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Strength Prediction of GPC using Alkali pH, Salinity, Temperature, and Conductivity as Continuous Predictors

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Abstract

This study explored the chemistry of alkaline activators, and their physical properties were used to predict the compressive strength of geopolymer concrete (GPC). Sodium silicate (Na_2SiO_3) gel and six various pellets of sodium hydroxide (NaOH) were used as the alkaline activators. Ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) were utilized as supplementary cementitious materials (SCMs) in the production of GPC. A mix design proportion of Grade 30 MPa concrete and 14 M of alkaline activator (AA) was adopted. The concrete constituents were prepared, cured, and tested at 7, 28, 56, and 90 days. The relationship between the compressive strengths and the pH, temperature, salinity, and conductivity of alkaline activator was modelled. The experimental findings indicated that the temperature, conductivity and salinity of the alkali increased with increasing pH. Besides, the compressive strength of GPC increased with increasing alkali's pH, temperature, conductivity, and salinity. The coefficients of determinations (R^2) showed that the models were 84, 90, 90, and 89% fit to predict the relationship at 7, 28, 56, and 90 days curing, respectively. These findings can be used to predict the strength trends of GPC incorporating SCMs.

Keywords: Geopolymer concrete, supplementary cementitious materials, temperature, conductivity, salinity, compressive strength, modelling.

1. Introduction

Geopolymer concrete represents an emerging product with paramount significance in the construction sector, especially in this clarion call for a sustainable consumption and production pattern [1, 2]. Unlike Portland cement (PC), most geopolymer processes depend on minimally processed agro-industrial byproducts. These agro-industrial byproducts such as GGBFS, CCA, fly ash, metakaolin, silica fume, and rice husk ash, have been reported to be cementitious and pozzolanic [3-5], and can be activated with alkaline solutions, NaOH solution and Na_2SiO_3 gel, thus producing the hardened product [6-9].

The pH level of cement is attributed to the presence of Portlandite ($Ca(OH)_2$) and when added to the concrete mix, Portlandite is utilized while the hydrating product, C-S-H is formed; this resulted in the concrete's pH to decrease after setting. In the geopolymer mix, polymerization involves a process of the chemical reaction between the binders (aluminosilicate minerals) and the activators [10]. The polymerization products (calcium-silicate-aluminate-hydrate) paste remains stable between the pH values of 11 and 13 [10]. Also, this solution protects the steel reinforcement from being rust due to the formation of a thin oxide layer. Moreover, a reduction in the pH level may break the layers as a result of carbon dioxide and sulfide decomposition from the atmosphere, and this worsens the condition because chloride ions will be penetrated from the surrounding [10]. Alkali's pH plays a vital function when examining the development of setting and hardening mechanisms of concrete [11]. It is a vital parameter in the chemistry of concrete. *Grubb et al.* [12] stated that pH measures the basicity/alkalinity or the acidity of a solution. The pH has a scale value ranging from 0-14. A neutral content has a value of pH as 7, while the acidic solution has a value of pH < 7. The basic solution has a value of pH > 7. Typically, concrete starts its life at a highly alkaline pH of around 13. *Charles* [13] established that H^+ ions and OH^- ions are present in any solution, and the presence of both H^+ ions and OH^- ions in the solutions are termed acidic and basic solutions, respectively. Furthermore, the reaction between the acidic solution and water moves the equilibrium to the left at a decreasing rate of OH^- ions. In contrast, the basic solution with water resulted in the movement of equilibrium to the left at a decreasing rate of H^+ ions [13]. Geopolymerization mechanism and factors influencing the evolution of GPC were also investigated by *Khale and Chaudhary* [14]. It was found that the higher alkali pH improves the strength performance of GPC such that a pH value of 14 exhibited strength five times higher than the pH value of 12. Thus, it was concluded that the most preferable and suitable pH for the best reactive polymerization of GPC fresh mix with higher strengths ranged from 13-14 [14].

Conductivity is a quality parameter of alkaline activator, which measures the capacity of alkali to pass electrical flow. On the other hand, salinity is the total concentration of all dissolved salts of alkaline liquid and contributes to the conductivity of a solution [13]. *Rusydi* [15] reported that alkali conductivity increases with increasing pH temperature. Moreover, conductivity increases with increasing alkali salinity [15]; this, according to *Rusydi* [15], influences the solution concentrations and the mobility of their charged particles. Thus, research on conductivity and salinity of alkali is still limited in the area of GPC production, and this is responsible for limited literature. Although, many researchers [16-18] have established a minimal increase in strength of Portland cement concrete (PCC) when the sea (salt) water is used as mixing water against the normal (fresh) water.

Many parameters, such as reactivity, lime, hydraulic, silica, and lime moduli of GGBFS and CCA, have been applied in the strength prediction of GPC. However, the application of alkali's properties, pH, temperature, salinity, and conductivity is still limited. Therefore, this study filled a research gap by determining the alkali's properties and applying the results to predict the compressive strength of GPC produced under ambient curing conditions. In achieving these objectives, M 30 was selected as a mix design proportion because of its widespread uses in the construction sector. Besides, six (6) different types of NaOH pellets were used and mixed with Na_2SiO_3 gel to examine the variability of the alkali's properties.

2. Materials and Methods

2.1 Materials

The supplementary cementitious materials, GGBFS and corncob, were obtained locally. Corncob was dehydroxylated at 600 °C for 3 h under a closed condition to obtain CCA. The specific gravity (SG) and fineness of GGBFS and CCA were obtained following the procedure stated in *British Standard, BS EN* 196-3 [19]. The results showed the SG of 2.90 and 2.44 g/cm^3, and fineness of 7.3 and 7.4% for GGBFS and CCA, respectively. The results of XRF analysis for both GGBFS and CCA are presented in Table 1.

Table 1: The oxide compositions of GGBFS and CCA

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	LOI
GGBFS (%)	36.52	35.77	14.11	0.92	1.08	9.45	0.30	0.32
CCA (%)	12.62	60.50	8.78	9.13	1.25	1.23	0.65	0.49

LOI denotes loss of ignition at 800 ^{0}C

Sharp sand and granite were used as both fine and coarse aggregates, and obtained from an aggregate dealer in Ota, Nigeria. The physical properties were determined based on the procedure outlined in *BS EN* 12620 [20]. The results indicated 2.60 and 2.64 g/cm^3 as specific gravity, 0.7 and 0.8 % as water absorption, and 0.3 and 0.2% as moisture content for FA and CA, respectively.

The alkaline activators, NaOH pellets and Na_2SiO_3 gel were obtained from Dan Obi Chemical dealer, Lagos, Nigeria. Following the technical specifications, the average purity and specific gravity of NaOH pellets obtained were about 99% and 1.50 g/cm^3, respectively. Also, Na_2SiO_3 gel possessed SiO_2/Na_2O weight ratio of 3.20, the specific gravity of 1.40 g/cm^3 at 20 ^{o}C, and Na_2O, SiO_2, and H_2O contents of 9.4, 30.1, and 60.5%, respectively. The water used for mixing the NaOH pellets was clean and fit for drinking.

2.2 Experimental methods and tests

A 1 kg of NaOH pellets was measured and added to 1.5 litres of clean water to obtain 14 M per cubic metre following the procedure established by *Rajamane and Jeyalakshmi* [21]. A 14 M activator was adopted because it exhibited the highest mechanical strengths compared with 12 M and 16 M activators [9]. Afterwards, a 6.25 kg of Na_2SiO_3 gel was measured and added to the premixed NaOH solution to obtain the Na_2SiO_3 to NaOH ratio of 2.5:1 after 24 hours of preparing NaOH solution. A 2.5:1 was selected because it yielded the highest mechanical strengths compared with 1.5:1, 2:1, and 3:1 [8]. A HANNA pH, model 211 microprocessor, as shown in Figure 1, was used to determine the alkali pH and temperature. In contrast, the JENWAY conductivity metre, model 4510, as shown in Figure 2, was used to measure the alkali conductivity and salinity. The average temperature and relative humidity (RH) during the test were 28 ^{o}C and 65% RH, respectively. The mix was designed in consonance with the procedure stated in BS EN [22]. The mix proportion is presented in Table 2. For the mix, the quantities of FA, CA, Na_2SiO_3, and NaOH were 675, 1032, 150, and 60 kg/m^3, respectively, hence indicating the alkaline liquid to binder ratio as 0.54. The mix constituents were prepared based on the procedure stated in *BS EN* 12390-2 [23]. The concrete samples were tested at 7, 28, 56 and 90 days. Both slump and compressive strength were determined in accordance with *BS EN* 12350-2 [24] and *BS EN* 12390-4 [25], respectively.

Table 2: Mix design quantity for M 30

Mixture ID	GGBFS (kg/m^3)	CCA (kg/m^3)
R1	390	0
R2	312	78
R3	234	156
R4	156	234
R5	78	312
R6	0	390

Figure 1: HANNA pH metre

Figure 1: JENWAY 4510 conductivity metre

3. Results and Discussion

3.1 Chemical compositions of Binders

The oxide compositions, as indicated in Table 1, revealed that the GGBFS satisfied 67% minimum specification of *BS EN* [26] for SiO_2 + CaO + MgO, and 3% maximum specification for LOI. Also, CCA met 70% minimum requirements of *BS EN* [27] for SiO_2 + Al_2O_3 + Fe_2O_3, and 5% maximum specification for LOI. Therefore, the materials are desirable for use as SCMs.

3.2 pH, temperature, conductivity, and salinity of alkaline activators

The properties of alkaline activators based on each and combined components are presented in Tables 3 and 4, respectively. The combined part was the alkaline activator used for the GPC production.

Table 3: Each element of alkali properties

Sample	Component	pH	Temp. (^{0}C)	Conductivity (mS)	Salinity (g/l)
1	NaOH pellets 1 + Water	13.55	35.75	39.50	19.75
2	NaOH pellets 2 + Water	13.27	35.22	38.78	19.30
3	NaOH pellets 3 + Water	13.08	34.78	37.25	18.76
4	NaOH pellets 4 + Water	12.85	34.70	36.74	17.93
5	NaOH pellets 5 + Water	12.63	34.25	35.96	17.45
6	NaOH pellets 6 + Water	12.55	33.64	35.27	16.95
	Na_2SiO_3 gel	12.65	25.15	28.71	13.62
	Water	6.95	23.22	0.056	0.030

Table 4: Combined component of alkali properties

Mix ID	Alkaline activator	pH	Temp. (°C)	Conductivity (mS)	Salinity (g/l)
AA1	NaOH pellets 1 + Water + Na_2SiO_3 gel	13.98	28.43	3.89	2.12
AA2	NaOH pellets 2 + Water + Na_2SiO_3 gel	13.75	27.85	3.67	1.85
AA3	NaOH pellets 3 + Water + Na_2SiO_3 gel	13.44	27.65	3.39	1.54
AA4	NaOH pellets 4 + Water + Na_2SiO_3 gel	13.16	26.80	2.85	1.39
AA5	NaOH pellets 5 + Water + Na_2SiO_3 gel	12.98	26.47	2.68	1.12
AA6	NaOH pellets 6 + Water + Na_2SiO_3 gel	12.80	26.21	2.30	1.05

The results from Table 3 indicated that sample 1 exhibited an increase in pH by 2, 4, 5, 7, and 7% compared with Samples 2, 3, 4, 5, and 6, respectively. In the same vein, a higher temperature, conductivity and salinity was noticed for Sample 1 compared with Samples 2, 3, 4, 5, and 6. The increase in pH could be associated with the increase in OH- ions and decrease in H+ ions of NaOH solution as the water equilibrium moves to the left [13]. The higher temperature indicated that an exothermic reaction was evolved [13]. Thus, these results were consistent with the findings of *Rusydi* [15] that the temperature, conductivity and salinity of a solution increased with increasing pH. Moreover, the Na_2SiO_3 gel has a pH value of 12.65; this agrees with the *Concrete Institute of Australia* [28], which specifies that commercial Na_2SiO_3 gels have a pH value in the range of 10-13. On the other hand, it was generally noticed from the combined mixture in Table 4 that the alkali pH was increased by 3, 4, 3, 2, 3, and 2% for AA1, AA2, AA3, AA4, AA5, and AA6, respectively, when Na_2SiO_3 gel was added to the premixed NaOH solution. This result aligns with *Charles* [13] in that pH increases from its natural state when an alkaline solution with a pH greater than 9 is added to it. However, it was observed that the temperature, conductivity and salinity of the premixed NaOH solution were decreased immediately Na_2SiO_3 gel was added to it because of lower pH, temperature, conductivity, and salinity of Na_2SiO_3 gel, hence reducing the high temperature generated by the NaOH solution.

3.3 Slump of the fresh concrete

The fresh concrete slump, as shown in Figure 4, decreased as the pH, temperature, conductivity, and salinity of the alkaline activator increased. This may be attributed to the higher pH which in turn raised the temperature, conductivity and salinity of the solution, quicken the setting mechanism of the geopolymer paste, released monomers of higher reaction, thus reducing the flow of the fresh concrete [10, 11, 14]. In the same vein, it was observed that the slump decreased with increasing GGBFS content in the mix. The reason may be as a result of glassy material of GGBFS, which is generally more reactive than the CCA [10]. Thus, it can be established that the slump of a fresh GPC reduced with increasing pH, conductivity and salinity of the alkaline activator.

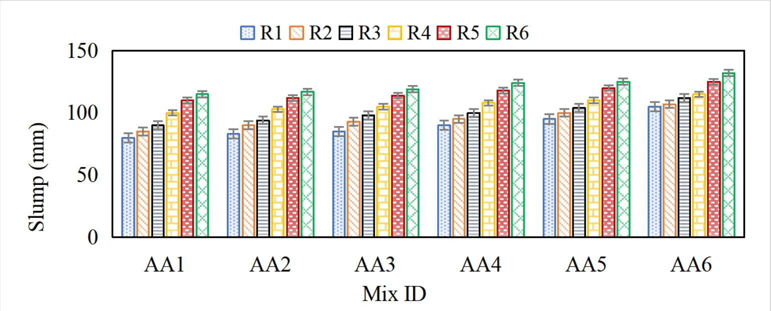

Figure 2: The slump of fresh GPC at various types of alkaline activators

3.4 Compressive strength

The compressive strength (fc) results, as shown in Figure 5 (a)-(d) for 7, 28, 56, and 90 days, respectively, showed that the fc decreased with decreasing alkali pH, temperature, conductivity and salinity. The results further revealed that Mix AA1 exhibited the highest fc compared with AA2, AA3, AA4, AA5, and AA6 at the same levels of curing conditions. This shows that higher pH, temperature, conductivity and salinity of alkaline activator, is required for geopolymer formation with higher strength, and this is agreeable to *Khale and Chaudhary* [14] that pH values in the of range 13-14 are suitable for the polymeric development with higher mechanical strengths. Also, the fc of GPC increased with increasing GGBFS content and curing ages. This supports the findings reported by Davidovits [10] in that x-ray amorphous aluminosilicate gel (XRAAG) is formed when the glassy phase of GGBFS content reacts with alkaline liquid. The XRAAG is responsible for the higher mechanical properties of hardened GPC [10]. It can be established that the alkali properties and the composition of binding agents affect the mechanical performance of the hardened GPC. Therefore, these findings would be advantageous in the strength prediction and appropriate mix design of GPC by saving cost and time for conducting experimental laboratory work provided the alkali's properties are tested before using as activating agents.

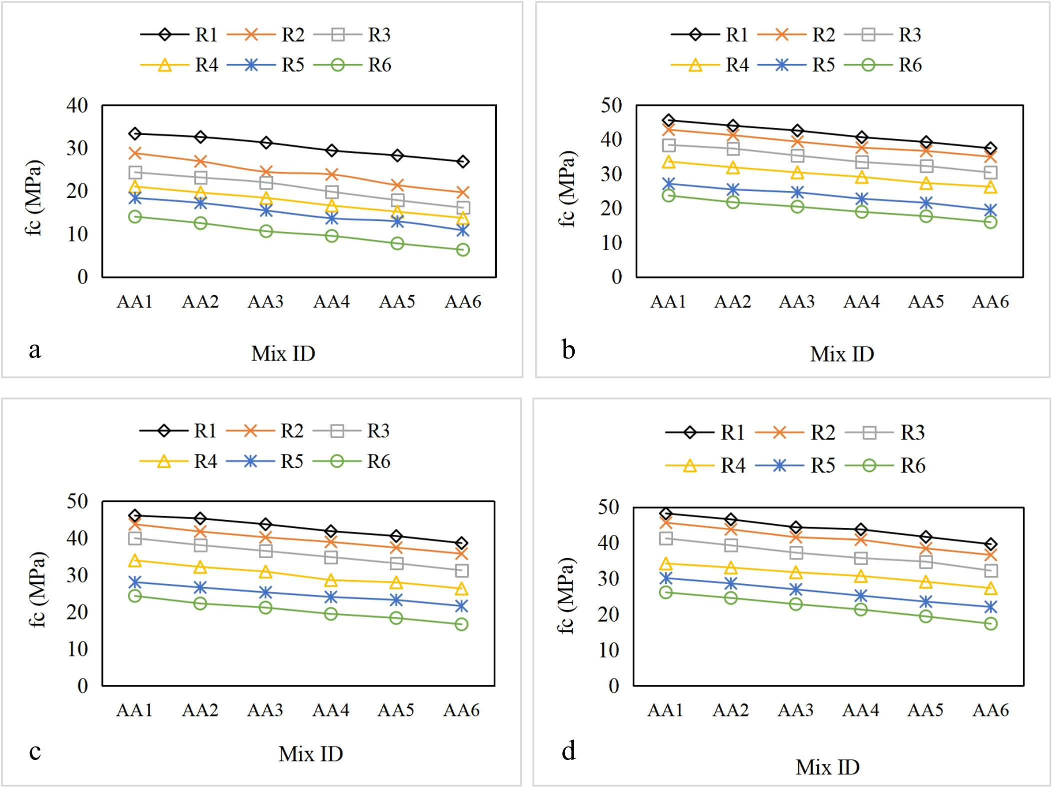

Figure 3: Compressive strengths at (a) 7, (b) 28, (c) 56, and (d) 90 days curing

3.5 Regression analysis

For this regression analysis, the results of alkali's properties, pH, temperature, conductivity and salinity were used as the continuous predictors to predict the response variable, compressive strength using the fit regression model of Minitab 17 statistical software. The regression models revealed that the coefficients of determinations (R^2) were 84, 90, 90, and 89% fit to predict the relationship between the alkali's pH, temperature, conductivity, and salinity and the fc of GPC at 7, 28, 56 and 90 days curing, respectively. Besides, the analysis of variance (ANOVA) for the regression models indicated P-value of 0.00 for all curing days, hence indicating that at least one of the regression coefficients is significantly different than zero because P-value (0.00) was lower than 0.05 level of significance (α). The regression model equations are illustrated in Equations (1)-(4) for 7, 28, 56 and 90 days curing, respectively. On the other hand, the difference between the observed fc and fitted fc was analyzed, and the normal probability plots are illustrated in Figure 6 (a)-(d) for 7, 28, 56, and 90 days curing. The results, as shown in Figure 7 (a)-(d), followed a straight-line pattern, thus indicating normality or identified variables in the analysis [29]. Moreover, Figure 7 (a)-(d) show the difference between the observation orders and the fitted fc for 7, 28, 56, and 90 days curing. The results, as shown in Figure 7 (a)-(d), revealed that the fc data were randomly scattered around the centre line (about zero), hence indicating that no evidence exists that the error terms are correlated with one another. Therefore, the findings obtained herein can be used to predict future data trends and enhance data quality on the compressive strength of GPC.

$$f_c = -4 + 0.60p^H - 0.56t + 4.50\mu + 10.80\lambda \qquad (1)$$

$$f_c = 867 - 67.10p^H - 4.80t + 37.10\mu + 49.60\lambda \qquad (2)$$

$$f_c = 655 - 51.40p^H - 3.45t + 32.10\mu + 37.20\lambda \qquad (3)$$

$$f_c = 525 - 40.40p^H - 3.13t + 27.60\mu + 31.00\lambda \qquad (4)$$

where *fc is the compressive strength (MPa); pH is the hydrogen potential of alkaline activator; t is the temperature of alkaline activator (^{o}C); μ is the activator's conductivity (mS); and λ is the activator's salinity (g/L).*

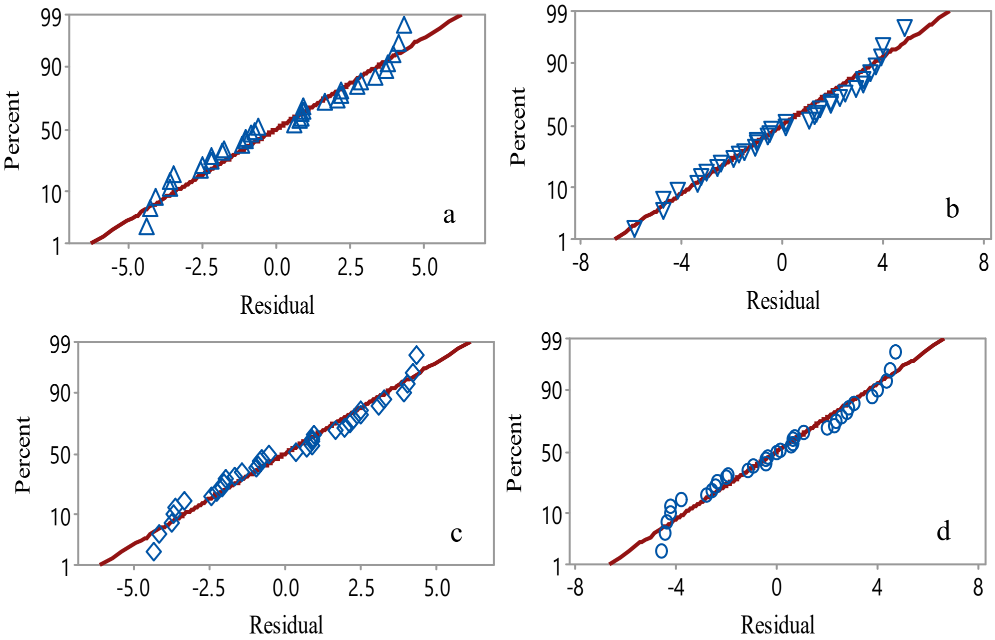

Figure 4: Normal probability plots for (a) 7, (b) 28, (c) 56, and (d) 90 days curing

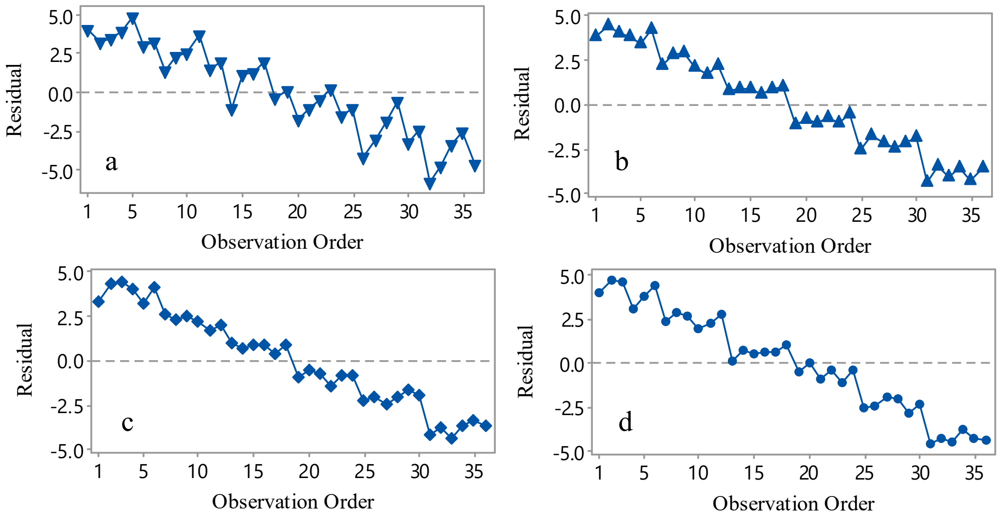

Figure 5: Residual versus order plots for (a) 7, (b) 28, (c) 56, and (d) 90 days curing

3.6 Comparison of experimental fc (Efc) with predictive fc (Pfc)

Following the experimental compressive strengths and the Equations (1)-(4), Figure 8 (a)-(d) present the relationship between the Efc and Pfc at 7, 28, 56, and 90 days curing, respectively. The results, as indicated in Figure 8 (a)-(d), revealed that both Efc and Pfc exhibited a similar pattern and trend without any significant difference at all curing days, thus yielding a strong correlation. Also, the results confirmed and established the regression model relationships illustrated in Equations (1)-(4).

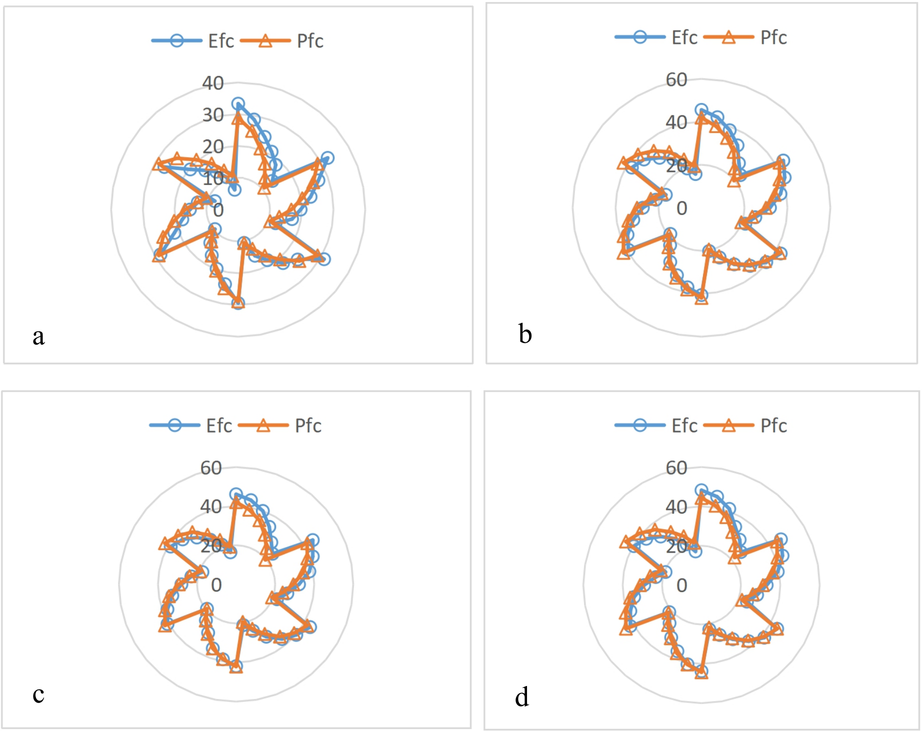

Figure 6: Relationship between Efc and Pfc for (a) 7, (b) 28, (c) 56, and (d) 90 days curing

4. Conclusions

This study examined and analyzed the alkali properties such as pH, temperature, conductivity, and salinity, and applied the results to predict the fc of GPC. Consequent upon the study findings, the following conclusions are drawn:

i. The temperature, conductivity, and salinity of the alkaline activator increased with increasing pH.
ii. There was about 13-25% decrease in the slump of fresh GPC as the alkali pH, temperature, conductivity and salinity increased from 2-8%, 2-8%, 6-14%, and 13-51%, respectively.
iii. There was about 18-33% increase in fc of GPC as the alkali pH, temperature, conductivity, and salinity increased from 2-8%, 2-8%, 6-14%, and 13-51%, respectively.
iv. A strong correlation exists between the fc of GPC and alkali pH, temperature, conductivity, and salinity with 84-90% R^2.

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