Advances in Concrete Construction, *Vol. 7, No. 4 (2019) 231-239*
DOI: https://doi.org/10.12989/acc.2019.7.4.231

Effect of ultra-fine slag on mechanical and permeability properties of Metakaolin-based sustainable geopolymer concrete

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(Received August 17, 2018, Revised April 10, 2019, Accepted April 18, 2019)

Abstract. The present study deals with the development of metakaolin-based geopolymer concrete (GPC) and thereafter studying the effects of adding ultra-fine slag on its mechanical and permeability characteristics. The mechanical characteristics including compressive, split tensile, flexural strengths and elastic modulus were studied. In addition, permeability characteristics including water absorption, porosity, sorptivity and chloride permeability were studied up to 90 days. The results showed the effective utilization of metakaolin for the development of elevated temperature cured geopolymer concrete having high 3-day compressive strength of 42.6 MPa. The addition of ultra-fine slag up to 15%, as partial replacement of metakaolin resulted in an increase in strength characteristics. Similar improvement in durability properties was also observed with the inclusion of ultra-fine slag up to 15%. Beyond this optimum content of 15%, further increase in ultra-fine slag content affected the mechanical as well as permeability parameters in a negative way. In addition, the relationship between various properties of GPC was also derived.

Keywords: geopolymers; metakaolin; ultra-fine slag (alccofine); mechanical properties; permeability properties

1. Introduction

The demand of concrete is increasing exponentially with the boom in housing sector and infrastructure development which also increases the demand of conventional cement. However, cement industry is responsible for the release of approximately 7% of total greenhouse gases emissions such as nitrogen oxide (NO_x) and carbon dioxide (CO_2) which makes it unfit in the virtual picture of sustainable environment. Geopolymer technology, coined by Davidovits (Davidovits 1988, Davidovits 1988) involves the binder produced by the polymerization of alumina and silica with the alkali activators solution in presence of elevated or ambient curing, which have a potential of replacing conventional concrete and reducing the CO_2 emissions by approximately 80%. Geopolymers have found to exhibit very high chemical stability which possess high values of mechanical and durability parameters (Petermann, Saeed *et al*. 2010).

With the on-going industrial revolution across the globe, there is a major problem of landfill and disposal problems of industrial by-products such as rice husk ash (RHA), fly ash etc. Geopolymer technology relies on utilizing these industrial by-products that are rich in silica and alumina. Previous studies have reported the effective utilization of some pozzolanic materials (Allahverdi *et al*. 2008), alumino-silicate materials (Xu and Van Deventer 2002) industrial by-products such as metakaolin (Latella *et al*. 2008), fly ash (Rattanasak and Chindaprasirt 2009, Nematollahi *et al*. 2014) granulated blast furnace slag (Cheng and Chiu 2003) etc.

Metakaolin which is commonly known as china clay is thermally treated material. India is on the second place after USA in the annual production of kaoline with 4.48 million metric tonnes in the year 2015 (Jewell and Kimball 2015). Ultra-fine slag named Alccofine is obtained through controlled granulation and highly reactive. Ultra-fine slag have been used previously to develop high strength conventional and fly ash based geopolymer concrete but literature on the its effects on the metakaolin based geopolymer concrete is not available (Jindal *et al*. 2017).

The objective of present study is to develop metakaolin-based GPC and to evaluate the effects of adding ultra-fine slag (0-25%) as partial replacement of metakaolin, on mechanical properties such as compressive, split tensile, flexural strengths and permeability properties such as water absorption, porosity, sorptivity, chloride permeability, respectively, up to the age of 90 days. In addition, relationship between strength and permeability properties of geopolymer concrete have also been derived.

2. Material and methods

2.1 Materials

Metakaolin, as shown in Fig. 1, with specific gravity

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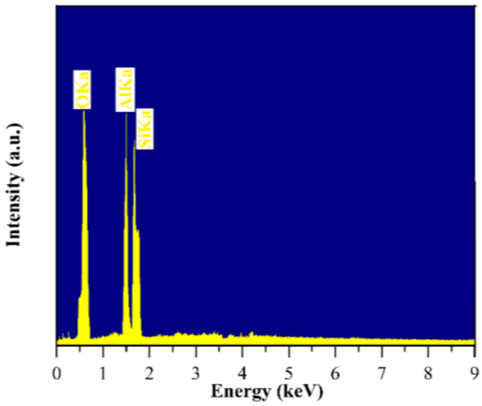
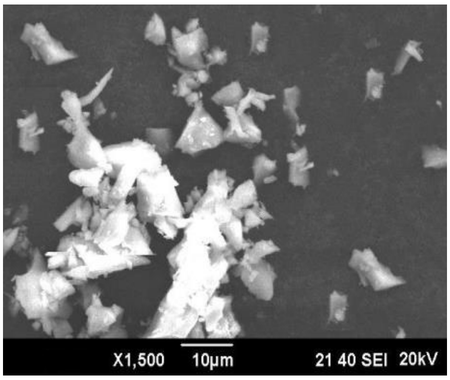
ISSN: 2287-5301 (Print), 2287-531X (Online)

Fig. 1 Raw image of metakaolin



(a)



(b)

Fig. 2 EDS (a) and SEM(b) images of metakaolin

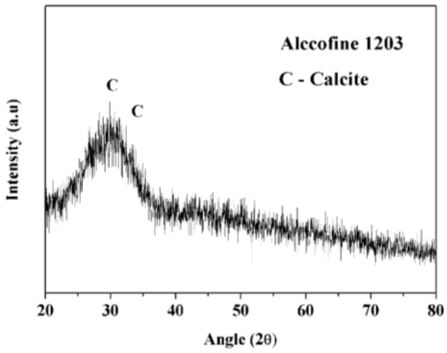
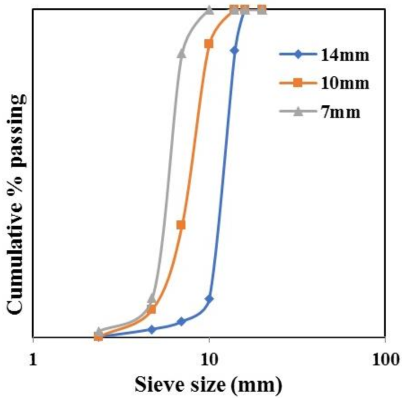
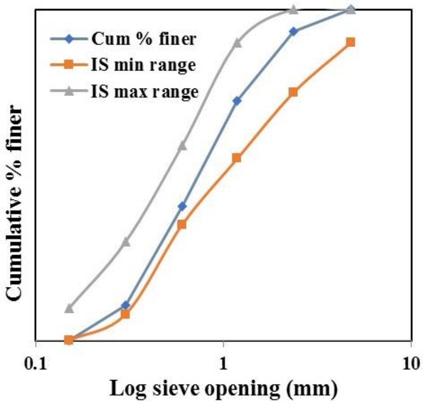


Fig. 3 XRD pattern of Ultra fine slag/Alccofine 1203



(a)



(b)

Fig. 4 Grading curves of (a) Coarse aggregate (b) Fine aggregate

2.61, specific surface area 19.75 m^2/gm, particle size below 45 μm and density around 475 g/litre was used in this study. Fig. 2 shows the SEM analysis of the metakaolin which indicated the presence of Si and Al atoms along with other elements whereas Table 1 shows the EDS analysis of the metakaolin. Ultra-fine slag with physical properties shown in Table 2 was used as partial replacement of metakaolin. Fig. 3 shows the XRD analysis of metakaolin which indicated the presence of calcite compounds. The chemical analysis was performed on metakaolin and ultra-fine slag particles as shown in Table 3. It was observed that metakaolin has considerable amount of alumina and silica so that to be used as a source material for geopolymers and ultra-fine slag has fair amount of calcium making it suitable to be used as a calcium source. The alkali-activating solution consists of mixture of sodium hydroxide (molarity 10M) and sodium silicate (16.20% Na_2O, 34.72% SiO_2 and 49.08% water), prepared approximately 24 hours prior to casting in order to achieve co-relation between the mixture and casting temperature (Li and Liu 2007, Kong *et al*. 2008). Coarse aggregates were used as crushed stone aggregates of 14, 10 and 7 mm in size and in the proportion of 45, 35 and 20% (Parveen and Singhal 2017), respectively, whereas river sand with 2.56 fineness modulus was used as fine aggregates. The aggregates were tested in accordance with the Indian standards (1970). The specific gravity was found to be 2.72 and 2.56 whereas water absorption was found to be 1.04% and 0.30% for coarse and fine aggregates, respectively. In addition, the grading curves were also developed for coarse and fine aggregates as shown in Fig. 4.

Table 1 EDS analysis of metakaolin

Element	keV	Mass (%)	Counts	Error (%)	Atom (%)	Cation K
O K	0.527	35.69	16813.7	0.011	49.15	1.331
Al K	1.498	33.47	21654.2	0.012	26.96	1.001
Si K	1.752	30.84	19112.1	0.021	23.89	1.015
Total	-	100.00	-	-	100.00	-

Table 2 Physical properties of ultra-fine slag

Physical properties	Ultra-fine slag
Average particle size (μ)	4-6
Bulk density (kg/m^3)	600-700
Specific gravity	2.86
Fineness (cm^2/gm)	12000

Table 3 Chemical properties of ultra-fine slag and metakaolin

Oxides	Ultra-fine slag (%)	Metakaolin (%)
Silica oxide (SiO_2)	35.30	58.10
Aluminium oxide (Al_2O_3)	21.40	37.15
Iron oxide (Fe_2O_3)	1.20	1.19
Calcium oxide (CaO)	32.20	0.26
Magnesium oxide (MgO)	0.85	0.29
Potassium oxide (K_2O)	0.64	0.24
Sodium oxide (Na_2O)	0.29	0.23
Sulphur trioxide (SO_3)	2.79	0.19

2.2 Methods

Based on the results obtained from various trial mixtures, the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) and ratio of alkali activating solution to the total geopolymer precursors (metakaolin and ultra-fine slag) was obtained as 2.5 and 0.45, respectively. Trial mixtures also achieved the adequate workability at 1% dosage of naphthalene-based super plasticizer by weight of total geopolymer precursors. The final design mixture was developed as shown in Table 4. The casting process commenced with the mixing of dry constituents i.e. metakaolin, ultra-fine slag and aggregates in a pan mixer for about 5 minutes with the further addition of already prepared alkali-activating solution and super plasticizer.

The mechanical parameters were evaluated by conducting compressive strength, split tensile strength, flexural strength and elastic modulus on compression testing machine (CTM), in which the load was applied gradually. Permeability parameters contained the detailed investigation of water absorption and porosity, sorptivity (ASTM 2004), and chloride permeability (ASTM 2012) up to the age of 90 days. The cubical specimens of size 150×150×150 mm, cylindrical specimens of size 100×200 mm, beams of 100×100×500 mm and discs of size 100×50 mm (from parent 100×200 mm cylindrical specimens) were cast to evaluate compressive, split tensile and flexural strengths, elastic modulus, and water absorption, porosity, sorptivity and chloride permeability; respectively. After the delay time of 1 hour, the specimens were cured at 90℃ for 24 hours so as to obtain minimum strength required for structural purposes. For each mixture, results reported are average of three specimens. As observed from the previous studies (Hardjito 2005, Kong and Sanjayan 2008, Kong and Sanjayan 2010, Parveen and Singhal 2017) that geopolymer mechanism involves polymeric reactions where most of the strength develops up after elevated temperature curing period (Hardjito 2005), still mechanical and durability parameters were studied up to age of 90 days.

Table 4 Mixture proportions

Mixture	Ultra-fine slag (%)	Metakaolin (kg/m^3)	Ultra-fine slag (kg/m^3)	Coarse aggregates (kg/m^3)	Fine aggregates (kg/m^3)	Alkali content (kg/m^3)	Super plasticizer (kg/m^3)
G100C0	0	306.0	0	1187	639	137.7	6.12
G95C05	05	290.7	15.3	1187	639	137.7	6.12
G85C15	15	260.1	45.9	1187	639	137.7	6.12
G75C25	25	229.5	76.5	1187	639	137.7	6.12

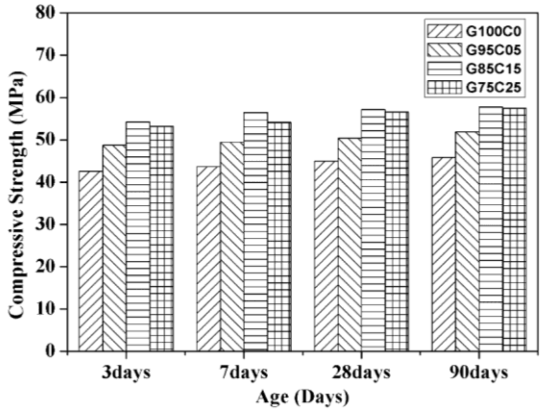


Fig. 5 Compressive strength results for geopolymer concrete

3. Results and discussion

3.1 Compressive strength

Compressive strength results of the metakaolin-based geopolymer concrete incorporating cement are shown in Fig. 5. It was observed that with the increase in ultra-fine slag content, the values of strength first increased and then decreased at all ages. For instance, at 3 days, strength values were observed as 42.57, 48.78, 54.29 and 53.28 MPa for the specimens with 0, 5, 15 and 25% ultra-fine slag, respectively. Similar trend was observed at 7, 28 and 90 days as maximum strength value was obtained for specimens with 15% ultra-fine slag and beyond that, the values decreased. Therefore, high strength at early age can be achieved by substituting ultra-fine slag into the GPC. The increase in strength with the increase in calcium content was due to the additional CSH hydration products caused by the reaction of calcium with the alkalis. This additional CSH coexisted with the geopolymeric binders sodium aluminate silicate hydrate (NASH) and calcium aluminate silicate hydrate (CASH) might resulting in modification of microstructure (Parveen *et al.* 2017).

Table 5 Ratio of splitting tensile strength and compressive strength

Mixture	3 days	7 days	28 days	90 days
G100C0	0.093	0.092	0.091	0.090
G95C05	0.088	0.087	0.087	0.085
G85C15	0.084	0.082	0.082	0.082
G75C25	0.085	0.084	0.082	0.082

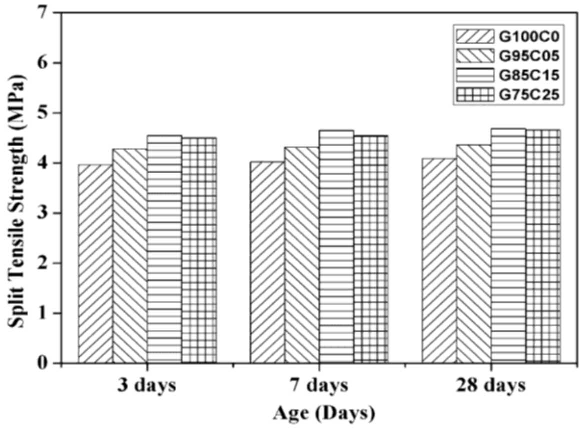


Fig. 6 Split tensile strength results for geopolymer concrete

Similar increase in strength was observed in previous studies (Alonso and Palomo 2001, Rovnaník 2010) as well. However, with the further increase in calcium content at 25%, decremented values were observed. Previous studies (Yip and Van Deventer 2003, Yip *et al*. 2005, Tailby and MacKenzie 2010, Jindal *et al*. 2017, Parveen *et al*. 2017) reported that in a blended geopolymer medium and ultra-fine slag, CSH was formed after the polymeric reactions took place; therefore, increase in ultra-fine slag relatively reduces the amount of alumina and silica which slightly hampered the polymeric reaction. Also, with the additional calcium, although CSH was introduced in the geopolymer system, but due to absence of water curing, CSH could not further developed resulting in lesser strength. It was also observed that for all mixtures, the increase in strength values after 3 days was not significant that is why 3 days strength of heat cured geopolymer is equivalent to 28 days strength of conventional concrete. For example, for mixture with 15% ultra-fine slag, strength values were observed to be 54.29, 56.48, 57.19 and 57.82 MPa at 3, 7, 28 and 90 days, respectively. This was attributed to that fact that the mechanism of geopolymers was related to polymeric reactions which initiated at high temperature. Therefore, the geopolymeric binders NASH and CASH were formed at early age only. Similar decrement in strength values were observed after a certain limit of calcium addition in previous studies also (Pacheco-Torgal *et al*. 2008, Temuujinn *et al*. 2009).

3.2 Split tensile strength

Split tensile strength results of metakaolin-based geopolymer concrete incorporating ultra-fine slag are as shown in Fig. 6. The increase of 7.3 to 15.7% for the mixes G95C05 to G85C15 with respect to reference mix G100C0 and decrease of 13.0% for the mix G75C25 was observed at the age of 7 days with regards to optimum mix G85C15. Similarly, decrease of 15.8% for the mix G75C25 with regards to optimum mix G85C15 and increase of 8.4% and 16.6% at the age of 28 days was observed with regards to the reference mix G100C0. At 3, 7, 28 and 90 days all the mixes showed higher split tensile strength than reference mix, but optimum strength was achieved for the mix G85C15. Further, strength of the mix G75C25 at all ages was almost comparable to that of G85C15. Ratio of split tensile strength to compressive strength has been depicted with the help of the Table 5. Results indicate that split tensile strength vary from 0.084 to 0.093, 0.082 to 0.092, 0.082 to 0.090 and 0.081 to 0.090 times the compressive strength, at the age of 3, 7, 28 and 90 days, respectively. This showed that geopolymer concrete have the ratio of split tensile to compressive strength in the range of 8% to 9%, however, for conventional concrete this ratio varies from 7%-9% (Mehta 2006).

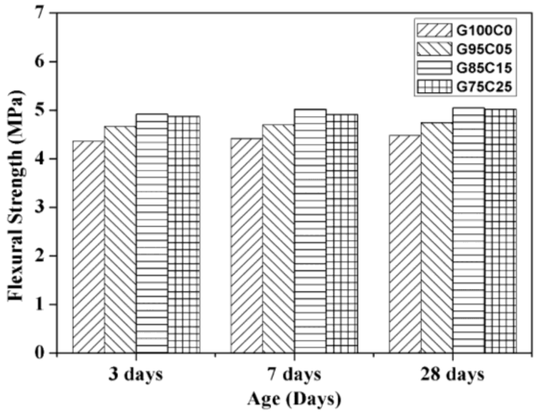


Fig. 7 Flexural strength results for geopolymer concrete

3.3 Flexural strength

Flexural strength results of the metakaolin-based geopolymer concrete incorporating ultra-fine slag are as shown in Fig. 7. The flexural strength of the geopolymer concrete specimens prepared by incorporating ultra-fine slag was observed higher than the strength observed for the mix prepared with 0% ultra-fine slag in all the cases. Further, this trend was same at all the ages. The trend of increased and decreased in flexural strength was just like compressive and split tensile strength results. The 28-day flexural strength of mix G100C0 was 4.48 MPa whereas mixes G95C05, G85C15 and G75C25 showed 4.74, 5.05 and 5.02 MPa, respectively. Flexural strength decreased marginally after 15% replacement. It is evident from the results of the Fig. 7 that flexural strength increased with age and decreased after 15% ultra-fine slag replacement.

3.4 Elastic modulus of GPC specimens

Fig. 8 illustrates the elastic modulus comparison of the geopolymer concrete specimens prepared with ultra-fine slag and 0% ultra-fine slag. It can be concluded that elastic modulus (E_c) increased with the increase in ultra-fine slag

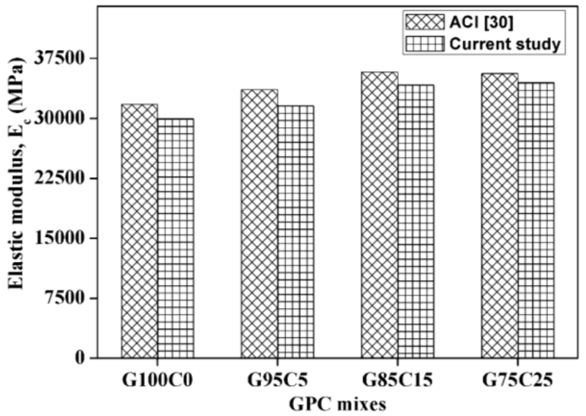


Fig. 8 Elastic modulus for conventional and geopolymer concrete

percentage but upto a limit of 15% replacement. Further, it was expected that relationship between the elastic modulus (E_c) and compressive strength (f_c) in geopolymer concrete would be nearly same as well established relationship in the case of conventional concrete. The same can be seen from the Fig. 8 that elastic modulus increased with the increase in compressive strength. Results indicated the strong relationship between the compressive strength (f_c) and elastic modulus (E_c). American Concrete Institute (ACI) code gives the elastic modulus as a direct function of the characteristics compressive strength (f_c) for conventional concrete in terms of cylinders, which is shown in Eq. (1).

$$E_c = 4733 \times \sqrt{f_c} \tag{1}$$

Where, E_c=Elastic modulus and f_c=Compressive strength

It can be concluded from the Fig. 8 that ACI overestimate the elastic modulus (E_c) of the geopolymer concrete, however, there was a marginally difference of 3-12% between the values proposed by ACI and geopolymer concrete.

3.5 Relationship of split tensile and flexural strengths to compressive strength

Fig. 9 showed the relationship between compressive and split tensile strengths for the metakaolin based GPC incorporating alccofine. Table 6 confirmed the close relationship between split tensile and compressive strength and the same has been confirmed by other researchers also (Gardner and Poon 1976, Carino and Lew 1982, Raphael 1984, Sofi *et al*. 2007, 318 2008, Anuradha *et al*. 2011, Lee and Lee 2013, Ryu *et al*. 2013). Regression analysis was performed to obtained the non-linear equations between split tensile and compressive strength of metakaolin based geopolymer concrete as depicted in Eq. (2). Fig. 9 showed the realistic representation of the regression lines for metakaolin based GPC and it has a direct relationship with the compressive strength similar to conventional concrete.

$$f_{spt} = 0.467 \times f_c^{0.57} \quad \text{MPa} \tag{2}$$

Where, f_{spt}=Split tensile strength and f_c=Compressive strength in MPa

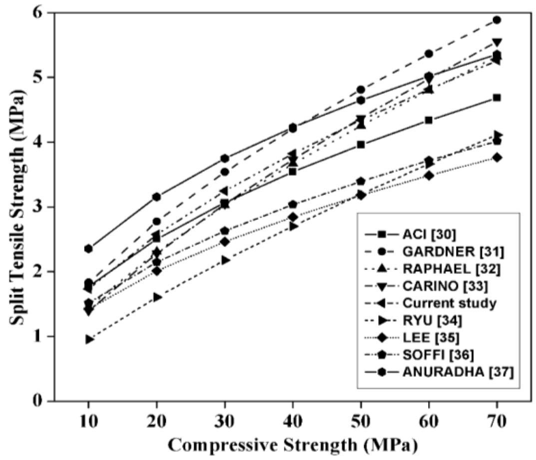


Fig. 9 Relationship between compressive and split tensile strength

Table 6 Relationship between compressive and split tensile strength

	ACI 318-99	Gardner *et al.*	Raphael *et al.*	Carino *et al.*	Current study	Ryu *et al.*	Lee *et al.*	Sofi *et al.*	Anuradha *et al.*
	Conventional concrete				Geopolymer concrete				
	Split tensile strength, f_{spt}=a* (Compressive strength, f_c) ^{ß}								
a	0.56	0.46	0.313	0.272	0.467	0.17	0.45	0.48	0.892
ß	0.50	0.60	0.66	0.71	0.57	0.75	0.50	0.50	0.422

Where, *a* and *ß* are constants.

Table 7 Relationship between compressive and flexural strength

	AS 3600	ACI 318	IS 456	NZS-3101	Current study	Gunasekara *et al*. (2017)
	Conventional concrete				Geopolymer concrete	
	Flexural strength, f_s = α *sqrt (*Compressive strength*, f_c)					
a	0.60	0.62	0.70	0.60	0.667	0.70

Where, *a* and *ß* are constants.

Fig. 10 shows a scattered plot in between flexural and compressive strengths which were developed by using the relationships (3600 2001, 3101:2006 2006, Gunasekera *et al*. 2017) as shown in Table 7. The proposed equation is based on the nonlinear regression model and is shown in Eq. (3).

$$f_s = 0.668 \times \sqrt{f_c} \quad \text{MPa} \tag{3}$$

Where, f_s=Flexural strength and f_c=Compressive strength

It can be concluded from the Figs. 9 and 10 that the non-linear proposed equations for the geopolymer concrete fall within the already existing equations for conventional concrete in the various standards such as American Concrete Institute code (ACI 318 2008), Australian Standard (AS) (AS 2009) and Indian Standard (IS) (BIS 2000). In addition, the relationship developed by other researchers has also considered for comparison. It is clear from the above proposed equations that split tensile and flexural strengths increased with the increase in compressive strength. It is worth noting that design

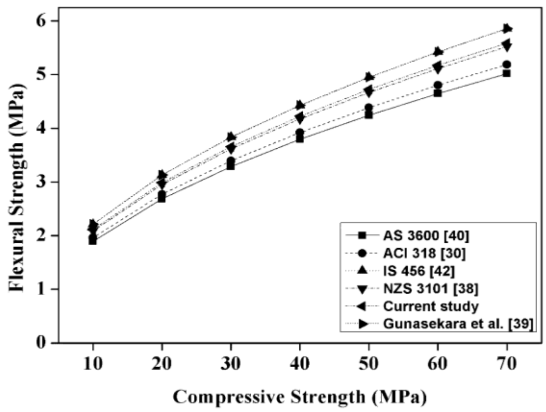


Fig. 10 Relationship between compressive and flexural strength

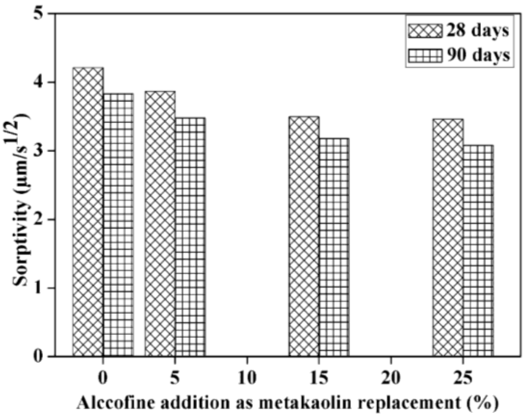


Fig. 12 Sorptivity for geopolymer concrete

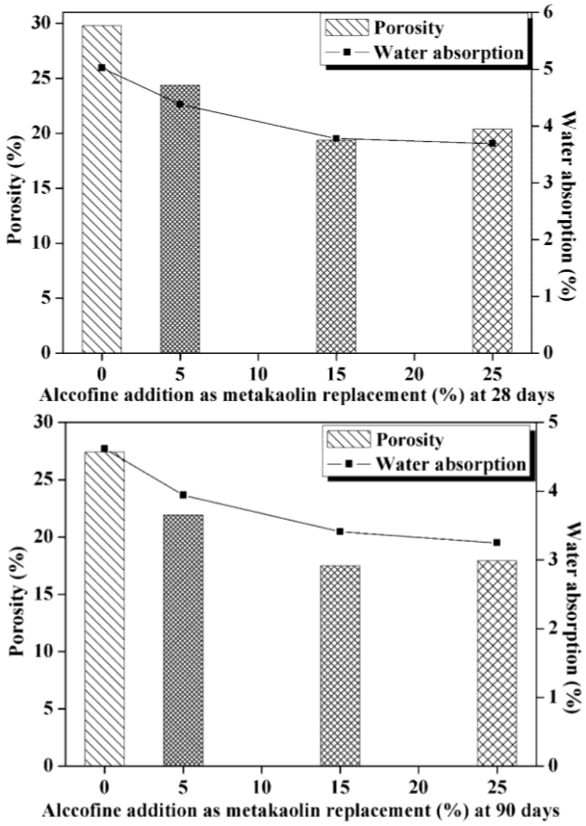


Fig. 11 Water absorption and Porosity for geopolymer concrete

equation provided by ACI and AS for conventional concrete underestimate the flexural strength. Further, IS overestimate the flexural strength but the difference noticed was much lower therefore, application of the ACI and AS would provide conservative design than IS in terms of flexural strength. Overall, flexural strength and split tensile strength of the GPC can be well predicted by using the proposed equations and can be utilised with confidence while designing the structural members.

3.6 Water absorption, porosity and sorptivity

Fig. 11 showed the results of water absorption and porosity for the GPC specimens with the addition of ultra-fine slag as metakaolin replacement at 28 and 90 days. It was observed that both water absorption and porosity decreased with the increase in ultra-fine slag addition. For example, water absorption was found to be 5.02, 4.37, 3.78 and 3.69% for the mixtures with 0, 5, 15 and 25% ultra-fine slag, respectively. Similar trend was observed with the porosity as the values obtained were 29.79, 24.37, 19.38 and 20.36% for specimens with 0, 5, 15 and 25% ultra-fine slag, respectively. Although the best results were obtained for the specimens with 25% ultra-fine slag but the difference between 15 and 25% ultra-fine slag specimens was not significant as almost similar values were observed. Fig. 12 showed the results of sorptivity values at 28 and 90 days. The values were calculated as 4.214, 3.869, 3.498 and 3.462 $\mu m/s^{1/2}$ for specimens with 0, 5, 15 and 25% ultra-fine slag specimens at the age of 28 days. This was due to the fact that with the increase in ultra-fine slag in the geopolymer system, extra calcium based products would have filled the pores and increased the denseness of the matrix. The conventional CSH hydrate coexisted with the geopolymeric reaction products NASH and CASH which modified the microstructure significantly. With the increase in calcium content, CSH in the binder increased further and made the microstructure less porous.

3.7 Chloride permeability

The discs from the parent cylindrical specimens were cut and tested for chloride permeability at 28 and 90 days. One end of the specimen was immersed in sodium hydroxide solution and the other end in sodium chloride solution. Electric charge was passed and readings were recorded up to 6 hours with a constant potential difference of 60V. Based on charge passed (in coulombs) the chloride resistance was observed as negligible, very low, low, moderate and high as shown in Table 8 (ASTM 2012). The results as shown in Fig. 13 showed that with the increase in calcium content in the geopolymer system, the total charge passed decreased. For specimens with no calcium, the chloride permeability was found to be in “moderate” category as shown in Table 9. With the increase in calcium content, at 5% ultra-fine slag, the category changed to “low” whereas for the specimens with 15% and 25% ultra-

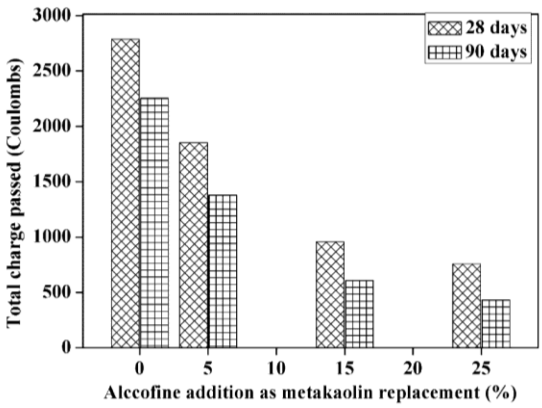


Fig. 13 Chloride permeability of geopolymer concrete

Table 8 Chloride ion permeability based on total charge passed (ASTM C1202)

Charge passed (in coulombs)	Chloride ion permeability range
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Table 9 Rapid chloride permeability test results for specimens at 28 and 90 days

Mixture	Ultra-fine slag (%)	Charge passed (in coulombs) at 28 days	Charge passed (in coulombs) at 90 days	Permeability range (as per ASTM C1202)
G100C0	0	2789	2255	Moderate
G95C05	05	1853	1381	Low
G85C15	15	957	611	Very Low
G75C25	25	758	434	Very Low

fine slag, the permeability changed to “very low” category. It can be concluded that with the increase in ultra-fine slag content in the matrix, the resistance of the geopolymer concrete increased considerably. This was due to the improvement in microstructure which became more compact and dense due to the addition of hydrated products like CSH with the geopolymeric binders NASH and CASH which decrease the pores and made it less permeable. However, the difference between the values of charge passed for the specimens with 15% and 25% ultra-fine slag was not significant.

3.8 Relationships

Permeation properties i.e., porosity, sorptivity, chloride permeability and water absorption can be referred to as dependent on compressive strength as more compressive strength relates to more compact and dense microstructure which results in reduction in pores and makes it less permeable. Polynomial regression analysis was performed on the obtained results and a relationship between compressive strength and porosity was derived as shown in Fig. 14. The equation was derived as shown in Eq. (4) below.

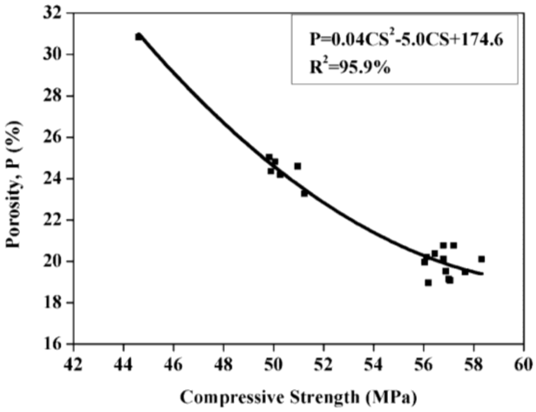


Fig. 14 Relationship between compressive strength and porosity

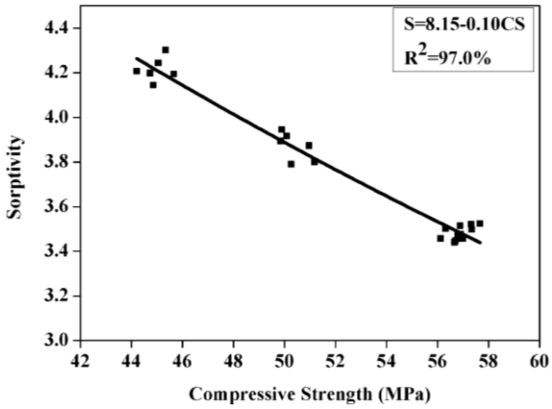


Fig. 15 Relationship between compressive strength and sorptivity

$$P=0.04\text{CS}^2-5.0\text{CS}+174.6 \tag{4}$$

Where, P refers to the porosity (%) and CS denotes compressive strength. A high value of coefficient of determination of R-Sq=95.9% was obtained which confirmed a good correlation between the curve values and actual values.

Linear regression analysis was conducted to derive the relationship between compressive strength and sorptivity as shown in Fig. 15. The equation was obtained as shown in Eq. (5) below.

$$S=8.15-0.10\text{CS} \tag{5}$$

Where, S denotes sorptivity (μm/s$^{1/2}$) and CS denotes compressive strength. Regression curve was authenticated with the actual values as a high coefficient of determination value (R-Sq=97.0%) was obtained.

In addition, the relationship was also derived between the compressive strength and the total charge passed in the chloride permeability test as shown in Fig. 16. Linear regression analysis was performed on the results and the equation was obtained as shown in Eq. (6).

$$TC=19889.95-158.77\text{CS} \tag{6}$$

Where, TC denotes the total charge passed in the RCPT and CS refers to the compressive strength values obtained in this study. For this equation, a high value of determination

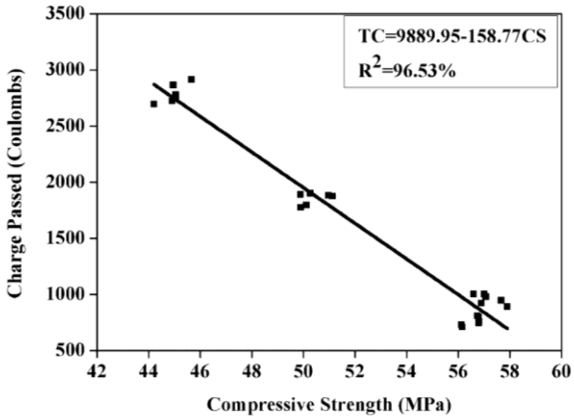


Fig. 16 Relationship between compressive strength and chloride permeability

coefficient (*R-Sq*=96.1%) was obtained which indicate a good relation between the actual values and the values obtained from this equation.

4. Conclusions

The present study indicates the utilization of metakaolin in the development of geopolymer concrete and the positive effect of adding optimum content of ultra-fine slag on mechanical and permeability properties of GPC. Based on the results obtained, following conclusions can be drawn:

1. The compressive strength of metakaolin-based GPC incorporating increased with the increase in ultra-fine slag content. Maximum strength of 57.19 and 57.82 MPa was observed at the age of 28 and 90 days, respectively, for the specimens with 15% ultra-fine slag. Similar, behaviour was observed in the case of split tensile and flexural strengths.
2. ACI standards overestimate the elastic modulus of the geopolymer concrete, however there was marginally difference (max -12%) between the observed and calculated values.
3. Mechanical behaviour of the geopolymer concrete incorporating ultra-fine slag was comparable to that of conventional concrete for all the mixes. Further, ultimate strength was achieved by substituting 15% of metakaolin with ultra-fine slag.
4. Mechanical properties of the GPC were found to be similar to that of conventional concrete. Therefore, design methodologies of conventional concrete can be applied to geopolymer concrete.
5. Permeation properties such as water absorption, sorptivity and porosity found to be improved with the addition of ultra-fine slag in the geopolymer matrix. Best results were obtained for the specimens with 15% ultra-fine slag. However, marginal difference between the values obtained for specimens with 15 and 25% ultra-fine slag was not significant.
6. Metakaolin based geopolymer concrete with partial replacement of ultra-fine slag found to have excellent resistance against chloride penetration with "low" and "very low" category.

Acknowledgment

The authors acknowledge the financial support provided by Ministry of Environment, Forest and Climate Change, India (grant number 19-38/2014-RE; 2016). The authors are further highly thankful for the administrative support provided by DCR University of Science and Technology, Murthal, Sonepat.

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