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Original Research Article

An Experimental and Predictive Models for Compressive Strength of Geopolymer Concrete Made with GGBFS and Fly ash

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Abstract

This work investigated the potential synergy between Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) as binder solids in the manufacturing of Geopolymer Concrete (GPC), a concrete that does not contain Ordinary Portland Cement (OPC). At a ratio of 1:1, the ideal mixture of binder solids was attained. Based on absolute volume, the mix design was created using techniques akin to those found in ACI 211.1. In order to investigate the impact on the evolution of strengths, the alkaline activator content (AAC) to binder solid ratio—which is comparable to the water/binder ratio in OPC concrete—was varied in the ratios of 0.25, 0.3, 0.35, 0.4, and 0.5. For every mixture, the ratio of sodium hydroxide to sodium silicate was maintained at 1.5. To evaluate the functional relationships between the response variable (strength) and the independent variables (GPC constituents), a nonlinear regression analysis was conducted. Experimental results on workability for all mixes are in agreement with ACI 211.1 criteria. In all mixes, GPC specimens exhibited higher compressive strengths than OPC specimens; with a maximum value of 73.67 Mpa and 72.67 Mpa respectively. Nonlinear regression results provide equations that predict the strengths with excellent correlation. In addition to F-statistics that are statistically significant within acceptable probabilities.

Keywords: Fly ash, geopolymer concrete, compressive strength, water-binder ratio, regression.

INTRODUCTION

Concretes are most widely used construction materials of which cement is the primary constituent. However, 5 – 7% of the total global carbon dioxide emission is attributed to the use of limestone cement (Mithanthaya *et al*., 2017). The demand for cement is second only to water globally hence, the need for alternative cementitious materials that are environmentally friendly. Consequently, the development of an alkali activated cement – geopolymer (Mohseni *et al*., 2019). Geopolymer which was first proposed by French Professor Davidovits in 1978 due its important characteristics is an inorganic polymer formed through alkaline activation of aluminosilicates materials such as fly ash from thermal power plants, granulated blast furnace slag (GBFS) from steel plants and other aluminosilicate rich materials (Aldrin and Sreevidya, 2019). The process of forming geopolymer is known as geopolymerization and is classified into three broad steps: Dissolution, Transportation /Orientation /Condensation and Poly-condensation. Geopolymerization can either take place at ambient temperatures or at elevated temperatures depending on the materials used (Davidovits, 2014). The Silica and alumina contained in the primary materials are dissolved in an alkaline activating solution aiding geopolymerization reaction to take place and subsequently polymerizes into molecular chains and become the binder (Abdul Aleem *et al*., 2012).

Some structural importance of geopolymer concretes include high resistance to fire attack, sulphate attack, acid attack, low creep, little drying shrinkage, higher compressive strength and better workability performances (Vijaya, 2014). Also, due to rapid growth in industrialization processes, high amount of industrial waste such as fly ash, glass powder, GBFS and others are produced and pose environmental challenges. The need for disposal, decomposition and recycling becomes a problem. The reuse of these wastes as geopolymer materials therefore becomes advantageous through the prevention/reduction of waste accumulation (Bajad *et al*., 2012; Mohseni, 2018). The proponent of geopolymer, Davidovits noted that geopolymers emit 70

– 80% less CO_2 to the environment and consumes 43 – 59% less energy in production compared to limestone cement (Davidovits, 2013). (Reddy, 2013) proposed mix design was a great achievement in the development of geopolymer mix design however, the concrete grade developed in their study did not achieve high strength performance, and there were no prediction models available to determine the functional relationship between binder solids ratio (AAC/BS), strength parameters, and alkaline activator content. Therefore, the main aim of this study was to improve the understanding of the mechanical performance of geopolymer concrete and to develop strength prediction models as a function of the ratio of alkaline activator content and binder solid content.

MATERIALS AND METHODS

The materials used in this study consisted of Ordinary Portland cement (OPC), sand, 20mm coarse aggregate, class C fly ash (FA), granulated blast furnace slag (GBFS). The FA and GBFS were used in combined form as solid binders in the production of the geopolymer concrete samples in the ratio of 1:1. The GBFS was included to complement FA which geopolymerizes at lower rate under ambient curing. Solutions of Sodium Hydroxide (NaOH) and Sodium silicate (Na_2SO_3) were implemented as alkaline activator, and the ratio of Na_2SiO_3 to NaOH in the alkali activation solution was 1.5:1. Two types of concrete were produced namely Portland cement concrete and geopolymer concrete, and Polycarboxylate ether-based superplasticizer (PSP) was implemented in the study as water reducing agent to enhance the flow ability of fresh concrete. The polycarboxylate ether-based superplasticizer was implemented in the proportion of 1.2% of the binder content. Preliminary tests implemented on the aggregates included specific gravity, bulk density and sieve analysis test, carried out in conformity to **BS 812-124:2009.** Table 1 and Fig. 1, show the chemical composition of the solid binders, and the particle size distribution curve for the aggregates used in this study. Freshly mixed concrete were prepared and tested for flow ability through slump test following the procedure outlined in BS EN 12350-2:2000. Samples of 100 x 100 x 100mm cubes, 100mm dia x 200mm cylinders and 100 mm × 100 mm × 500 mm beams were prepared and cured at ambient temperature for 7, 14 and 28 days. A total of number of 270 samples comprising of equal number of concrete cubes, cylinders and beams were prepared and subjected to compressive, tensile and flexural strength test following the procedures outlined in BS EN 12390-2:2000, BS EN 12390-6:2000 and BS EN 12390-5:2009. The selection of the OPC concrete proportions and mix design followed the procedure outlined in ACI 211.1-91 and same was simulated for the geopolymer concrete.

Table 2 and 3 show the proportions of the OPC and geopolymer concrete respectively.

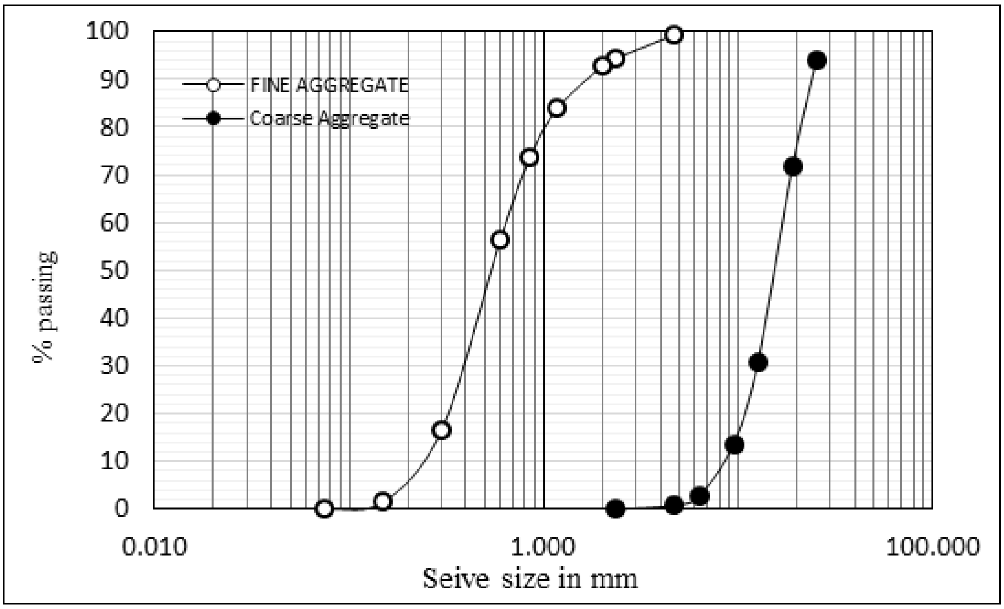

Fig. 1: Particle size distribution for fine and coarse aggregate

Table 1: Chemical Composition of Fly Ash and GBFS

Oxide %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	P_2O_5	Mn_2O_3	SO_3
OPC	20.7	4.6	2.3	64	1.7	0.4	0.1	0.3	-	0.1	2.9
Ash	62.2	27.5	3.92	2.27	1.05	1.24	0.52	0.16	0.30	0.09	-
GBFS	32.4	14.96	0.83	40.7	5.99	0.29	0.42	0.84	0.38	0.40	2.74

Table 2: Mix Proportion for the OPC Concrete (Control)

Mix	Water-binder ratio	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	PSP (kg/m^3)
1	0.25	640	993.87	645.40	160	7.68
2	0.30	533.33	1049.76	681.70	160	6.40
3	0.35	457.14	1089.45	707.47	160	5.49
4	0.40	400	1119.42	726.93	160	4.80
5	0.45	355.56	1142.59	741.98	160	4.27

Table 3: Geopolymer Concrete Mix Proportion

Mix	AAC/BS	Fly Ash (kg/m^3)	GBFS (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	PSP (kg/m^3)
1	0.25	320	320	64	96	979.29	635.93	7.68
2	0.30	266.665	266.665	64	96	1049.92	681.80	6.40
3	0.35	228.57	228.57	64	96	1100.3	714.52	5.49
4	0.40	200	200	64	96	1138.21	739.14	4.80
5	0.45	177.78	177.78	64	96	1167.70	758.28	4.27

Nonlinear Regression Analysis

Nonlinear regression analysis was implemented on experimental strength value to fit power models that would predict the functional relationship between the mechanical strengths and the alkaline activator content to binder solids ratios (AAC/BS). The regression analysis outputs show expository statistical parameters that define the correlation of strength values and the AAC/BS. The nonlinear regression analysis was adopted to develop prediction models for compressive strength, splitting tensile strength and flexural strength of geopolymer concrete as a function of the ratio alkaline activator content and binder solid content. The regression model implemented in fitting the strength parameters is a power model defined as stated in equation: $Y = \beta X^{\gamma}$

Where Y represents the dependent variables such as compressive strength, splitting tensile strength and flexural strength, and X represents the ratio of alkaline activator content to binder solids, β and γ = coefficients. The regression carried out examines parameters such as coefficient of determination, R^2, Adjusted R-square, R^2_{adj}, Standard error of estimate, SE, F-statistics and their significance level, Durbin-Watson amongst others from the model. The coefficient of determination is defined as proportion of the total sum of squares of the dependent variable explained or predicted by the independent variables in the model.

$$R^2 = \frac{SS\,(Regr)}{SS\,(Total)}$$

Adjusted R-square, on the other hand considers the mean square rather than the sum of square. It is a measure of the behaviour of the R-square when more variables are added to the model.

$$R^2_{adj} = 1 - \frac{MS(Regr)}{MS(Total)} = 1 - \frac{(1-R^2)(n-1)}{(n-p')}$$

Where n = number of observation and p' = number input variables.

Standard error of estimate shows the deviation of the observations from the regression line. The more reduced it is, the better the regression.

$$SE = \left(\sqrt{1 - R^2_{adj}}\right).\sigma$$

Where SE = Standard error of estimate and σ = standard deviation of observations from mean value. The partial least square method of regression analysis is implemented to minimize the residual mean square, MS (Res) of the estimate. In the nonlinear regression, the logarithmic transformation approach is implemented to prevent error due to divergence usually encountered by the iterative method.

RESULTS AND DISCUSSIONS

The results from tests on concrete cubes, cylinders, and bars that obtained their compressive strength, splitting tensile strength, and flexural strength after 7, 14, and 28 days of curing are discussed in the following paragraph. Additionally, nonlinear regression analysis is used to generate exponential models in order to develop strength models for the strength at different curing ages. These models establish functional relationships between the alkaline activator content to the binder solids for the geopolymer concretes and the strength parameters.

Compressive Strength

Table 4 below shows the results of the compressive strength tests for the concrete based on geopolymer and the concrete based on limestone cement (implemented as control specimens).

Table 4: Compressive Strength for Geopolymer Concrete and Control Samples

Age	Concrete	Compressive Strength Result [Mpa]				
AAC/BS or W/B		**0.25**	**0.3**	**0.35**	**0.4**	**0.45**
7	Geopolymer	57.67	43.67	38.67	33.67	29.67
7	Limestone	55.67	42.67	37.33	32.33	27.67
14	Geopolymer	64.33	53.67	49.33	44.33	38.33
14	Limestone	62.57	51.67	47.67	42.33	36.33
28	Geopolymer	73.67	66.33	62.33	55.33	48.33
28	Limestone	72.67	63.67	60	54	47

For all curing ages, Table 4 above shows that the alkaline activator content to binder solids ratio causes the compressive strength of the geopolymer concrete to decrease, just like it does for cement-based concrete. This decline is the consequence of a decrease in the amount of binder solids, which lowers the rate of geopolymerization. After 28 days of curing, geopolymer concrete reaches its maximum compressive strength value of 73.67 MPa at an alkaline activator content to binder solid ratio of 0.25. In addition, when comparing the compressive strengths of the geopolymer concrete and the control samples (concrete made of limestone cement), at each mix ratio (the ratio of liquid to binder solids) the compressive strengths of the geopolymer concrete are marginally higher. Comparable to the concrete's compressive strength output at 7, 14 and 28 days, both groups' concrete's compressive strength decreased as the ratio of liquid to binder solids continued to increased.

The improvement of compressive strength of the geopolymer concrete caused by the inclusion GBFS in the concrete mix which allows for faster geopolymerization and also contributing to better microstructure formation in the concrete. GBFS compensate for the poor geopolymerization performance of fly ash which requires elevated temperature to perform better. Higher calcium oxide content in GBFS causes the gel components of calcium-silcate-hydrate and calcium-aluminum-silicate-hydrate to form in concrete. This gels together with sodium-aluminum-silicate-hydrate, forms to increase the geopolymer concrete's compressive strength when calcium fly ash levels are low.

According to published research, the development of calcium-aluminum-silicate-hydrate and calcium-silicate-hydrate causes a water deficit in the concrete mixture, which raises the mix's alkalinity. This further improves the aluminosilicate's faster and higher dissolution rate. As a result, the concrete mixture achieves geopolymerization or poly-condensation. The geopolymer concrete mixtures' compressive strengths after 7, 14, and 28 days of curing are shown in the bar chart represented in Fig 2. below and also shows that of the control samples.

Fig 2 shows that, geopolymer concretes have a slightly higher compressive strength than concrete based on limestone cement at the same liquid to binder solids ratio. For both concrete groups, the compressive strength drops as the ratios rise.

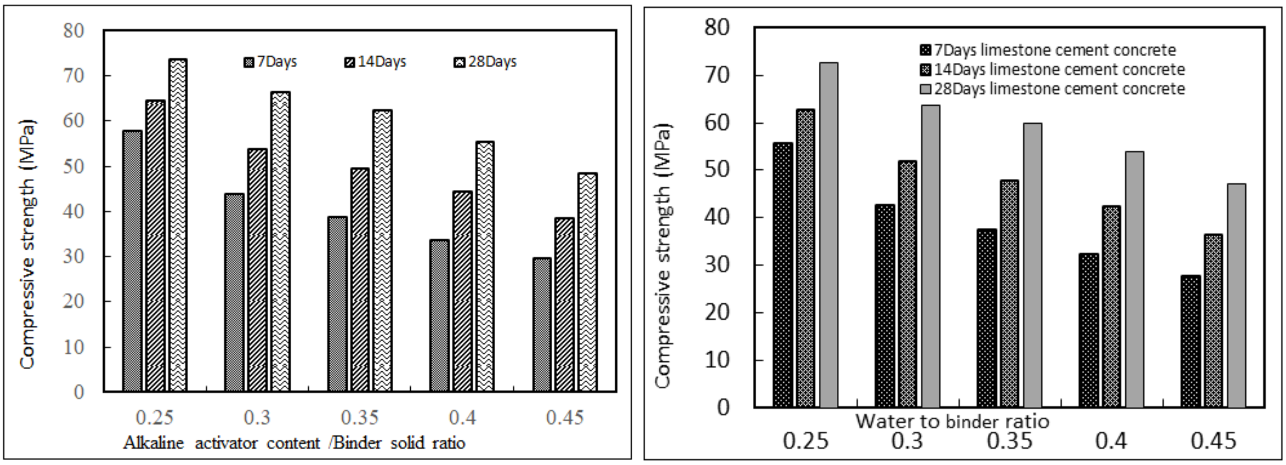

Fig. 2: Compressive Strength of Concrete after 7, 14 and 28 Days Curing

Splitting Tensile Strength

Table 5 below shows the results of the splitting tensile strength test conducted on cylindrical samples for concrete based on limestone cement and concrete based on geopolymer.

Table 5: Splitting Tensile Strength for Geopolymer Concrete and Control Samples

Curing Age	**Concrete**	**Splitting Tensile Strength Result [Mpa]**				
AAC/BS or W/B		**0.25**	**0.3**	**0.35**	**0.4**	**0.45**
7	Geopolymer	2.55	2.33	2.07	1.96	1.91
7	Limestone	2.33	2.02	1.91	1.8	1.559
14	Geopolymer	2.75	2.44	2.33	2.12	2.02
14	Limestone	2.65	2.39	2.17	2.02	1.91
28	Geopolymer	2.86	2.75	2.54	2.44	2.33
28	Limestone	2.75	2.65	2.54	2.44	2.23

For all curing ages comparable to the control specimens, Table 5 demonstrates that the splitting tensile strength of the geopolymer concrete falls as the alkaline activator content to binder solids ratio increases for both 7, 14 and 28 days. For geopolymer concrete, the maximum splitting tensile strength is achieved at a ratio of 0.25 liquid to binder solids and after 28 days of curing. On comparing the splitting tensile strength of the geopolymer concrete to the control samples (limestone cement-based concrete), at each mix ratio (liquid to binder solids ratio), the splitting tensile strength of geopolymer concrete is slightly higher than that of the limestone cement based concrete samples. However, unlike the trend for 7 days and 14 days the 28 days splitting tensile strength of geopolymer concrete and limestone cement-based concrete are the same for liquid to binder ratios of 0.35 and 0.40.

Graphical presentation of the splitting tensile strengths at 7, 14 and 28 days are presented and discussed below. As stated earlier, the bar chat in Fig 3 below shows pictorially that the splitting tensile strength of geopolymer samples are higher than the limestone cement-based concrete. For both groups of concrete, the splitting tensile strength decrease with increasing liquid to binder solids ratio.

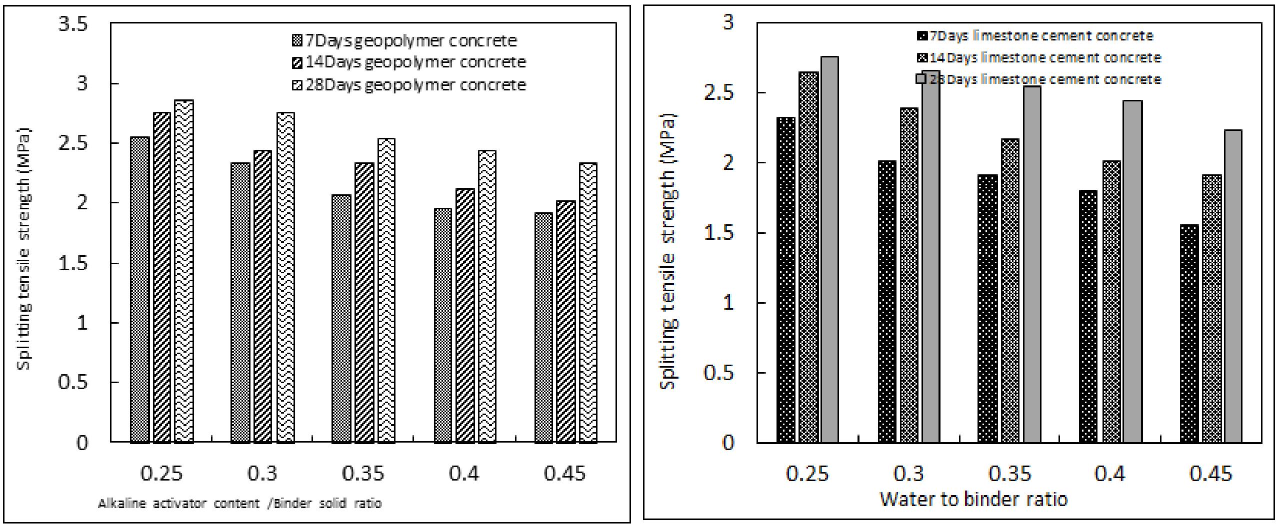

Fig. 3: Splitting Tensile Strength of Concrete after 7, 14 and 28 Days Curing

Flexural Strength

The result of the flexural strength obtained from the test implemented on prism samples for both geopolymer based concrete and limestone cement-based concrete are presented in Table 6. below.

Table 6 shows that the flexural strength of the geopolymer concrete decreases as the alkaline activator content to binder solids ratio increases for all curing ages similar to the limestone cement-based specimens. The maximum flexural strength (10.83 MPa) is obtained at 0.25 liquid to binder solids ratio and 28 days curing for geopolymer concrete. When comparing the flexural strength of the geopolymer concrete samples to the control samples (concrete based on limestone cement), the geopolymer concrete samples exhibit slightly higher flexural strength at every mix ratio (battery to solids). The fourteen-day flexural strength exhibits a similar trend to the seven-day flexural strength, with higher values for the geopolymer concrete than for the limestone cement concrete across all liquid to solid binder ratios and the alkaline activator content to binder solids concrete's flexural strength at 7 and 14 days, however at 28 days, an increase is achieved. Similar trends in splitting tensile strength and compressive strength are depicted in the figure below.

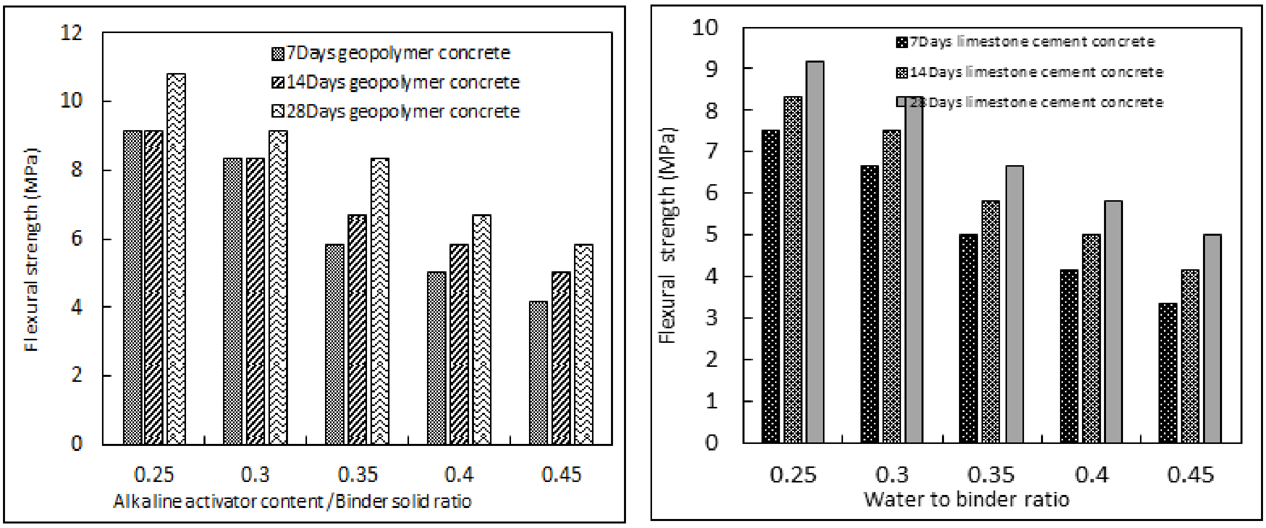

Fig. 4: Flexural Strength of Concrete after 7, 14 and 28 days Curing

Table 6: Flexural Strength for Geopolymer Concrete and Control Samples

Curing Age	Concrete	Flexural Strength Result [Mpa]				
AAC/BS or W/B		**0.25**	**0.3**	**0.35**	**0.4**	**0.45**
7	Geopolymer	9.17	8.33	5.83	5.00	4.17
7	Limestone	7.50	6.67	5.00	4.17	3.33
14	Geopolymer	9.17	8.33	6.67	5.83	5.00
14	Limestone	8.33	7.50	5.83	5.00	4.17
28	Geopolymer	10.83	9.17	8.33	6.67	5.83
28	Limestone	9.17	8.33	6.67	5.83	5.00

Mathematical Modelling

Regression analysis was used to develop mathematical models in accordance with the objective outlined in this study. Power models were developed using partial least square nonlinear regression analysis in order to 1. determine the functional relationship between compressive strength and the ratio of alkaline activator content to binder solids, 2. determine the functional relationship splitting tensile strength and the ratio of alkaline activator content to binder solids, and 3. determine the functional relationship between flexural strength and alkaline activator content to binder solids ratio.

Table 7: Regression model Result Summary

Days	R	R^2	Adjusted R^2	Std. error of Estimate	F-test	Sig.	Durbin-Watson
	Compressive Strength model						
7	0.994	0.987	0.983	0.035	229.632	0.001	2.515
14	0.993	0.986	0.981	0.027	212.494	0.001	2.373
28	0.981	0.962	0.950	0.037	76.265	0.003	1.495
	Split Tensile Strength model						
7	0.981	0.963	0.951	0.026	78.134	0.003	1.564
14	0.993	0.986	0.981	0.017	208.116	0.001	1.437
28	0.992	0.985	0.980	0.012	193.416	0.001	3.105
	Flexural Strength model						
7	0.982	0.965	0.954	0.072	83.231	0.003	3.013
14	0.989	0.978	0.971	0.043	134.184	0.001	2.536
28	0.988	0.976	0.968	0.045	120.484	0.002	1.985

Mathematical Modelling of Compressive Strength for Geopolymer Concrete

The excerpts coefficients as obtained from the regression output for 7, 14 and 28 days compressive strength regression are presented in Table 8, below. The equation is given as:

For 7 days $CS_7 = e^{2.508}(AAC/BS)^{-1.093}$
For 14 days $CS_{14} = e^{3.002}(AAC/BS)^{-0.835}$
For 28 days $CS_{28} = e^{3.365}(AAC/BS)^{-0.689}$

Where; CS = Predicted compressive strength

The compressive strength exhibits a similar decrement at 7, 14, and 28 days as the AAC/BS values increases as indicated by the negative power coefficient and the t-statistics are statistically significant as their probabilities are less than 0.05. From table 5, the regression coefficient, R, coefficient of determination, R square and standard error of estimate indicate high degree correlation between the compressive strength and alkaline activator content to binder solids ratio and high accuracy of fitting. There is also a significant influence level of alkaline activator content to binder solids ratio on the compressive strength as indicated by the F-statistics and its p-value The F-statistics has a p-value that is statistically significant (For 7 days p = 0.001 < 0.05, For 14 days p = 0.001 < 0.05, For 28 days p = 0.003 < 0.05). The Durbin-Watson value for 7 days shows there is negative residual autocorrelation, negative residual autocorrelation for 14 days and positive residual autocorrelation for 28days.

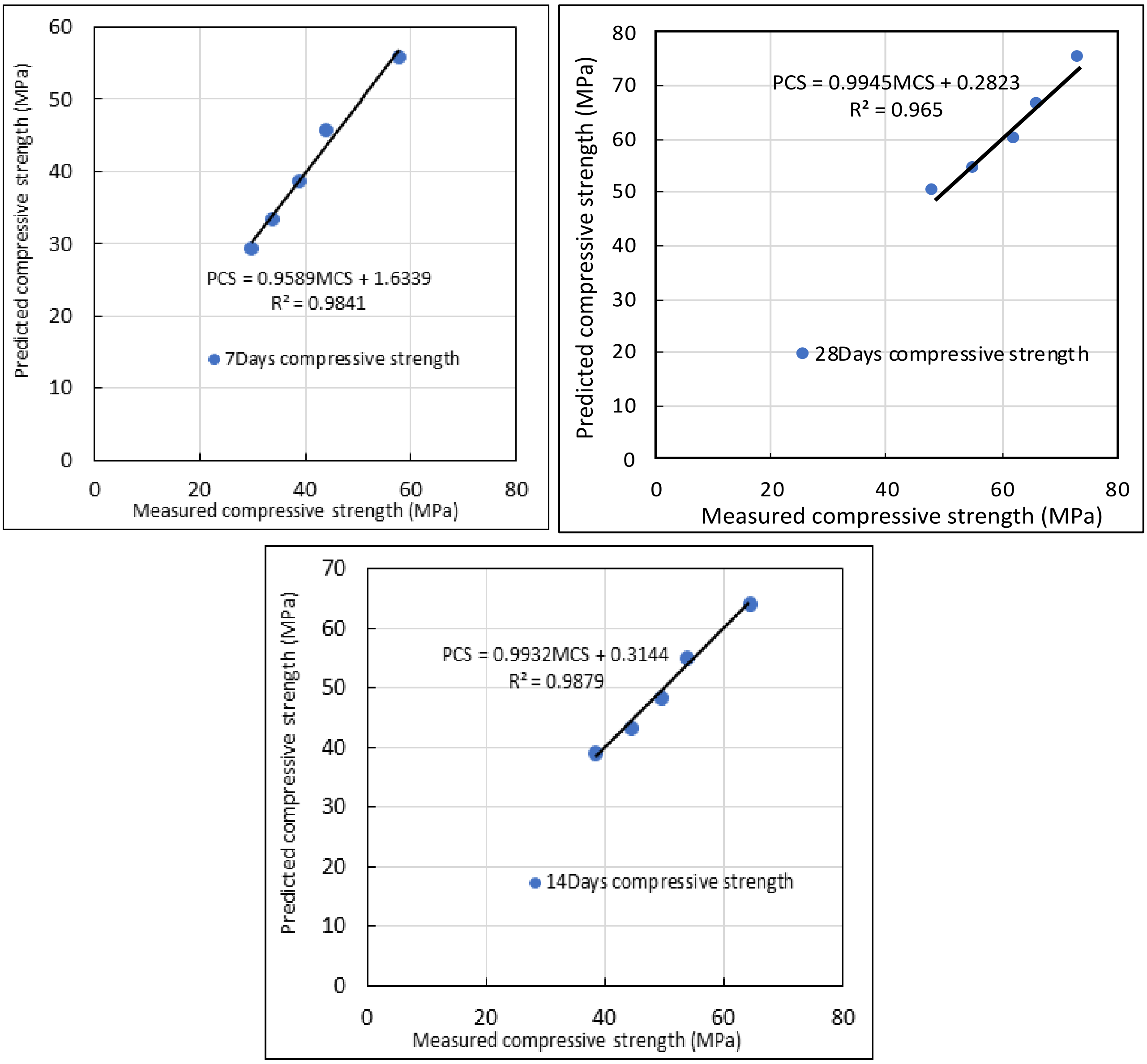

Fig. 5: Scatter plot with line of best fit for compressive strength at 7, 14, and 28 days curing

Table 8: Compressive strength regression models

Time (days)	Variable	Coefficient	Standard error	T-test	Sig.	Compressive strength models
7	Constant	2.508	0.079	31.873	0.000	$CS_7 = e^{2.508}\left(\frac{AAC}{BS}\right)^{-1.093}$ or $CS_7 = 12.28\left(\frac{AAC}{BS}\right)^{-1.093}$
	AAC/BS	-1.093	0.072	-15.154	0.001	

Time (days)	Variable	Coefficient	Standard error	T-test	Sig.	Compressive strength models
14	Constant	3.002	0.063	48.021	0.000	$CS_{14} = e^{3.002}\left(\frac{AAC}{BS}\right)^{-0.835}$ or $CS_{14} = 20.13\left(\frac{AAC}{BS}\right)^{-0.835}$
	AAC/BS	-0.835	0.057	-14.577	0.001	
28	Constant	3.365	0.086	39.077	0.000	$CS_{28} = e^{3.365}\left(\frac{AAC}{BS}\right)^{-0.689}$ or $CS_{28} = 28.93 * \left(\frac{AAC}{BS}\right)^{-0.689}$
	AAC/BS	-0.689	0.079	-8.733	0.003	

Mathematical Modelling for Splitting Tensile Strength for Geopolymer Concrete

Basic and necessary coefficients as obtained from the regression output for 7, 14 and 28 days splitting tensile strength regression are presented in Table 9 below. The equation is given as:

For 7 days $STS_7 = e^{0.231}(AAC/BS)^{-0.491}$
For 14 days $STS_{14} = e^{0.272}(AAC/BS)^{-0.523}$
For 28 days $STS_{28} = e^{0.561}(AAC/BS)^{-0.360}$

Where; STS = Splitting tensile strength

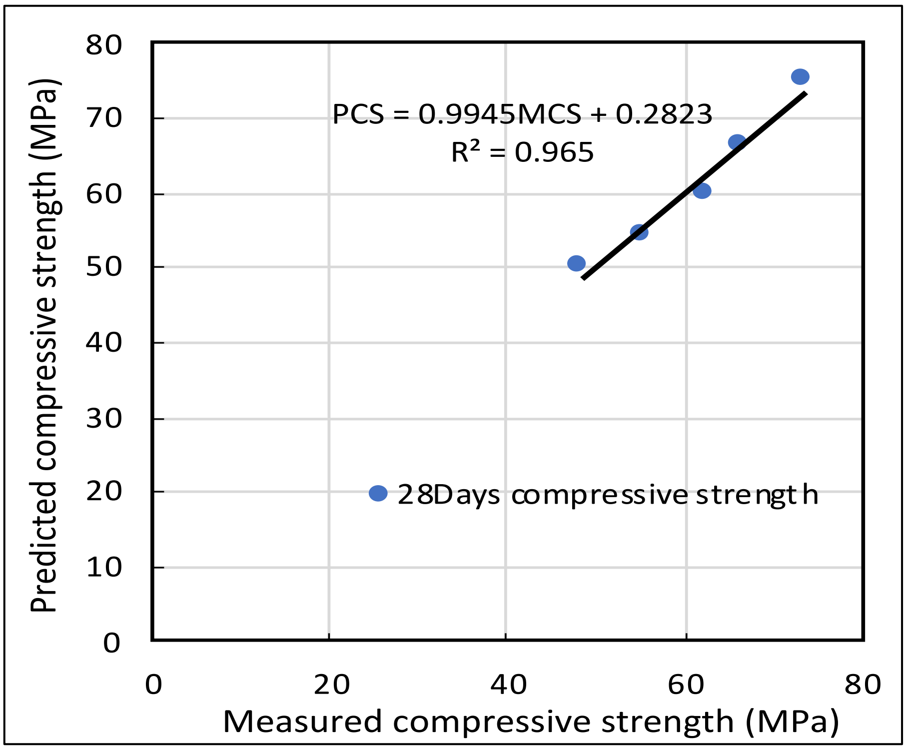

Fig. 6: Scatter plot with line of best fit for compressive strength at 7, 14, and 28 days curing

The t-statistics which is a measure of deviation of the coefficient are statistically significant as their probabilities are less than 0.05 as shown by the significant values in Table 5 above. The regression coefficient, R, coefficient of determination, R square and standard error of estimate indicate high degree correlation between the splitting tensile strength and alkaline activator content to binder solids ratio and high accuracy of fitting. The F-statistics has a p-value that is statistically significant (At 7 days p = 0.003 < 0.05, At 14 days p = 0.001 < 0.05, At 28 days p = 0.001 < 0.05) indicating that alkaline activator content to binder solids ratio has significant effect on the splitting tensile strength. The Durbin-Watson value shows there is positive residual autocorrelation for 7 days, positive residual autocorrelation for 14 days and negative residual autocorrelation for 28days.

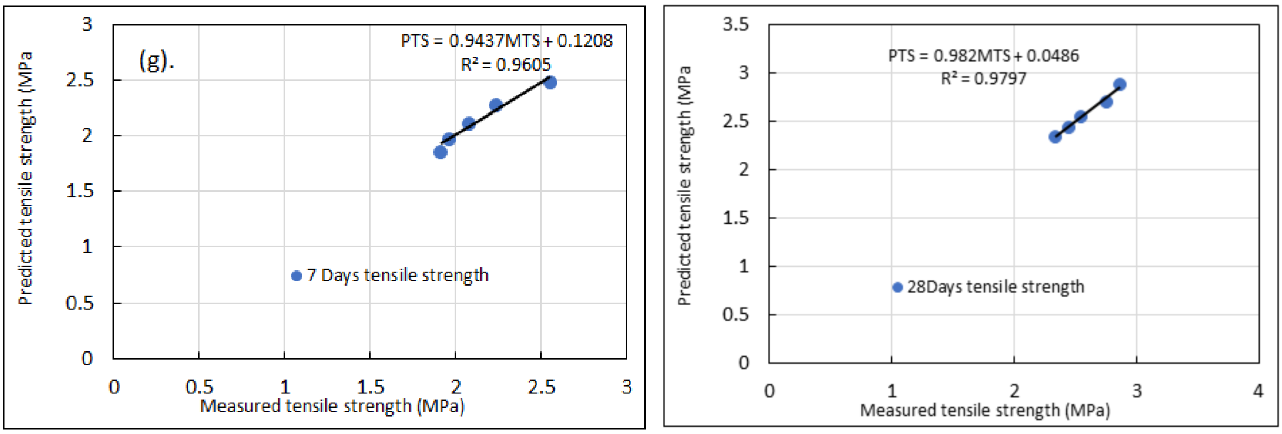

Fig. 7: Scatter plot with line of best fit for Splitting tensile strength at 7, 14 and 28 days curing

Table 9: Splitting tensile strength regression models

Time (days)	Variable	Coefficient	Standard error	T-test	Sig.	Split tensile strength models
7	Constant	0.231	0.061	3.805	0.032	$STS_7 = e^{0.231}\left(\frac{AAC}{BS}\right)^{-0.491}$ or $STS_7 = 1.31\left(\frac{AAC}{BS}\right)^{-0.491}$
	AAC/BS	-0.491	0.056	-8.839	0.003	
14	Constant	0.272	0.040	6.874	0.006	$STS_{14} = e^{0.272}\left(\frac{AAC}{BS}\right)^{-0.523}$ or $STS_{14} = 1.31\left(\frac{AAC}{BS}\right)^{-0.523}$
	AAC/BS	-0.523	0.036	-14.426	0.001	
28	Constant	0.561	0.028	19.845	0.000	$STS_{28} = e^{0.561}\left(\frac{AAC}{BS}\right)^{-0.360}$ or $STS_{28} = 1.75\left(\frac{AAC}{BS}\right)^{-0.360}$
	AAC/BS	-0.360	0.026	-13.907	0.001	

Mathematical Modelling for Flexural Strength for Geopolymer Concrete

The necessary coefficients as obtained from the regression output for 7, 14 and 28 days Flexural strength regression are presented in Table 10 below. The equation is given as:

For 7 days $FS_7 = e^{0.311}(AAC/BS)^{-1.415}$
For 14 days $FS_{14} = e^{0.783} * (AAC/BS)^{-1.063}$
For 28 days $FS_{28} = e^{0.948} * (AAC/BS)^{-1.053}$

Where; FS = Flexural strength

The t-statistics shows that the coefficient of the independent variable is statistically significant as its probability is less than 0.05 as shown by the significant values in Table 5 above. Whereas, the constant coefficient for 7 days is not significant as its p-value is greater than 0.05.

As shown in Table 3 above, the regression coefficient, R, coefficient of determination, R Square and standard error of estimate indicate high degree correlation between the flexural strength and alkaline activator content to binder solids ratio and high accuracy of fitting. The F-statistics has a p-value that is statistically significant (For 7 days p = 0.003 < 0.05, For 14 days p = 0.001 < 0.05, For 28 days p = 0.002 < 0.05) indicating that alkaline activator content to binder solids ratio has significant effect on the flexural strength. The Durbin-Watson value for 7 days shows there is negative residual autocorrelation, negative residual autocorrelation for 14 days and positive residual autocorrelation for 28days.

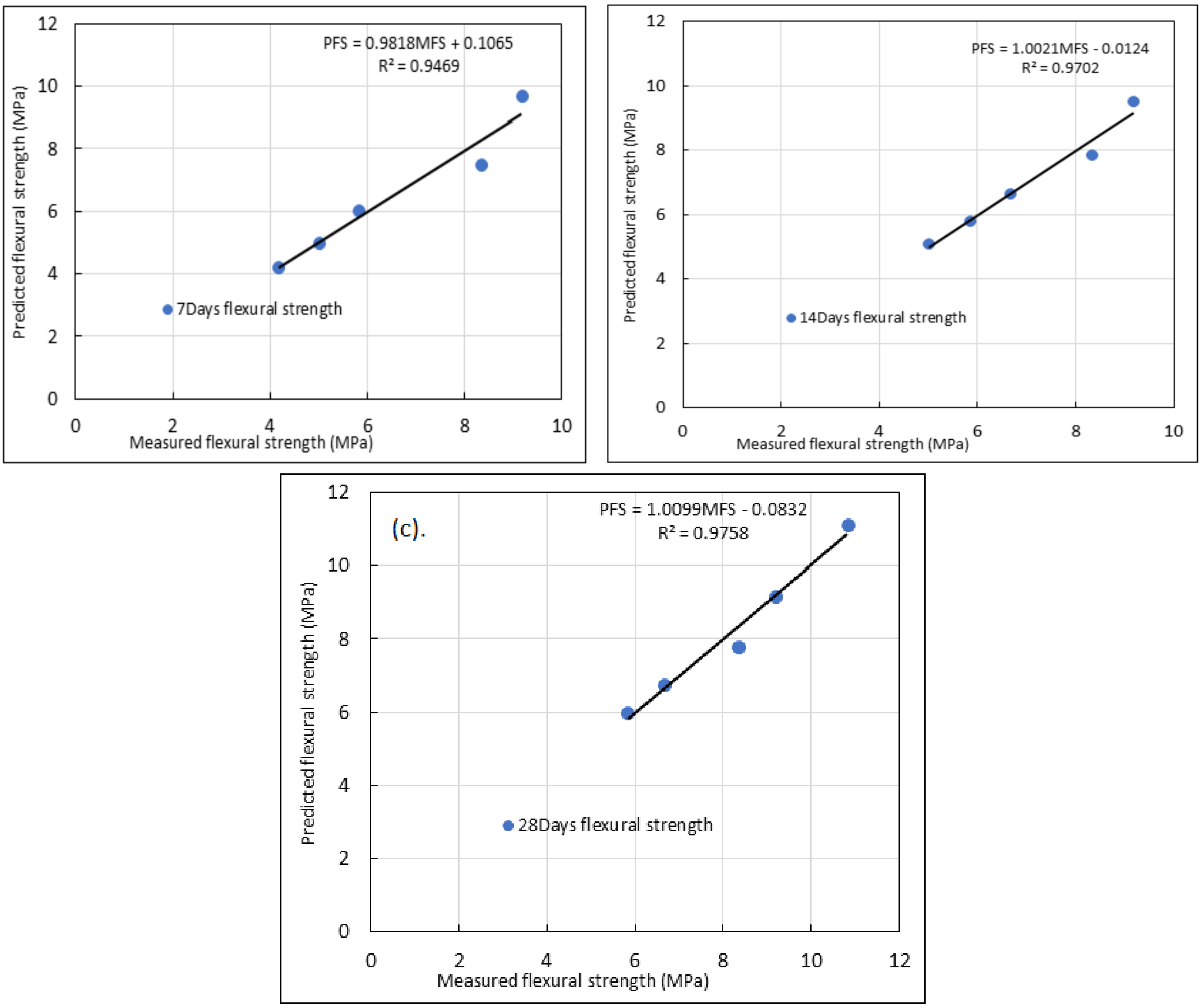

Fig. 8: Scatter plot with line of best fit for Flexural strength at 7, 14 and 28 days curing

Table 10: Flexural strength regression models

Time (days)	Variable	Coefficient	Standard error	T-test	Sig.	Flexural strength models
7	Constant	0.311	0.169	1.840	0.163	$FS_7 = e^{0.311}\left(\frac{AAC}{BS}\right)^{-1.415}$ or $FS_7 = 1.36\left(\frac{AAC}{BS}\right)^{-1.415}$
	AAC/BS	-1.415	0.155	-9.123	0.003	
14	Constant	0.783	0.100	7.823	0.004	$FS_{14} = e^{0.783}\left(\frac{AAC}{BS}\right)^{-1.063}$ *or* $FS_{14} = 2.19\left(\frac{AAC}{BS}\right)^{-1.063}$
	AAC/BS	-1.063	0.092	-11.584	0.001	
28	Constant	0.948	0.105	9.060	0.003	$FS_{28} = e^{0.948}\left(\frac{AAC}{BS}\right)^{-1.053}$ *or* $FS_{28} = 2.58\left(\frac{AAC}{BS}\right)^{-1.053}$
	AAC/BS	-1.053	0.096	-10.977	0.002	

CONCLUSION

This study examined the mechanical performance and workability of environmentally friendly fly ash and GBFS based geopolymer concrete in order to address the issue of CO2 emissions from cement-based concrete that affect the environment. An enhanced mix design that imitates the ACI 211.1 mix design was used in this investigation. As a reference concrete, the performance of geopolymer concrete was compared to cement-based concrete.

The following is a summary of the findings from the experimental study and statistical analyses:

i. Both limestone cement- and geopolymer-based concrete showed good workability results. The slump values for the control and geopolymer concrete samples were all within the ACI 211.1 guidelines' specified range.

ii. After 28 days of curing, the geopolymer concrete samples with a 0.25 AAC/BS ratio tested showed compressive strength, splitting tensile strength, and flexural strength up to 73.67 MPa, 2.86 MPa, and 10.83 MPa, respectively. In contrast, the reference concrete's (cement-based concrete's) maximum values were 72.67 MPa, 2.75 MPa, and 9.17 MPa, respectively.

iii. As the alkaline activator content to binder solids ratio increased, the compressive strength, splitting tensile strength, and flexural strength of geopolymer concrete decreased for all curing ages. This explains that a lower binder content lowers the rate of geopolymerization. For the cement-based concrete (control samples), a similar pattern was noted.

iv. According to the standard errors of estimate outputs from the regression analysis carried out using the IBM SPSS computational package, the mathematical models developed for the compressive strength, splitting tensile strength, and flexural strength at 7, 14 and 28 days from the strength versus AAC/BS curves at these ages showed high degree of accuracy. Since all of the developed models' probabilities (p-values) fell below the 0.05 threshold required for the null hypothesis to be rejected, the F-statistics for each model were statistically significant. Consequently, considering the alkaline activator content to binder solids ratios, the developed models are trustworthy for the estimation of compressive strength, splitting tensile strength, and flexural strength.

RECOMMENDATIONS

The following recommendations are offered in light of the study's limitations and observations made during the investigation. In light of this research:

i. It is recommended to adopt the mix design used in this study, which is a replica of ACI 211.1, for the development of geopolymer concrete.

ii. It is recommended to estimate the compressive strength, splitting tensile strength, and flexural strength of geopolymer concrete using the power model derived from the strength versus AAC/BS curves.

Considering Further Research:

i. Future research should be conducted to investigate the durability performance of geopolymer concrete made with this mix design.

ii. As noted in this study, fly ash geopolymerizes slowly at ambient temperature. It is recommended that in future study, other pozzolans in combination with GBFS should be implemented in the production of geopolymer concrete.

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