Chapter 28
Assessment of the Shear Strength of Fly Ash-Based Geopolymer Concrete

S. Kumar, S. Rajendra and K. S. Sreekeshava

Abstract Analytical approaches determine the shear strength of geopolymer concrete on experimentally evaluated parameters of strength such as compressive strength, tensile strength and flexural strength. The analytical approach has been introduced by using the equations of the correlated stress functions to evaluate the shear strength. The new approach has been introduced over traditional Mohr's failure envelope to assess the shear strength. The shear stress evaluated under these approaches is compared with the solution by the equation suggested by ACI-318-95. The variation of results from these approaches varied a maximum of 40% with results by the equation (ACI-318-95). The validation of each approach would be subjected to further discussion with previous research significance under the same context.

Keywords Geopolymer concrete · Shear strength · Fly ash-based concrete · Shear stress

28.1 Introduction

There are several research works carried on geopolymers as binder or inorganic polymer but some intensive research works carried on Geopolymer concrete under the context of structural applications. Numerous studies by experimentations were recorded and still continuing on material properties. There are some effective works which incorporate the classical theories and experimental investigations to elucidate the material properties under structural applications. Some of the analytical and experimental approaches are explicated by traditional methods which are being used for conventional concrete.

S. Kumar (✉) · K. S. Sreekeshava
Jyothy Institute of Technology, Bengaluru, Affiliated to Visvesvaraya Technological University, Belagavi, India
e-mail: s.kumar@jyothyit.ac.in

S. Rajendra
Vijaya Vittala Institute of Technology, Bengaluru, Affiliated to Visvesvaraya Technological University, Belagavi, India

M. Vinyas et al. (eds.), *Advances in Structures, Systems and Materials*,
Lecture Notes on Multidisciplinary Industrial Engineering,
https://doi.org/10.1007/978-981-15-3254-2_28

Several researchers have considered concrete as an isotropic material which has the same material properties along with all directions. In reality, it is a mixture of sands and gravels and it is not an isotropic material. Its tensile stress is near 1/10 of the compressive stress in the perpendicular direction measured on an experimental specimen. It is important to notice that mixtures have the same properties like orthotropic or anisotropic materials but they are considered as homogeneous materials. So they do not have the same E1 and E2 and others.

Several experimental investigations have been conducted to study the shear strength of concrete and predicted the results as a function of the compressive strength. The shear strength of concrete generally varies with the several associated factors such as internal frictions due to aggregate interlocking, the strength of cement paste and aggregates. In this study, the shear strength of concrete is discussed and predicted by the general strength of concrete as a whole without assessing the properties of individual materials by which is made up of.

28.1.1 Research Significance

Most of the experimental investigations on the mechanical properties of geopolymer concrete were compared with the code recommendations. Some of the expressions on the correlation of strength parameters of the conventional concrete are highlighted to compare with the present investigation. The correlation of split tensile strength to compressive strength is expressed as $f_t = 0.59 f_{\mathrm{ck}}^{0.5}$, $f_t = 0.30 f_{\mathrm{ck}}^{0.5}$, $f_t = 0.23 f_{\mathrm{ck}}^{0.5}$ by ACI-318-99, CIB FIB and Neville, respectively [1]. The correlation of flexural strength to compressive strength of conventional concrete is expressed as $f_r = 0.7 f_{\mathrm{ck}}^{0.5}$, $f_r = 0.62 f_{\mathrm{ck}}^{0.5}$, $f_r = 0.60 f_{\mathrm{ck}}^{0.5}$ by IS 456-2000, ACI-318 and BS 8110, respectively [2].

28.2 Basic Materials and Mix Proportion

The geopolymer is prepared by using fly ash, aggregates and alkaline solutions ($NaOH + Na_2SiO_3 + H_2O$). The fly ash and aggregates used for mix are conforming to IS: 3812 [3] IS: 383 [4], respectively. The geopolymer concrete is prepared with different mix proportions. The basic material testing and mix proportions are discussed elsewhere [5]. Same molarity (14 Molar) of alkaline solutions is used for all the mix. The detail of mix used for this work is shown in Table 28.1.

Table 28.1 Selected mix details of GPC

Mixture	Fly ash (%)	Fly ash (Kg/m^3)	Coarse aggregate (Kg/m^3)	Fine aggregate (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)	Plasticizer (Kg/m^3)
FGC-M6	25	521.44	876.02	688.30	89.76	224.4	4.8

Table 28.2 Test results of the strength parameters of concrete

Mixtures	Compressive strength (f_{ck}) MPa	Split tensile strength (f_t) MPa	Fexural strength (f_r) MPa
FGC-M1	13.35	1.88	2.52
FGC-M2	15.69	2.13	2.87
FGC-M3	18.56	2.44	3.13
FGC-M4	22.75	3.08	3.68
FGC-M5	26.35	3.52	4.28
FGC-M6	28.56	3.67	4.53
FGC-M7	31.98	4.12	4.98
FGC-M8	33.69	4.33	5.1
FGC-M9	35.58	4.53	5.32
FGC-M10	37.64	4.65	5.77
FGC-M11	40.23	5.14	6.05
FGC-M12	41.54	5.33	6.34

28.2.1 Testing of Concrete

Compressive strength split tensile strength and flexural strength tests of concrete are conducted as per IS: 516-1959 [6] and presented in Table 28.2.

28.2.2 Correlation of Strength Parameters

Graphically representing correlations of split tensile strength to compressive strength and flexural strength to compressive strength as shown in Figs. 28.1 and 28.2 respectively.

The correlation of corresponding strength parameters (f_s) by regression analysis are presented in the power function in the form $f_s = f(f_{ck}) = k(f_{ck})^n$ and are given in Eqs. (28.1) and (28.2).

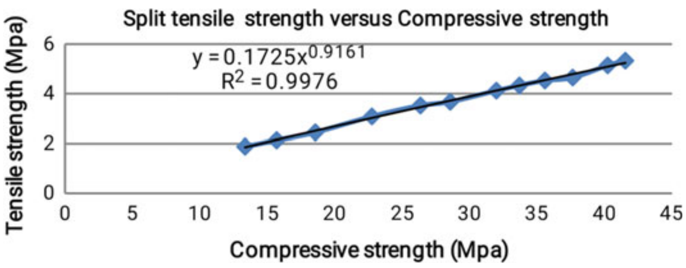

Fig. 28.1 Correlation of compressive strength to split tensile strength

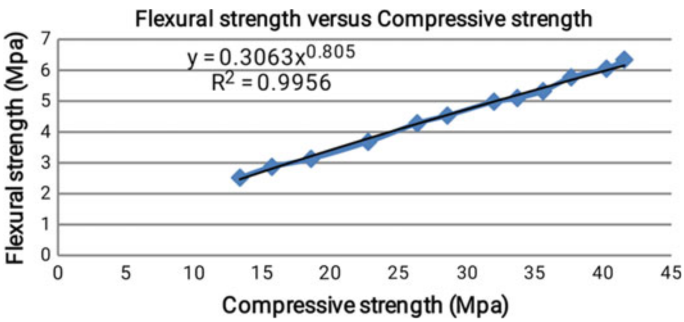

Fig. 28.2 Correlation of compressive strength to flexural strength

$$f_t = f(f_{\mathrm{ck}}) = 0.1725(f_{\mathrm{ck}})^{0.9161} \tag{28.1}$$

$$f_r = f(f_{\mathrm{ck}}) = 0.3063(f_{\mathrm{ck}})^{0.805} \tag{28.2}$$

28.3 Assessment of Shear Strength

28.3.1 Assessment of Shear Strength by Split Tensile Strength

The shear stress is analysed under classical theories of mechanics by considering cylindrical specimen subjected to split tensile test as shown in the Fig. 28.3a, b and c. The shear mechanism is explicated in Eqs. 28.3–28.5. The direct tensile strength of conventional concrete is expected to be 90% of split tensile strength [7]. Due to non-availability of the proper experimental evidences on direct tensile strength of geopolymer concrete, the direct tensile strength of concrete is considered as equal to split tensile strength to compute principal tensile strength. The relevant multiplication factor on direct to split tensile strength can be incorporated based on experimental investigation.

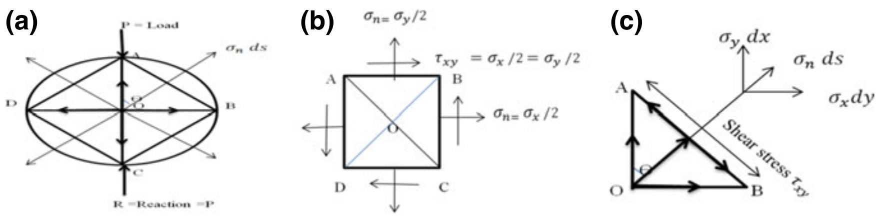

Fig. 28.3 Shear mechanisms by split tensile strength test

AO = OB = $d/2$ (where d is the diameter)

$$\frac{f_t}{2} = \tau_{xy} = \tau_c = \frac{4P}{\pi dl} \tag{28.3}$$

Principal stress $(\sigma_{1,}\sigma_2)$

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \tag{28.4}$$

$$\sigma_1 = \sigma_x = \frac{f_t}{2}, \sigma_2 = 0$$

$$\tau_c = f(f_t) = \frac{f_t}{2} \tag{28.5}$$

28.3.2 Assessment of Shear Strength by Flexural Strength

The Shear strength of concrete is analysed by considering the shear stress of prism without reinforcement subjected to flexure test under two points load placed at a shear span of "a" as shown in Fig. 28.4. The flexural strength of the beam f_r is assessed from simplified bending equation of two points loading. The shear strength of the concrete is arrived through Eqs. 28.6–28.13.

$$f_{cr} = \frac{3Pa}{bD^2} \tag{28.6}$$

$$f_{cr} = \frac{3P}{bD}\left(\frac{a}{D}\right) \tag{28.7}$$

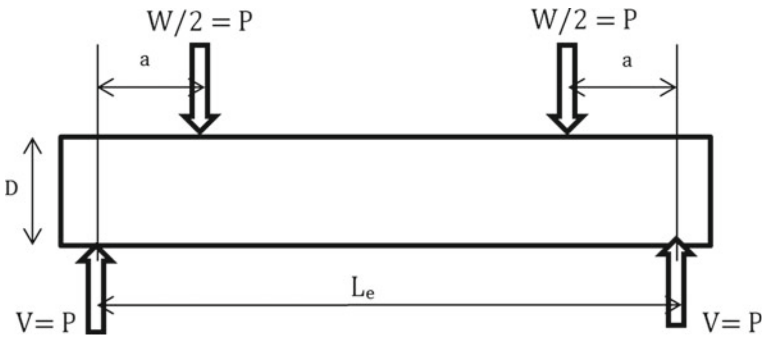

Fig. 28.4 Flexural strength by two points loading

$$\text{Shear force } V = \frac{P}{2} \tag{28.8}$$

$$V = \frac{f_r}{6}\left(\frac{D}{a}\right)bD \tag{28.9}$$

$$V = \frac{f_r}{6}\left(\frac{D}{a}\right)bD \tag{28.10}$$

$$\frac{V}{bD} = \tau_v = \frac{f_r}{6}\left(\frac{D}{a}\right) \tag{28.11}$$

$$\tau_v = 0.167 \times \left(\frac{D}{a}\right) \times f_r \tag{28.12}$$

Experimental investigations shows that maximum shear arrived at section when $\left(\frac{D}{a}\right) = 1$ (when $\theta = 45°$) hence the Eq. (28.4) become

$$\tau_v = 0.167 f_r \tag{28.13}$$

Shear strength of prism τ_v is equated to the shear strength of concrete τ_c, and from Eq. 28.2, the shear strength of concrete is assessed and explicated in Eqs. 28.14 and 28.15.

$$f_r = f(f_{\text{ck}}) = 0.3063(f_{\text{ck}})^{0.805}$$

$$\tau_c = \tau_v = 0.0511 \times f_{\text{ck}}^{0.8063} \tag{28.14}$$

$$\tau_c = \tau_v = f(f_r(f_{\text{ck}})) = 0.0511 \times f_{\text{ck}}^{0.805} \tag{28.15}$$

From Eq. 28.1, the compressive strength of concrete is explicated through Eq. (28.16)

$$f_t = f(f_{\text{ck}}) = 0.1725(f_{\text{ck}})^{0.9161}$$

$$f_{\text{ck}} = 6.8(f_t)^{1.09} \tag{28.16}$$

From Eqs. (28.15) and (28.16), the shear strength of concrete as a function of tensile strength is given in Eq. (28.17)

$$\tau_c = \tau_v = f(f_r(f_{ck}(f_t))) = 0.0511 \times (6.8(f_t)^{1.09})^{0.805}$$

$$\tau_v = f(f_r(f_{\text{ck}}(f_t))) = 0.0511 \times 4.679(f_t)^{0.87}$$

$$\tau_v = f(f_r(f_{\text{ck}}(f_t))) = 0.23 \times (f_t)^{0.87} \tag{28.17}$$

28.4 Failure Envelopes

Generally in triaxial shear test, the specimen is subjected to like stresses (compressive stresses) in mutually perpendicular axis and the shear stress is assessed as the function of compressive stress but the tensile strength of the materials is not considered.

Mohr's theory of failure provides acceptable strength prediction of concrete. The parabolic and straight line envelope has been suggested for the family of Mohr's circle representing the failure condition. The research works on mechanism of shear transfer were referred in ASCE-ACI-426 [8], and this shows the failure envelope drawn on the corresponding circles of stresses to assess the shear strength.

The principal stresses are graphically represented by drawing the Mohr's circles. The principal compressive stress is drawn in a positive quadrant, and principal tensile stress is in negative quadrant of the axis. The Mohr's failure envelope is drawn as the function of principal compressive and tensile stresses. The value of shear stress is the function of principal stresses measured between the points of intersection of the tangent of the circles on *y*-axis to the origin.

$$\text{When } \tau_c = f\left(\sigma_{1,}\sigma_2\right)$$

$$\text{Graphically } \tau_c = ED$$

$$\tau_c = \frac{\sigma_1}{2}; \quad \text{When } \sigma_2 = 0$$

$$\tau_c \neq 0; \quad \text{Even if } \sigma_2 = 0$$

The value of τ_c is existed even when the principal tensile stress is zero. The concrete is generally weak in tension and can be considered as critical strength parameter rather than compressive stress parameter. The concrete structure will fail even though it has good compressive strength when the principal tensile stress is reached to its maximum limit. Under this condition, the shear strength of the concrete could be considered on the tensile strength of the concrete. A new approach is introduced here over modified failure envelope by drawing the triangle AO1O2 with angle Φ as shown in Fig. 28.5.

In this approach, the shear strength of the material is zero when the tensile strength of material tends to zero. The shear strength from the modified approach can be assessed as explained below.

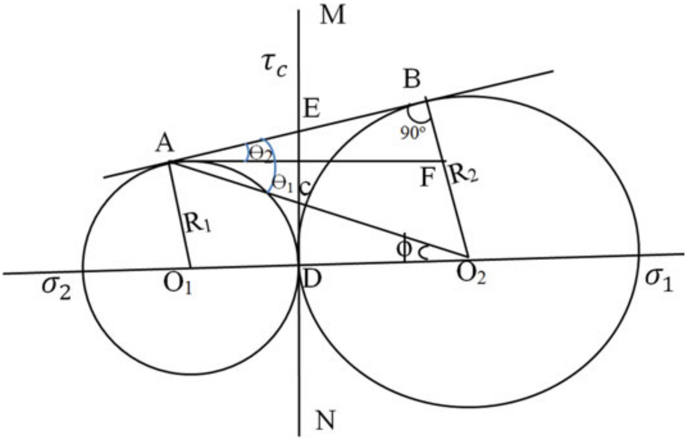

Fig. 28.5 Modified failure envelope

τ_c is the modified function (f_m) of $\sigma_{1,}\sigma_2$ and ϕ

$$\sigma_1 = f_{\text{ck}}; \quad \sigma_2 = f_t$$

$$\tau_c = f_m\left(\sigma_{1,}\sigma_2, \phi\right)$$

Graphically, $\tau_c = CD$

When $\sigma_2 = 0$ then $\phi = 0$ and $\tau_c = 0$; the shear strength CD is given in Eq. (28.23), derived through Eqs. (28.18)–(28.22)

$$\tan\theta_1 = \frac{R_2}{2\sqrt{(R_1 R_2)}} \tag{28.18}$$

$$\tan\theta_2 = \frac{R_2 - R_1}{2\sqrt{(R_1 R_2)}} \tag{28.19}$$

$$R_2 = \frac{\sigma_1}{2} \tag{28.20}$$

$$R_1 = \frac{\sigma_2}{2} \tag{28.21}$$

$$\Phi = \theta_1 - \theta_2 \tag{28.22}$$

$$\tau_c = CD = \frac{\sigma_1}{2}\tan\Phi \tag{28.23}$$

The shear strength of geopolymer concrete is compared with the empirical equation suggested by ACI-318-08 [9] as shown below in Eq. (28.24)

$$\tau_c = \frac{1}{6}\sqrt{f_c'} \tag{28.24}$$

Codes are suggesting certain material properties in the absence of experimental results. Here, ACI-318 suggesting the shear strength is based on the compressive strength of the concrete. The results of series of shear strength from the respective equation are shown in Table 28.4 and graphically represented in Fig. 28.6.

Table 28.4 Assessment of shear strength

Mixtures	$\tau_c = f(f_t)$ MPa (Eq. 28.5) (Series1)	$\tau_c = f(f_r(f_{ck}))$ MPa (Eq. 28.15) (Series 2)	$\tau_c = f(f_r(f_{ck}(f_t)))$ MPa (Eq. 28.17) (Series 3)	$\tau_c = f_m(\sigma_1, \sigma_2, \phi)$ MPa (Eq. 28.23) (Series 4)	τ_c (ACI 318-95) MPa (Eq. 28.24) (Series 5)
FGC-M1	0.94	0.41	0.34	0.49	0.54
FGC-M2	1.06	0.47	0.45	0.55	0.59
FGC-M3	1.22	0.53	0.50	0.63	0.64
FGC-M4	1.54	0.63	0.62	0.80	0.71
FGC-M5	1.76	0.71	0.69	0.90	0.76
FGC-M6	1.83	0.76	0.72	0.94	0.79
FGC-M7	2.06	0.83	0.79	1.05	0.84
FGC-M8	2.16	0.87	0.83	1.11	0.86
FGC-M9	2.26	0.90	0.86	1.15	0.88
FGC-M10	2.32	0.95	0.88	1.18	0.91
FGC-M11	2.57	1.00	0.96	1.32	0.94
FGC-M12	2.66	1.02	1.00	1.37	0.96

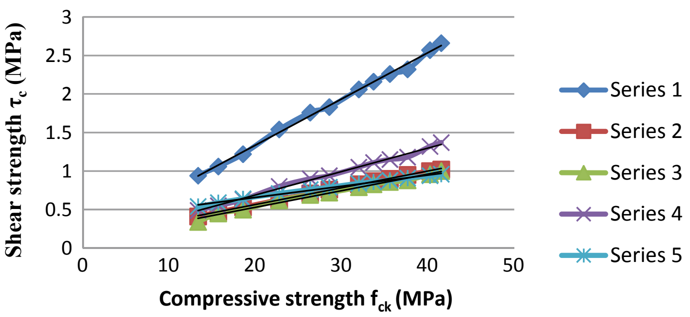

Fig. 28.6 Comparison of results

28.5 Conclusions

The experimental analysis of shear strength is concluded by comparing the results with the solution by the equation suggested by ACI-318-08 for conventional concrete which is taken as reference.

1. The shear strength of the concrete evaluated as a function of tensile stress only (Series 1) shows a higher value. The concrete fails when the maximum tensile strength is equal to principal tensile strength. This solution can be considered as the upper bound solution for the maximum shear strength of plain concrete.
2. The shear strength computed on the flexural strength as a function of compressive strength $f(f_r(f_{ck}))$ varied with range maximum of 24% and the minimum of 6% with the result of reference equation (ACI-318-08).
3. The shear strength based on the tensile stress which is the function of compressive and flexure strength $f(f_r(f_{ck}(f_t)))$ shows the maximum of 38% and minimum of −4% of variations.
4. The shear strength on modified function of principal stresses $f_m(\sigma_1, \sigma_2, \phi)$ shows the maximum of +40% and minimum of 10% variation.
5. The new approach on modified failure envelope provides consistent solution of average 13% with the reference equation up to the concrete strength equal to M-25 grade.
6. The shear strength of the concrete mix grade higher than M-25 showed comparatively higher shear strength by modified failure envelope in comparison of other series of solutions. The shear strength of concrete will be significantly more for higher grade concrete. The general equation on shear strength could not be justifiable for high-grade concrete unless modifying the equation or experimental formulation on the range of strength of concrete. The validation of these approaches is limited with one reference and could be considered for further discussion with other previous research significance.
7. The geopolymer concrete shows comparatively equal shear strength with conventional concrete and validates with the equations suggested for conventional concrete. The relationship between the strength parameters can be justifiable with conventional concrete.

References

1. Lavanya, G., Jagan, J.: Evaluation of the relationship between split tensile strength and compressive strength for geopolymer concrete of varying grades and molarity. Int. J. Appl. Eng. Res. **10**(15), 35523–35527 (2015). ISSN 0973-4562
2. Yusuf, I.T., Jimoh, Y.A., Salami, W.A.: An appropriate relationship between flexural strength and compressive strength of palm kernel shell concrete. Alexandria Eng. J. **55**, 1553–1562 (2016)
3. IS: 3812.: Specification for pulverised fuel ash" Part-2, Bureau Of Indian Standard, New Delhi (2003)

4. IS: 383.: Specification for coarse and fine aggregates" Bureau Of Indian Standard, New Delhi (1970)
5. Kumar, S., Pradeepa, J., Ravindra, P.M.: Experimental investigations on optimal strength parameters of fly ash based geopolymer concrete. Int. J. Struct. Civil Eng. Res. **2**(2), 143–152 (2013)
6. IS: 516-1956.: Methods of tests for strength of concrete" Bureau Of Indian Standard (1956)
7. Al-Sahawneh, E.I. A new approach for the determination of tensile and shear strengths of normal weight concrete. IOSR J. Eng. **05**(08), 38–48 (2015). ISSN (e): 2250-3021, ISSN (p): 2278-8719
8. ASCE-ACI Committee 426.: Shear strength of reinforced concrete members. ASCE Proc. **99**(6), 1091–1188 (1973)
9. AC1: 318-2008.: "Building Code Requirements for Structural Concrete", and Commentary Report (AC1 318-08), ACI Committee (2008)