# FRESH AND MECHANICAL PROPERTIES OF AMBIENT CURED TERNARY BLENDED GEOPOLYMER CONCRETE REINFORCED WITH STEEL FIBERS

[a] Muhammad Ibraheem, [b] Faheem Butt

[a, b] Department of Civil Engineering,
University of Engineering and Technology, Taxila
a:ibrahim.123456@yahoo.com
b: faheem.butt@uettaxila.edu.pk

***Abstract-*** This paper focuses on development of a substitute binding material to replace Ordinary Portland cement (OPC) in conventional concreting. A total of 15 mix types (cured at ambient temperature) for the fly ash (FA) and slag (SG) based geopolymer concrete (GPC) with quarry rock dust (QRD) as a partial replacement of SG, incorporated with steel fibers (SF), were prepared and tested. A series of tests to determine the fresh and hardened properties viz. slump, compressive, split tensile and flexural strength, were carried out on the prepared samples. The workability of GPC mixes decreases with the increase of QRD content. From mechanical properties, the optimum mix obtained in this study is GPC-D0.75F which contains 50% FA, 35% SG and 15% QRD by weight and 0.75% SF by volume. The compressive, splitting tensile and flexural strengths of the optimum mix have improved significantly than their OPC concrete counterpart.

***Keywords***- Ambient temperature curing, geopolymer concrete, quarry rock dust, steel fibers.

## 1 INTRODUCTION

One of the main important materials in conventional concrete is ordinary Portland cement (OPC) and its production and demand high energy. The discharge of carbon dioxide ($CO_2$) during the production of cement is a major problem and forced investigators to look for substitute of binding material in concrete. Geopolymer concrete (GPC), which omits conventional cement as binder, is considered as one of the potential substitutes to cement based concrete. The use of industrial by-products such as fly ash (FA), slag (SG), rice husk ash (RHA), metakaolin (MK), palm oil fuel ash (POFA), etc. as partial and whole cement replacement in conventional and geopolymer concrete has been reported [1]–[3]. It is reported that GPC production with low calcium FA resulted in a better mechanical properties at elevated temperature curing [4] which limits its use to precast members only. However, the results are relatively less promising at ambient temperature curing conditions. The reason for this is the polymerization process which efficiently takes place at elevated temperature and leads to the formation of calcium aluminate silicate hydrate (CASH) and sodium aluminate silicate hydrate (NASH) compounds [5]. Investigations have endorsed the use of SG to achieve the encouraging outcomes at ambient curing conditions [6]. In some studies the reactivity of FA was enhanced at the ambient temperature by the addition of calcium rich materials such as SG [6], alccofine [5] etc. It has been observed that FA and SG blended geopolymer mixes showed good resistance to elevated temperature [7], sodium sulphate attack but suffered deterioration in magnesium sulphate attack [8] and exhibited increased shrinkage [9]. It is also reported in an experimental work that calcium containing materials increase the rate of geopolymerization at ambient temperature, reduce the pore sizes in mix and produce compacted composite with good mechanical properties [10], [11].

Fibers are generally incorporated in concrete to control cracking due to plastic and drying shrinkages and decrease the permeability of concrete by decreasing bleeding water. Islam et al. 2017 [12] have investigated the effect of steel fibers on mechanical properties of slag-based GPC and stated that incorporation of steel fiber improve mechanical properties especially splitting tensile and flexural strength and reduce the fresh properties.

The quarry rock dust (QRD) is a residue and calcium rich material which can be used as a partial replacement of binder or filler material in GPC. This can help in reducing the environmental and land pollution by avoiding its deposition at landfills. From the literature review, it was observed that generally QRD has been used as a partial replacement of sand in geopolymer mortar [13] and cement concrete [14], [15]. However, the studies on QRD as a partial replacement of the binder material in GPC are rather limited. This study therefore, investigates the effect of steel fibers (SF) and QRD (as a partial replacement of SG), on the fresh and mechanical properties of FA-SG based GPC cured at ambient temperature. The objective of the present study is to find an optimum mix of ternary blended GPC comprising FA, SG and QRD, reinforced with SF and cured at ambient temperature condition. To achieve this, a series of mixes were prepared by varying the amount of SF and QRD (to partially replace SG) in FA-SG based GPC as shown in Table 1. Six groups of mixes were designed as shown in Table 2, comprising firstly the OPC concrete group serving as the control mix, then GPC groups with 0%, 5%, 10%, 15%, and 20% QRD, partially replacing SG (by weight of binder ), while keeping all the other ingredients the same in all the groups. Further, each group comprises three mix types with 0%, 0.75% and 1.5% (by volume of composites ) SF; thus making a total of 18 mix types in the six groups. The tests are then conducted to find an optimum mix from fresh properties i.e. workability and mechanical properties viz. compressive, split tensile and flexural strengths.

## 2 EXPERIMENTAL PROCEDURE

For preparing a mix, all the ingredients, coarse aggregate, fine aggregates and binders (FA, SG and QRD) were dry mixed thoroughly in the mixer for 2 minutes. Prior to the mixing, aggregates were prepared to the saturated surface dry (SSD) condition. The sodium hydroxide (SH) solution was prepared one day before the application [5] and mixed with sodium silicate (SS) solution at a required ratio about 30 min before its use to improve the reactivity of solution [6]. All the ingredients of concrete were mixed in a mechanical concrete mixer (tilting drum type mixer) having capacity of 0.15 $m^3$. The SF was then added in dry mixture and mixing is continued for another 2 minutes, ensuring adequate fiber dispersion. The purpose of adding fibers prior to the alkaline solution was to let the fibers disperse homogeneously in the mix before it becomes too viscous. Thereafter, premixed alkaline activator solution was added gradually in the mixer and mixing lasted for another 2-3 minutes to achieve uniformity. Finally, super plasticizer (SP) and remaining water were added in the mix to achieve the required workability.

The cylinders, cubes and prisms were filled with the prepared concrete mix in three layers, compacted by a vibrator and placed at ambient temperature for 24 to 48 hours. The specimens were then demolded and kept in the sunlight for 7, 28 and 56 days for testing. Three specimens were used for any test of a mix type and the average value was reported in the results.

### *2.1 Materials*

The OPC type-II cement conforming to ASTM C-150 [16] was used for control specimens of conventional concrete. The FA, SG and QRD in different proportions were used as a binder in the production of GPC mixtures. The low class FA is the preferred source than the high class FA because high amount of calcium interfere the polymerization process and alters the microstructure [17]. The QRD was collected from the aggregate crushing plants at Margallah hills (Taxila), and grounded using a ball mill machine at Pakistan Council of Scientific and Industrial Research (PCSIR) Peshawar. Further, it was sieved through 45µm sieve to choose the finest particles for using as a binder in the GPC production. The Figure 1 shows the pictures of the used materials in the study.

The alkaline activator solution used in this study (Figure 1) consists of SS and SH. The molarity of SH was 12M and was prepared a day before the use, by mixing 98% pure flakes of it with potable water. The SS solution was collected from local commercial manufacturer. The modulus ratio (MR) of $SiO_2$ to $Na_2O$ of SS was kept in between 1.90 and 2.01.

For fine and coarse aggregates, Lawrencepur sand and Margallah crush respectively was used and procured from the locally available resources. The fineness modulus of fine aggregate was conformed to ASTM-C-136-06 [18] whereas specific gravity and water absorption was conforming to ASTM-C128-15 [19]. The Specific gravity of coarse aggregate was conforming to ASTM-C127-07 [20].

The commercially available hooked end, hard-drawn wire (steel) fibers (MasterFiber® S 65), conforming to the provisions of ASTM A820 [21], Type 1 were used. The alkaline solution is generally stickier than the water; hence its use makes the GPC mixes more viscous than the OPC concrete mix. In order to increase the workability of freshly mixed GPC, a Naphthalene Sulphonate based super plasticizer confirming to ASTM C494 [22] was used in the present study. Different materials used in this study are shown in Figure 1.


Figure 1: Images of materials used in current study

Table 1 The mix designations based on the mix compositions of OPC and GPC mixtures

| Mix ID | Mix Composition | Mix ID | Mix Composition |
|---|---|---|---|
| OPC-0F | 100% cement (Control Mix) | GPC-C0F | 50% FA+40% SG+10% QRD |
| OPC-0.75F | 100% cement + 0.75% steel fibers | GPC-C0.75F | 50% FA+40% SG+10% QRD+0.75% Steel Fibers |
| OPC-1.5F | 100% cement + 1.5% steel fibers | GPC-C1.5F | 50% FA+40% SG+10% QRD+1.5% Steel Fibers |
| GPC-A0F | 50%FA+50% SG | GPC-D0F | 50% FA+35% SG+15% QRD |
| GPC-A0.75F | 50%FA+50% SG +0.75% Steel Fibers | GPC-D0.75F | 50% FA+35% SG+15% QRD+0.75% Steel Fibers |
| GPC-A1.5F | 50%FA+50% SG +1.5% Steel Fibers | GPC-D1.5F | 50% FA+35% SG+15% QRD+1.5% Steel Fibers |
| GPC-B0F | 50% FA+45% SG+5% QRD | GPC-E0F | 50% FA+30% SG+20% QRD |
| GPC-B0.75F | 50% FA+45% SG+5% QRD+0.75% Steel Fibers | GPC-E0.75F | 50% FA+30% SG+20% QRD+0.75% Steel Fibers |
| GPC-B1.5F | 50% FA+45% SG+5% QRD+1.5% Steel Fibers | GPC-E1.5F | 50% FA+45% SG+5% QRD+1.5% Steel Fibers |

## *2.2 Testing methods*

The fresh and mechanical properties of OPC and GPC mixes were measured by the slump test, compressive, split tensile and flexural strength tests. To determine the workability of fresh concrete, slump cone test was performed soon after the completion of mixing procedure according to ASTM C143M-15a [23]. A universal testing machine (UTM) of 3000 kN capacity was used for testing the cubes and cylinders after 7, 28 and 56 days of casting to determine the compressive [24] and splitting tensile strengths by applying loads at a rate of 8 kN/s, according to ASTM C39/C39M-03 [25] and C496/C496M−11, respectively. The flexural strength test using prismatic specimens after 28 and 56 days of casting, under third point loading was conducted using the same UTM according to ASTM C1609 / C1609M - 19a [26].

Table. 2 The mix proportion of OPC and GPC mixtures

| Group ID | Mix No. | Mix ID | Concrete mixture quantity (kg/m3) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Binders | | | | | | | | | | | CA | CA | | |
| | | | B | C | FA | SG | QRD | SF | AL/B Ratio | W/C Ratio | Molarity of SH | SS/SH Ratio | SH | SS | S | 10 mm | 20mm | SPs | Water |
| OPC | 1 | OPC-0F | 400 | 400 | - | - | - | - | - | 0.35 | - | - | - | - | 680 | 751 | 340 | 10 | 140 |
| | 2 | OPC-0.75F | 400 | 400 | - | - | - | 58.5 | - | 0.35 | - | - | - | - | 680 | 752 | 340 | 10 | 140 |
| | 3 | OPC-1.5F | 400 | 400 | - | - | - | 117 | - | 0.35 | - | - | - | - | 680 | 753 | 340 | 10 | 140 |
| GPC-A | 4 | GPC-A0F | 400 | - | 200 | 200 | 0 | - | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 751 | 340 | 11 | 35 |
| | 5 | GPC-A0.75F | 400 | - | 200 | 200 | 0 | 58.5 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 752 | 340 | 18 | 35 |
| | 6 | GPC-A1.5F | 400 | - | 200 | 200 | 0 | 117 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 753 | 340 | 20 | 35 |
| GPC-B | 7 | GPC-B0F | 400 | - | 200 | 180 | 20 | - | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 754 | 340 | 12 | 35 |
| | 8 | GPC-B0.75F | 400 | - | 200 | 180 | 20 | 58.5 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 755 | 340 | 17 | 35 |
| | 9 | GPC-B1.5F | 400 | - | 200 | 180 | 20 | 117 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 756 | 340 | 21 | 35 |
| GPC-C | 10 | GPC-C0F | 400 | - | 200 | 160 | 40 | - | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 757 | 340 | 14 | 35 |
| | 11 | GPC-C0.75F | 400 | - | 200 | 160 | 40 | 58.5 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 758 | 340 | 20 | 35 |
| | 12 | GPC-C1.5F | 400 | - | 200 | 160 | 40 | 117 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 759 | 340 | 22 | 35 |
| GPC-D | 13 | GPC-D0F | 400 | - | 200 | 140 | 60 | - | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 760 | 340 | 14.5 | 35 |
| | 14 | GPC-D0.75F | 400 | - | 200 | 140 | 60 | 58.5 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 761 | 340 | 21 | 35 |
| | 15 | GPC-D1.5F | 400 | - | 200 | 140 | 60 | 117 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 762 | 340 | 23 | 35 |
| GPC-E | 16 | GPC-E0F | 400 | - | 200 | 120 | 80 | - | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 763 | 340 | 14.5 | 35 |
| | 17 | GPC-E0.75F | 400 | - | 200 | 120 | 80 | 58.5 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 764 | 340 | 22 | 35 |
| | 18 | GPC-E1.5F | 400 | - | 200 | 120 | 80 | 117 | 0.5 | - | 12 | 1.5 | 80 | 120 | 680 | 765 | 340 | 24 | 35 |

**Note:** W (Water): B (Binder); C (Cement): OPC (Ordinary portland cement); SF(Steel fibers);AL (Alkaline Solution); QRD (Quarry rock dust); SG (Ground Granulated Blast Furnace ); FA (Fly ash); SH (Sodium Hydroxide); SS (Sodium Silicate); SP (Superplasticizers); S (Sand); CA (Coarse Aggregates).

## 3 RESULTS AND DISCUSSIONS

### *3.1 Workability*

The workability is defined as the ease of placement and compaction of a freshly made concrete. It can be observed from the Figure 2 that workability of GPC mixes decreases with the increase of QRD content (also observed by Venkata Sairam Kumar & Sai Ram [27]) and SF fraction. The decrease in the workability can be due to shape of binder particles, higher viscosity of alkaline solution and uneven scattering of fibers. The QRD particles are angular in shape [27] than FA [28] and SG [29] particles that decrease the workability and increase the water requirement. The larger surface area of fibers absorbs more binder (cement, FA, SG, QRD) mortar around the fibers which increases the shear resistance to flow, resulting in a lower slump value. The maximum workability for GPC mixes was obtained by GPC-A0F which does not have QRD and SF. However, the addition of 10-15% QRD and 0.75% SF resulted in the relatively less workable concrete. The results of different mixtures can be observed from Figure 2

### *3.2 Compressive strength*

It can be observed from Figure 3 that the compressive strength of GPC mixes goes on increasing by increasing the QRD replacement level up to 15% after which it decreased. The increase in compressive strength upto 15% QRD content can be due to an increased quantity of calcium containing materials which accelerates the rate of polymerization at ambient temperature (room temperature) and reduce the pore sizes. The effect of calcium rich compounds on the strength properties at ambient temperature has also been reported by other studies like Dutta and Ghosh, and Temuujin et al. [10, 11]. When amount of QRD is increased further from 15% to 20% (as in mix GPC-E0F), the GPC mix becomes too sticky (least workable) and can't be easily casted. In order to make it workable, extra water or super plasticizers was added during mixing procedure which ultimately resulted in reduced compressive strength. The maximum strength was obtained by GPC-D0.75F with 15% QRD by weight of binder and 0.75% SF by volume. The compressive strength of this GPC mix is 21% higher than the corresponding fiber reinforced OPC control mix.

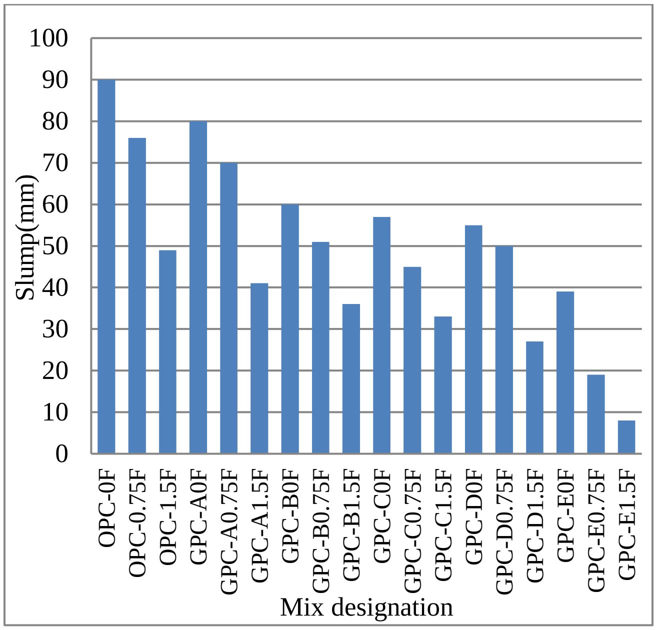



Figure 2: The result of slump test of the mixes

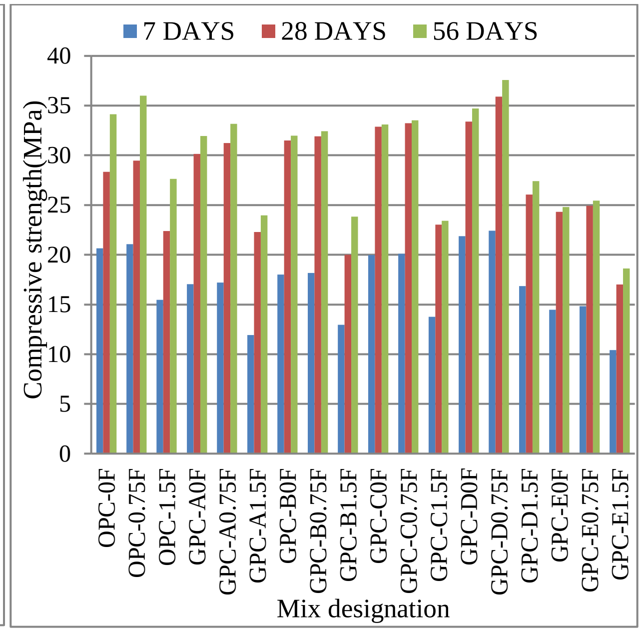


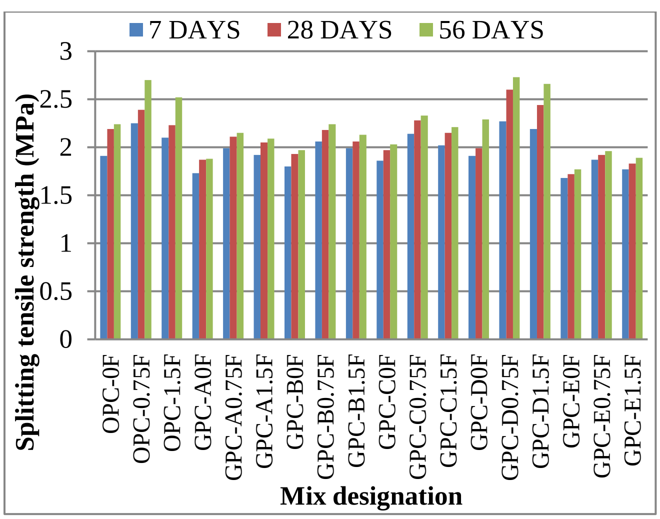

Figure 3: The result of compressive tests of the mixes

### 3.3 *Splitting tensile strength*

It can be observed from Figure 4 that splitting tensile strength of GPC mixes improved with the increase of QRD content up to 15% and SF up to 0.75%. After a further increase of QRD and SF resulted in a decreased strength of GPC mixes, due to a considerably low workable mix and a heterogeneous blend with improper distribution of SF in the mix, which ultimately reduced the splitting tensile strength. The maximum strength observed from the results is by GPC-D0.75F which has 9% more strength than its corresponding OPC concrete control mix. The splitting tensile strength of different mixes can be observed from Figure 4.

### 3.4 *Flexural strength*

It is an important property which affects the bending characteristics and brittleness ratio of concrete in structural concrete design. Figure 5 depicts the influence of QRD content and SF on flexural strength of GPC mixes. The flexural strength of the GPC mixes follows the similar trends as was observed for the compressive and splitting tensile strengths. The maximum strength was obtained by GPC-D0.75F with 15% QRD and 0.75% SF. The flexural strength of this GPC mix is 13% higher than its corresponding OPC control specimen due to better compactness and ductile nature.



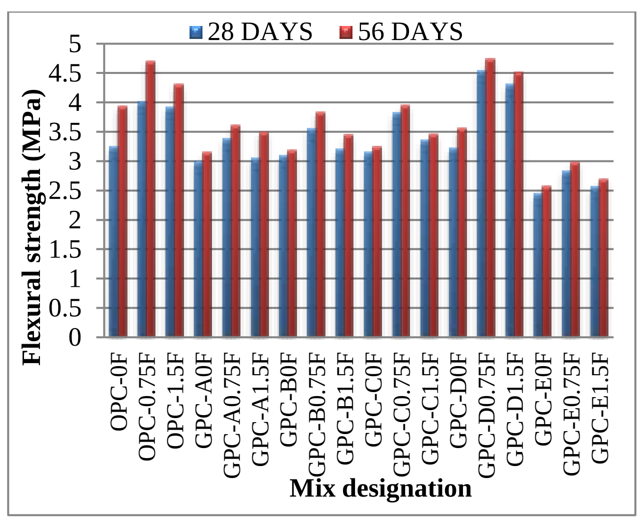



Figure 4: The result of tensile tests of the mixes

Figure 5: The results of flexural tests of the mixes

# 4 PRACTICAL APPLICATION

Generally, GPC has limited field application due to its limitation pertaining to heat curing for achieving a better strength. Due to this reason, the precast units of GPC have been manufactured and used in the field. The incorporation of calcium rich binder like SG and QRD makes possible the production of GPC at ambient temperature curing with good strength properties; hence, expanding its application to the areas beyond precast members. This also reduces the energy and cost associated with the heat curing.

# 5 CONCLUSIONS

Following conclusions can be drawn from this study:

1. The workability of GPC mixes deteriorates as QRD and SF incorporation increases.
2. Maximum compressive, splitting tensile and flexural strengths at ambient temperature curing was obtained by GPC-D0.75F which has 15% QRD of total binder and 0.75% SF by volume.
3. A substantial reduction was observed in the mechanical properties of GPC mixes when QRD was increased from 15% to 20% and steel fiber fraction from 0.75% to 1.5%. Hence, the optimum quantity to be used for achieving a superior GPC mix (than the OPC concrete) with an acceptable workability is with 15% QRD replacement with SG and 0.75% SF for a low calcium FA-SG based GPC mix.

# 6 REFERENCES

[1] M. Sumesh, U. J. Alengaram, M. Z. Jumaat, K. H. Mo, and M. F. Alnahhal, "Incorporation of nano-materials in cement composite and geopolymer based paste and mortar – A review," *Construction and Building Materials*. 2017.

[2] A. Sharmin, U. J. Alengaram, M. Z. Jumaat, M. O. Yusuf, S. M. A. Kabir, and I. I. Bashar, "Influence of source materials and the role of oxide composition on the performance of ternary blended sustainable geopolymer mortar," *Constr. Build. Mater.*, 2017.

[3] M. F. Alnahhal, U. J. Alengaram, M. Z. Jumaat, M. A. Alqedra, K. H. Mo, and M. Sumesh, "Evaluation of industrial by-products as sustainable pozzolanic materials in recycled aggregate concrete," *Sustain.*, 2017.

[4] M. T. Junaid, A. Khennane, O. Kayali, A. Sadaoui, D. Picard, and M. Fafard, "Aspects of the deformational behaviour of alkali activated fly ash concrete at elevated temperatures," *Cem. Concr. Res.*, vol. 60, pp. 24–29, 2014.

[5] Parveen, D. Singhal, M. T. Junaid, B. B. Jindal, and A. Mehta, "Mechanical and microstructural properties of fly ash based geopolymer concrete incorporating alccofine at ambient curing," *Constr. Build. Mater.*, vol. 180, pp. 298–307, 2018.

[6] P. Nath and P. K. Sarker, "Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," in *Construction and Building Materials*, vol. 66, pp. 163–171, 2014.

[7] M. G. and J. G. Sanjayan, "Behavior of combined fly ash/slag-based geopolymers when exposed to high temperatures," *Fire Mater.*, vol. 34, pp. 163–175, 2010.

[8] I. Ismail, S. A. Bernal, J. L. Provis, S. Hamdan, and J. S. J. Van Deventer, "Microstructural changes in alkali activated fly ash/slag geopolymers with sulfate exposure," *Mater. Struct. Constr.*, vol. 46, pp. 361–373, 2013.

[9] M. Chi and R. Huang, "Binding mechanism and properties of alkali-activated fly ash/slag mortars," *Constr. Build. Mater.*, vol. 40, pp. 291–298, 2013.

[10] J. Temuujin, A. van Riessen, and R. Williams, "Influence of calcium compounds on the mechanical properties of fly ash geopolymer pastes," *J. Hazard. Mater.*, vol. 167, pp. 82–88, 2009.

[11] D. Dutta and S. Ghosh, "Effect of lime stone dust on geopolymerisation and geopolymeric structure," 2012.

[12] A. Islam, U. J. Alengaram, M. Z. Jumaat, N. B. Ghazali, S. Yusoff, and I. I. Bashar, "Influence of steel fibers on the mechanical properties and impact resistance of lightweight geopolymer concrete," *Constr. Build. Mater.*, vol. 152, pp. 964–977, 2017.

[13] T. Venu Madhav, I. V. Ramana Reddy, V. G. Ghorpade, and S. Jyothirmai, "Compressivestrength study of geopolymer mortar using quarry rock dust," *Mater. Lett.*, vol. 231, pp. 105–108, 2018.

[14] B. K. Meisuh, C. K. Kankam, and T. K. Buabin, "Effect of quarry rock dust on the flexural strength of concrete," *Case Stud. Constr. Mater.*, vol. 8, pp. 16–22, 2018.

[15] K. S. Prakash and C. Hanumantha Rao, "Strength Characteristics of Quarry Dust in Replacement of Sand," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 225, p. 012074, 2017.
[16] ASTM C150-07, "Standard Specification for Portland Cement," *ASTM Int.*, 2007.
[17] J. S. J. van Deventer, J. L. Provis, P. Duxson, and G. C. Lukey, "Reaction mechanisms in the geopolymeric conversion of inorganic waste to useful products," *J. Hazard. Mater.*, vol. 139, pp. 506–513, 2007.
[18] ASTM C136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," *ASTM Int.*, 2006.
[19] ASTM C128-15, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate," *ASTM Int.*, 2015.
[20] ASTM C127-07, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate," *ASTM Int.*, 2007.
[21] ASTM A820-11, "Standard Specification for Steel Fibers for Fiber-Reinforced Concrete," *ASTM Int.*, 2011.
[22] ASTM C494-15, "Standard Specification for Chemical Admixtures for Concrete," 2015.
[23] ASTM C143/C143M-15, "Standard Test Method for Slump of Hydraulic-Cement Concrete," *ASTM Int.*, 2015
[24] ASTM C39-08, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens ," *ASTM Int.*, 2008.
[25] ASTM C496-11, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," *ASTM Int*,. 2011.
[26] ASTM C1609/C 1609M-05, " Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete ( Using Beam With Third-Point Loading ) ," *ASTM Int.*, 2005.
[27] N. Venkata Sairam Kumar and K. S. Sai Ram, "Experimental study on properties of concrete containing crushed rock dust as a partial replacement of cement," *Mater. Today Proc.*, vol. 5, pp. 7240–7246, 2018.
[28] A. S. Sayyad and S. V. Patankar, "Effect of Steel Fibres and Low Calcium Fly Ash on Mechanical and Elastic Properties of Geopolymer Concrete Composites," *Indian J. Mater. Sci.*, vol. 2013, pp. 1–8, 2013.
[29] P. S. Deb, P. Nath, and P. K. Sarker, "The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature," *Mater. Des.*, vol. 62, pp. 32–39, 2014.