binders such as GGBFS, fly ash (FA), rice husk ash (RHA), CCA, metakaolin (MK), silica fume (SF) and so on [1]. Most of these sustainable construction binders are waste products from industries and agricultural produces. In 2002, *Malhotra* estimated that the production of PLC approximately contributes 7% of the total greenhouse gas emissions to the earth's atmosphere [2]. Whereas, the production of GGBFS reduces the CO_2 emission by 70-80% and lesser energy required by 43-59% [1]. Thus, the emissions of CO_2 into the atmosphere can be significantly reduced through the application of these sustainable construction materials in the production of GPC. Geopolymer concrete is an eco-friendly and green concrete which utilizes aluminosilicate rich materials as source materials. These source materials are activated with alkaline solutions to produce a hardened product [1]. Moreover, many researchers have harnessed the utilization of both CCA and GGBFS in the production of concrete and they were established as sustainable binders [3-17].

The rheology of a geopolymer mixture typically differs from that of Portland limestone cement mixture. Conventionally, both the slump value of fresh geopolymer concrete and flow value of fresh geopolymer mortar do not coincide with the same value of Portland limestone cement mixtures in terms of workability [18]. Previous researches [19-21] revealed that rheology provides sufficient indications of the workability or flowability of geopolymer mixture. Moreover, it was established that the workability or flowability of geopolymer mixtures depend on different parameters used for the production of the mixture. In 2014, Nath and Sarker [18] examined the rheology of FA based-GPC incorporated with GGBFS, activated with sodium silicate gel and sodium hydroxide solution and cured at ambient condition. The findings showed that slump and flow values, initial setting time (IST) and final setting time (FST) reduced with increasing GGBFS's content [18]. In 2016, *Dave, Misra, Srivastava, and Kaushik* harnessed the supplementary cementitious materials (SCMs) such as FA, SF, GGBFS, MK and lime powder (LP) blended with OPC at a replacement level of 30% and 50% to produce quaternary cement binders and mortars. Based on the findings, it was noticed that the consistency of the paste and the setting times increased with increasing FA, SF, MK and LP's contents; while the consistency of the paste and the setting times reduced with increasing GGBFS's content [22]. Superplasticizer or extra water is normally added to the fresh mix to enhance its workability; however, the mechanical properties of the mix can be negatively affected at later ages [18].

Hence, this study offers an understanding of the workability or flowability of GPC applicable for curing at ambient condition. GGBFS and CCA were both harnessed as sustainable binders while the mixture of sodium silicate gel and sodium hydroxide solution were used as an alkaline liquid at 12, 14 and 16 molar concentrations of sodium hydroxide pellets. Moreover, slump test, compacting factor test, consistency and setting times were conducted while the compressive strength was performed on the hardened product of GPC. In the course of preparing, mixing and casting of concrete materials, no chemical admixture or extra water was added.

2. Materials and Methods

2.1. Materials

Grade 42.5 R Dangote 3X PLC was obtained and utilized to fulfil the requirements of the *Nigerian Industrial Standard* [23]. The PLC was used to serve as a control mix. The aggregates, fine aggregate (FA) and coarse aggregate (CA) used were sourced from Ota, Nigeria. They were used in accordance with the procedure stated in the American Standards for Testing and Materials (ASTM) [24].

Corncobs were obtained from Agbonle, Nigeria. They were dried under the sun for 5 days to enhance the burning process. Afterwards, they were burnt to ash to obtain corncob ash (CCA) under controlled temperature (600 ^{0}C) on a pilot scale gas furnace to lower the emission of carbon dioxide 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 [7-8]. Moreover, their oxides compositions were obtained based on the previous studies [7-8].

Water for the mixing and production process was obtained from the Covenant University laboratory, Ota, Nigeria, and conformed to the *British Standard* [25]. Finally, 99% purity of NaOH pellets and gel of Na_2SiO_3 were both used as activating liquid and obtained from Lagos, Nigeria.

2.2 Mix Design of Concrete Proportion

The concrete mix proportion was designed in conformity with the *British Standard (BS)* [26]. Moreover, the constituents' properties, moisture contents, water absorptions and specific gravities were obtained and put into consideration during the mix design. The design proportions are Portland cement concrete (control), 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 identified as C 0, C 1, C 2, C 3, C 4, C 5 and C 6 respectively. The results of the mix proportions for grade 30 MPa concrete (M 30) and grade 40 MPa concrete (M 40) are shown in Table 1 and Table 2 respectively.

Table 1. Mix design quantity for M 30 concrete

Mix ID	PLC (Kg/m^3)	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)	Liquid/ binder
C0	390	0	0	675	1032	0	0	0.54
C1	0	390	0	675	1032	60	150	0.54
C2	0	312	78	675	1032	60	150	0.54
C3	0	234	156	675	1032	60	150	0.54
C4	0	156	234	675	1032	60	150	0.54
C5	0	78	312	675	1032	60	150	0.54
C6	0	0	390	675	1032	60	150	0.54

Table 2. Mix design quantity for M 40 concrete

Mix ID	PLC (Kg/m^3)	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)	Liquid/ binder
C0	500	0	0	585	1032	0	0	0.42
C1	0	500	0	585	1032	60	150	0.42
C2	0	400	100	585	1032	60	150	0.42
C3	0	300	200	585	1032	60	150	0.42
C4	0	200	300	585	1032	60	150	0.42
C5	0	100	400	585	1032	60	150	0.42
C6	0	0	500	585	1032	60	150	0.42

2.3 Preparation of Alkaline Activators

The alkaline activators were prepared in consonant with the previous studies [7-8] and in conformity with the chemistry laboratory procedure [27]. The solutions were prepared 1440 minutes to concrete mixing to reduce the heat generated during the mixing process. Afterwards, the solution was added to sodium silicate gel 120 minutes prior to the casting of fresh concrete to buffer its performance for best result.

2.4 Mixing, Casting, Sample Preparation and Curing

The appropriate quantity of NaOH solution and Na_2SiO_3 gel were mixed together 45 minutes preceding the casting of the fresh concrete to improve the solutions' reactivity. The manual mixing was engaged for the concrete constituents. The paste was prepared for normal consistency (see Figure 1) and this was used to prepare the slump, compacting factor and the setting times of the concrete using the Vicat apparatus (see Figure 1). Thereafter, the aggregates prepared in SSD condition and the binders (PLC, GGBFS and CCA) were thoroughly mixed in a dry state for about 5 minutes. The premixed activating liquid was then added in a gradual manner and continued mixing for additional 8-10 minutes to attain the mixing homogeneity. The fresh concrete was then filled into the 150mm standard cubical concrete moulds in three layers and compacted on a hard level surface. Then, the concrete cubes were removed from the moulds after 72 hours rest period and cured under the ambient conditions (25-28 °C temperature and 60% ± 5% relative humidity) while the PCC samples were removed after a day casting and submerged in the water curing tank till the testing day, 28 days. Two specimens were made per each mix for test.

Figure 1. The workability tests (a) paste (b) setting time (c) fresh concrete mix (d) slump

2.5 Experimental Tests

The consistency, setting times, slump and compacting factor of the fresh concrete samples were conducted in conformity with the procedures stipulated by the *BS* [28-30] while the compressive strength of the hardened concrete samples was carried out in consonant with the requirements of the *BS* [31].

3. Result and Discussions

3.1 Oxides compositions of CCA and GGBFS

The oxide compositions of both CCA and GGBFS are indicated in Table 3 and Table 4 respectively. And it is obviously shown from the Tables that both CCA and GGBFS satisfied the requirements stipulated by the *ASTM* [32] and the *American Concrete Institute* [33] respectively. Therefore, it can be inferred that both CCA and GGBFS used are suitable materials in the production of GPC.

Table 3. Oxide compositions of the CCA used

Composition	SO_3	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	M.C	LOI
Properties (%)	1.25	60.50	8.78	9.13	12.62	1.23	0.65	1.25	0.49
ASTM C 618 Requirements	≤ 4%		SiO_2+Al_2O_3+ Fe_2O_3 > 70%		-	≤ 4%	> 0.70	≤ 3%	≤10%

Table 4. Oxide compositions of the GGBFS used

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	M.C	LOI
Properties (%)	36.52	35.77	14.11	0.92	1.08	9.45	0.30	0.52	0.32
ACI 233R Requirements	32-45	32-42	7-16	0.1-1.5	0.7-2.2	5-15	-	-	-

3.2 Consistency, Initial Setting Time (IST) and Final Setting Time (FST) of Fresh Concrete

Figure 2 presents the consistency and setting times of the fresh pastes for both geopolymer pastes and the Portland limestone cement (PLC) paste.

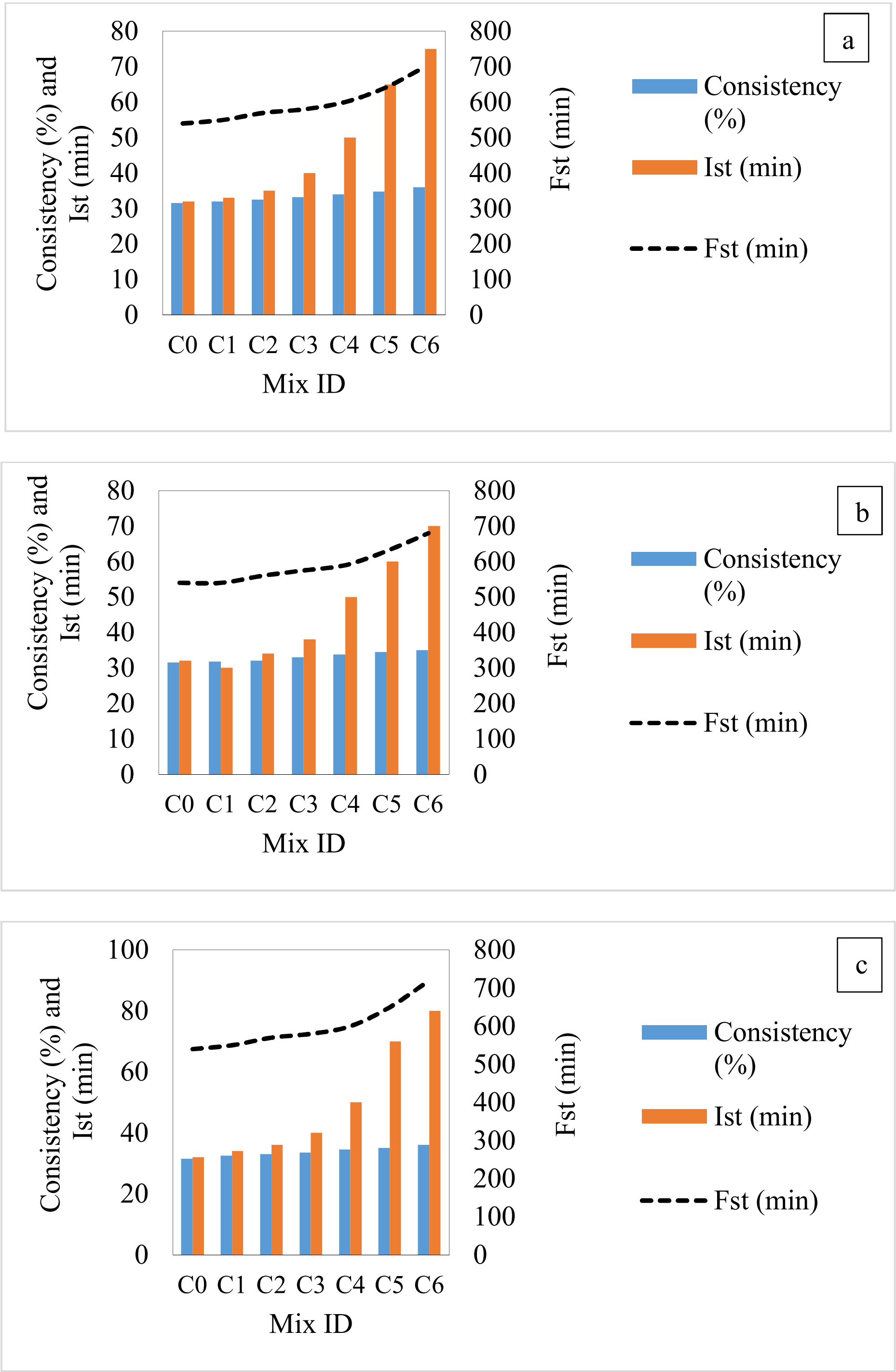
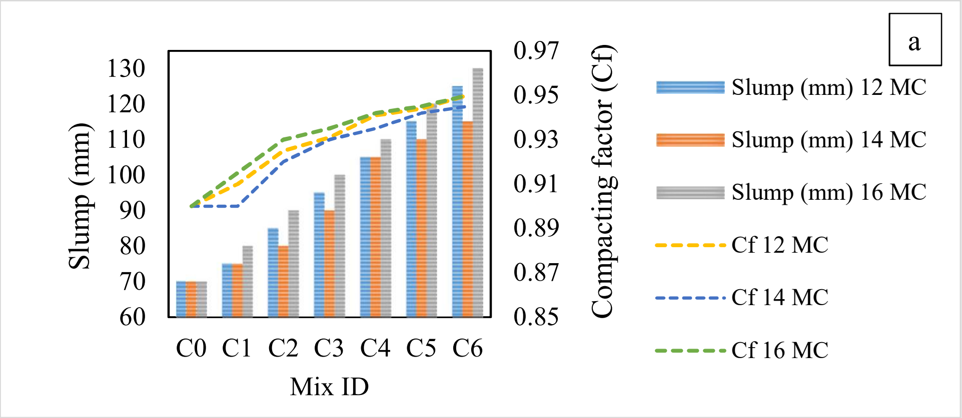


Figure 2. Consistency and setting times of fresh concrete (a) 12 molar concentration (b) 14 molar concentration (c) 16 molar concentration

The workability properties showed in Figure 2 reveal that the consistency and setting times of the fresh paste increased with increasing CCA content in all molar concentrations and geopolymer pastes used in this study. The reason for this increase may be ascribed to the increase in mobility of the spherical shape of CCA particles, in contrast to the irregular shape of GGBFS particles [18]. In addition, unlike GGBFS, the increase in CCA content reduces the intensity of calcium counts in the geopolymer paste; this obstructs polymerization, promotes an increase in consistency and setting times and slows down the corresponding strength performance of the product at the later age [16] [21]. Furthermore, it is also observed from the results that as the molar concentration of NaOH solution increase from 12 to 14, the corresponding consistencies and setting times reduced; however, the consistency and setting times for 16 molar concentration of sodium hydroxide pellets slightly increases when compared with 12 and 14 molar concentrations. The reduction in consistency and set times as a result of the increase in molar concentration of sodium hydroxide solution from 12 to 14 can be imputed to the increase in the quantity of sodium hydroxide pellets used to the reduction in the quantity of clean water used in preparing the solutions in that lesser water was used. And this supports the assertions of *Nath and Sarker* in 2014 and *Hardjito, Wallah, Sumajouw, and Rangan* in 2004 that the higher the water content in the geopolymer mix, the higher the workability and this in turns, influence the mechanical properties of the product at later ages [16] [18]. On the other hand, the increase in consistency and setting times witnessed in 16 molar concentration of sodium hydroxide pellets may be credited to the development of efflorescence due to the excess alkali solution in the paste which hinders the condensation action for polymerization and caused an increase in workability [18] [21]. To this point, it can be established from Figure 2 that C0 (control), C1, C2, C3 and C4 pastes satisfied the *BS EN* 's specifications for 45 minutes minimum IST and a maximum of 600 minutes FST [28]. However, C5 and C6 were out of range. In comparison, the C0 (control), C1 and C2 almost indicate a similar trend in consistency and setting times.

3.3 Slump and Compacting Factor

The results of the slump and compacting factor tests for both M 30 and M 40 at various molar concentrations (MC) and different mixes are illustrated in Figure 3 below.



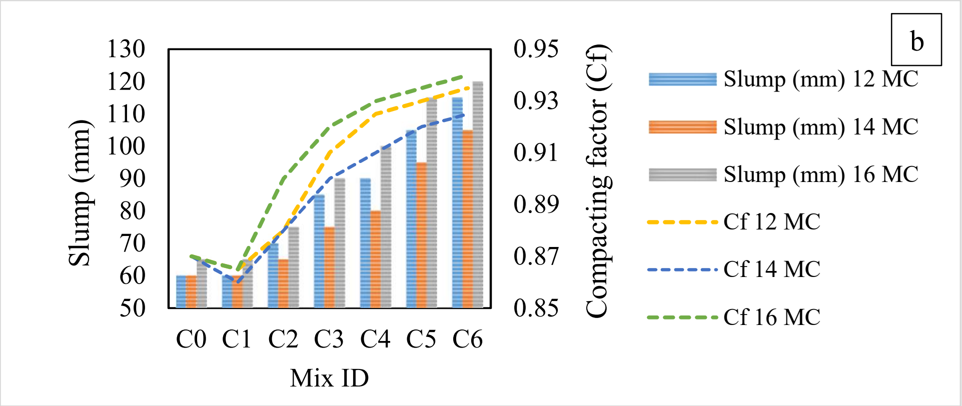


Figure 3. Slump and compacting factor tests (a) M 30 (b) M 40

It can be seen from Figure 3 that the incorporation of CCA content influences the workability properties, slump and compacting factor of the fresh geopolymer concrete. It is observed that both slump and compacting factor of the freshly made geopolymer concrete increased with increasing CCA content in all molar concentrations and concrete grades. The reason may be ascribed to the internal voids and specific surface area of CCA particles being higher than GGBFS particles ; this slows the rate of setting times and thus, increases the slump value [18]. Contrary to 16 molar centration of NaOH pellets, it is also noticed from the results that as the molarity of sodium hydroxide solution increased slump and compacting factor values decreased due to a reduction in water content. This corroborates the findings from previous studies [16] [18]. Moreover, the results also revealed that the slump and compacting factor values reduced with increasing grade of concrete. This is in consonant with *Nath and Sarker* in 2014 that the workability of fresh GPC reduces with increase in the grade of concrete due to the reduction in the ratio of water (alkaline liquid) to binders [18]. Furthermore, as the slump of the fresh concrete increases, the compacting factor also increases. This indicates the existence of a linear relationship between the slump of fresh concrete and its compacting factor. Therefore, it can be inferred that both slump and compacting factor values of the fresh concrete produced with M 30 and M 40 design mix proportions satisfied the *BS EN*'s requirements of 50 to 150 mm for slump and 0.700 to 0.950 for compacting factor as a medium to the high degree of workability [29-30]. And this can be applied in normal reinforced concrete work without vibration and heavily reinforced sections with vibration.

3.4 Development of Compressive Strength

Figure 4 displays the development of compressive strengths of the hardened concrete at 28 days curing correlating with the slump values and final setting times of 14 molar concentrations of sodium hydroxide pellets for both M 30 and M 40.

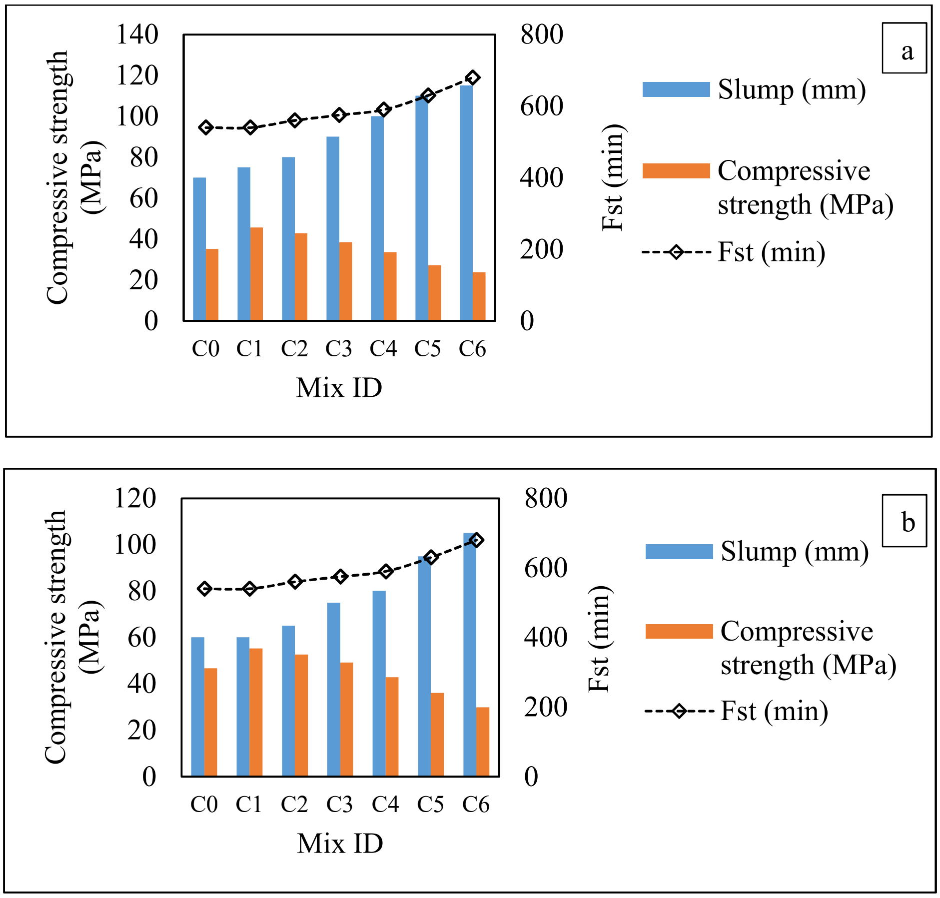


Figure 4. Correlation of setting time of paste, slump value of fresh concrete and 28-day compressive strength of 14 molar concentration of NaOH pellets (a) M 30 (b) M 40

It is obvious from Fig.4 that workability properties of freshly made concrete influence the final result of mechanical properties of the hardened product at a later age. It is noteworthy to point out that extra water or chemical admixture was not added to the mix. Therefore, the results from Figure 4 buttress the effect of consistency and setting times of the paste, slump and compacting factor of the fresh concrete on the strength performance of hardened concrete and it is clearly noticed that the more the setting times, slump and compacting factor values, the lesser the compressive strength of the hardened product. Moreover, it is shown from Figure 4 that the compressive strength of the GPC reduces with increasing CCA content due to a lesser rate of silicate or aluminate reactivity in the interface of the concrete to enhance aluminosilicate bonds [18]. However, C4, C5, and C6 manifest lower strength when compared with the PCC (control), C1, C2 and C3. This may be attributed to higher workability properties and low reactivity of calcium-bearing compound available in the geoplymeric gel of the mixture [18].

4. Conclusions

Consequent upon the findings established from this study, it can be concluded that the incorporation of CCA content as a pozzolan in the slag-based GPC increases the rheology of the fresh concrete. Also, a 40 % optimum replacement level of GGBFS by CCA in the GPC mix exhibits a similar trend of rheology with the fresh property of the C0 (control) mix. However, consistency and setting times of the paste, and slump and compacting factor of the fresh concrete reduced with increase in the grade of concrete. It can be affirmed that both GGBFS and CCA has proved to be emerging sustainable binders in place of PLC. Thus, the study finding is beneficial in that fresh concrete can be handled for a longer period without any form of stiffness, thus resulting in lesser construction joints. It is also advantageous especially in hot weather conditions and can be applied in normal reinforced concrete work without vibration and heavily reinforced sections with vibration at ambient conditions.

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