Influence of Various Types of Steel Fibre on the Mechanical and Physical Characteristics of GGBS Based Geopolymer Concrete

M. Ali Sadawy¹*, Ahmed Serag Faried²* and H. A. El-Ghazaly²

¹Department of Construction and Building Engineering, October High Institute for Engineering and Technology, Egypt.
²Department of Civil, Faculty of Engineering, Fayoum University, Egypt.

ABSTRACT

This study provides experimental investigation of the mechanical and physical properties of reinforced geopolymer concrete based on Ground Granulated Blast Furnace Slag (GGBS). This research demonstrates the influence of various types of steel fibre on compressive, split tensile, flexural strengths and elastic modulus of hardened GPC, workability of reinforced geopolymer concrete and also analyzed the workability, setting time and flow test of fresh geopolymer concrete. Additionally, corrosion test was conducted on reinforced geopolymer concrete. Mixtures of alkaline liquid to GGBS ratio of 0.5 with steel fibers had been added to the mixture of 0% volume fractions (Vf %), 0.5%, 1.0%, and 1.5% concrete amount. Based on the result of the experiments, the presence of steel fibres enhanced the compressive and tensile strength of the SERGPC, in terms of volume fraction of steel fibres as compared to the regular GPC without fibres. It was observed that there was a significant improvement in GPC's mechanical characteristics and corrosion rate as the lifespan of concrete increased. The incorporation of steel fibres resulted in increased compressive and flexural strengths in the early age and consequently tensile splitting power was increased. The increase in concrete geopolymer content improved the rate of corrosion over time.
1. INTRODUCTION

Pollution is one of the issues connected with the building sector. During the manufacturing of several tons of normal Portland cement, carbon dioxide emissions were huge because it emitted about one ton of CO$_2$ into the atmosphere [1,2] in addition of causing earth degradation owing to mining operations [3]. Geopolymer concretes had appeared over the past two centuries as fresh products for engineering with the ability to become a significant component in an industry of environmentally sustainable building and building products [4-6]. The strength characteristics studied were compressive, split tensile strength, rupture and post-cracking performance modulus, elasticity modulus, Poisson ratio and peak compressive stress strain. The factors were a concrete grade, i.e. ordinary strength of 35 MPa, moderately high strength of 65 MPa, and high strength concrete 85 MPa, and fibre volume fraction $V_f=0.0$, 0.5, 1.0 and 1.5\% [7]. Mahmud et al. [8] investigated fibre reinforced concrete impact strength with and without silica fume addition. End-Hooked steel fibre 60 mm long and an aspect ratio of 80 were used. The findings proved that by adding steel fibre and silica fumes to concrete, the energy absorption capability and ductility were improved. Alavi Nia et al. [9] provided a numerical computation by studying the effect of end-hooked and polypropylene fibre on impact strength of variable volume fractions. Six cylindrical specimens of 150 mm and 64 mm, the drop weight test were used for this purpose. The results showed a good agreement between the numerical computation and the acquired experimental data. Additionally, it was observed that hooked steel fibres showed better efficiency compared to polypropylene fibre. The steel, glass and polypropylene fibre-reinforced concrete cubes (100 mm) was studied by Taner Yildirim et al. [10] under repeated impact loads and reduced strength by ultrasonic pulse velocity testing. Test findings showed that the efficiency under impact load in hybrid steel FRC was relatively high. Several experimental studies indicated that the use of fibres, especially steel fibres enhanced concrete impact strength [8-12]. Bernal et al. [13] performed studies on the effect of steel fibre on slag-based GPC’s mechanical properties. The results provided that steel fibre use decreased compressive strength but considerably increased tensile splitting and flexural strength. They pointed out that strengthened slag concrete with alkali-activated fibre showed better mechanical effectiveness than cement concrete from Portland. Aldahdooh et al. [14] researched that ultrafine micro steel fibre POFA considerably enhanced mortar compressive strength. In their studies, they used micro-steel fibres (6 and 13 mm) with a diameter of 0.16 mm and tensile strength of up to 2850 MPa. Puertas et al. [15] performed a GPC-reinforced polypropylene (PP) analysis and discovered no decrease in compressive strength. Various types of source materials such as slag, fly ash and mixture of slag / fly ash were used in their research. They used 0.5\% and 1\% by mortar volume polypropylene (PP) fibres. The addition of 0.5\% and 1\% PP fibre have no effect on the compressive strength of the 2-and 28-day slag based FRGPC. Although the compressive strength of 2 days was improved in fly ash based FRGPC owing to the rise in PP fibre content, a slight decrease was observed in the same composite at 28 days. Shaikh et al. [16] investigated steel FRGPC’s mechanical characteristics at high temperatures. Two kinds of alkaline activators (Na and K-based) were used. The findings reported that Na-based activators showed considerably higher compressive and indirect tensile strengths in GPC improved steel fibre. N. Ranjbar et al. [17] carried out tests to determine mechanical features of fly ash-based geopolymer composites regarding the effects of micro steel fibres. It was demonstrated that adding micro steel fibres significantly improved flexural strength and energy absorption ability. Yu et al. [18] studied the impacts of single and hybrid steel fibres on standard high-performance concrete. It was depicted that hybrid steel fibres were more effective in enhancing concrete’s ability to dissipate energy under impact load. K.H. Mo et al. [19] noticed that adding GGBS increased the performance of OPS concrete (OPSC) by decreasing water absorption and using the best executed 40 \% GGBS as reduced permeable pores. R.Ahmmad et al. [20] performed an investigation using two industrial waste products from palm oil mill, OPS and palm oil clinker (POC) and replacing OPS with POC had a positive impact on compressive strength. Bernal et al. [21] provided steel fibre reinforced geopolymer concrete based on slag.

From the experiments, there was a decrease in compressive strength and an increase in flexural
and splitting tensile strengths when the volume fraction of fiber increased. Henki Wibowo Ashadi et al. [22] researched the effect of steel slag replacement in fly ash-based geopolymer concrete as a coarse aggregate on compressive strength. In contrast to geopolymer concrete with gravel aggregate, the compressive strength of geopolymer concrete with steel slag replacement was found to be greater. Reinforcement corrosion was assessed using a linear polarization potentialstat scan to assess the current density of corrosion. The corrosion rate of geopolymer concrete with metal slag replacement was provided to be smaller than ordinary geopolymer concrete. The corrosion rate was very high and decreased over time at an early stage. The objective of this experimental study was to investigate the mechanical and physical characteristics of steel fibre-enhanced geopolymer concrete. Mixed ground granulated blast furnace slag to study the fresh and hardened characteristics of geopolymer concrete. (This sentence should be re-stated, the meaning is not clear).

2. MATERIALS USED

2.1 Ground Granulated Blast Furnace Slag (GGBS)

GGBS was used as a geopolymer concrete manufacturing binder. The specific gravity was 2.86 and 2.78 fineness. The composition of binder concrete (slag) was of 31.73%, Al2O3 of 11.48%, MgO of 7.32% and CaO of 42.47%. This material was accessible from Helwan's Iron and Steel Factory in Egypt.

2.2 Aggregates

2.2.1 Fine aggregate

Fine aggregate (Sand) used was clean, dry, river sand. To extract all Pebbles, the sand was sieved using 4.75 mm sieve. The specific gravity of sand was 2.65.

2.2.2 Coarse aggregate

Locally available crushed basalt size number 1 from quarries in Elminia aggregate was used. The coarse aggregate had specific gravity of 2.73.

2.3 Alkaline Activator

A combination of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) solutions was used as alkaline activators for polymerization. A sodium hydroxide solution was prepared by dissolving sodium hydroxide pellets in water. NaOH pellets of 98% purity were used to make NaOH solution of 12 molar. The chemical structure of the sodium silicate solution was Na2O=15.59%, SiO2=34.08%, and water of 50.33% by volume. The ratio of Na2SiO3 to NaOH was fixed to 2.0.

2.4 Superplasticizer

The superplasticizer used was Sikament® R 2004 in all geopolymer mixtures.

2.5 Steel Fibre

End-Hooked Steel Fibres: The World Company for Drawing & Manufacturing Wires in Egypt used two different sizes of end-hooked steel fibres. The first 30 mm x 0.5 mm diameter had an aspect ratio of 60 and tensile strength of up to 1000Mpa. The second 50 mm x 1.0 mm diameter had an aspect ratio of 50 and tensile strength of up to 1000 Mpa. Fig. 1 shows that Steel fibre geometry and shape.

Crimped (Corrugated Round) steel Fibres: Similar to end-hooked steel fibres for two different sizes (CSF1 of length 30 mm x 0.5 mm diameter with an aspect ratio of 60 and CSF2 of length 50 mm x 1.0 mm diameter with an aspect ratio of 50 and tensile strength of up to 1000 Mpa). Steel fibre geometry and shape was depicted in Fig. 1.

3. EXPERIMENTAL WORK

3.1 Casting and Curing of Specimens

The solid constituents of the geopolymer concrete mixture i.e. Ground Granulated Blast Furnace Slag (GGBS), fine and coarse aggregates were dry mixed in a pan mixer for three minutes. The alkaline solution was added to the dry blend after dry blending and took 3–4 minutes to complete mix process. Finally, additional water was added to obtain a workable GPC blend together with superplasticizer. In various ratios such as 0.5%, 1.0% and 1.5% by the concrete quantity, steel fibre was added to the wet mix. Before casting, lubricating oil covered the internal walls of the molds to avoid adhesion to the concrete samples. All samples were cast in three layers horizontally. Using a tamping rod, each layer was compacted. The increase in strength was up to 24 hours in curing time. Specimens were kept at air for curing after casting until the day of the test after 28 days.
4. TEST METHODS

4.1 Geopolymer Concrete’s Mechanical Characteristics

4.1.1 Compressive strength test

For concrete specimens, twelve standard cubes were casted in steel cubic molds (100 x 100 x 100 mm) and compacted on a vibrating table. The samples were stored in air for curing until testing after roughly 24 hours. Cubic samples were evaluated to determine the compressive strength of blending at different ages according to ASTM C150 such as (7 days, 28 days). Fig. 2 showed the geopolymer concrete specimens during casting and testing.

4.1.2 Splitting tensile strength test

Nine standard cylinders (100 mm x 200 mm) were casted to study the splitting tensile strength behavior according to ASTM C150 at age 28 days of mixing.

4.1.3 Flexure strength test

Nine beams were casted (100 x 100 x 500 mm) to study flexure strength behavior according to ASTM C150 at age 28 days.

4.1.4 Modulus of elasticity and Poisson’s ratio

Test samples were casted on 150 mm diameter and 300 mm high cylindrical molds. The cylinders were evaluated using Universal Testing Machine to determine it. Three Linear Variable Differential Transducer (LVDTs) have been corrected at the cylinder's mid-height as shown in Fig. 3. The two LVDTs were used to evaluate lateral deformation on the left and right sides and the centrally positioned LVDT was used to assess longitudinal deformation.

4.2 Corrosion Test

For reinforced geopolymer concrete, the corrosion test was performed using a 75 x 150 mm cylinder. Each sample was reinforced by carbon steel-high grade (36/52) with a diameter of 10 mm and a length of 150 mm inserted in concrete. The purpose of this experiment was to assess the importance of corrosion rates at 7, 28, 60, 90, and 180 days. Samples were blended with tap water and handled with tap water, Qarun Lake water and 5% HCL aggressive hydrochloric acid of various concrete contents (OPC content =500Kg/m^3 and GGBS content as 300 and 500Kg /m^3 binder concrete). In order to achieve the corrosion rate, the samples were tested using Volta Lab PGZ301, -potentiostal/Galvanostate rules system France. The reinforced concrete sample was integrated in the electrochemical scheme (Volta Lab) performed cell. The work electrode (WE) was the integrated steel in the sample. With the exception of one centimeter left exposed, the operating electrode (WE) was coated by epoxy resin. The steel bar with a certain volume and height was actually surrounded by concrete. Corrosion test was used the 40 PGZ 301 Volta labs as shown in Fig. 4. In steel samples, the rate of corrosion was evaluated by the formula:

\[
\text{Rate of corrosion (µm/year)} = I_{corr} \times M \times 3270 / D \times V \times (1)
\]

Where,

- \(I_{corr}\) = Density of current corrosion in A/cm²
- \(M\) = atomic weight (g), \(V\)=Valance
- \(D\) = density (g/cm³)

**Note:** Qarun Lake was regarded as Egypt’s third largest lake. In Fayoum Down, it was considered...
an interior lake not connected to any sea and an area of roughly 53,000 acres with a total average water depth of 4.2 meters. Qarun Lake's chemical analysis is shown in Table 1.

Fig. 2. The geopolymer concrete specimens during cast and test
5. RESULTS AND DISCUSSION

All samples were tested and analyzed for fresh concrete properties i.e. Slump, flow test and setting time test. These samples were also provided for the properties of Hardened concrete, i.e. compressive, split tensile, flexural strengths and modulus of elasticity. These samples were also being analyzed for testing the corrosion rate.

5.1 Fresh Properties of Concrete without Steel Fibres

5.1.1 Effect of GGBS binder content

Slump, flow test, and setting time test were used to estimate fresh concrete properties. Fig. 5 and Table 2 illustrated the influence of varying proportions of GGBS on the characteristics of fresh geopolymer concrete. The increasing in GGBS content improved the workability of concrete. Furthermore, it was found that by increasing the of GGBS content in the concrete mix, the values of slump and flow test increased as depicted in Table 2 and Fig. 5. On the other hand, the setting time decreased. GGBS content was proportional to compressive strength. The increase in GGBS content decreased setting time.

In this study, the authors were needed to achieve compressive strength at 28 day from 40 to 44 MPa. Therefore, the optimum choice to achieve this compressive strength was the content of GGAB binder material at 400Kg/m$^3$ as shown in Table 2. So concrete mixture consisted of GGBS of 368.91 Kg/m$^3$, Fine aggregate of 582.30 Kg/m$^3$, Coarse aggregate of 1170.30 Kg/m$^3$, NaOH Soln of 62.86 Kg/m$^3$, Na$_2$SiO$_3$ Soln 125.72 Kg/m$^3$, and steel fibres of 97 Kg/m$^3$. By the literature study, it was concluded that volume fraction of 1.50% was achieve good strength and the molarity M12 of produce good workability in fresh concrete and the reliable on strength.
### Table 1. Qarun lake water chemical analysis

| Density (gm/cm³) | Soluble salts (gm/l) | Ions (gm/l) | Carbonates (gm/l) | Bicarbonate (gm/l) | Sulfate (gm/l) | Chlorides (gm/l) | Calcium (gm/l) | Magnesium (gm/l) | Sodium (gm/l) | Others (gm/l) |
|------------------|----------------------|-------------|-------------------|-------------------|---------------|-----------------|----------------|----------------|---------------|-------------|
| 1.025            | 35.438               | 0.030       | 0.35              | 9.712             | 12.985        | 0.500           | 1.325          | 10.109         | 0.472         |

### Table 2. Fresh properties of concrete as a result of the effect of binder content (GGBS)

| Fresh mixes | GGBS (Kg/m³) | Na₂SiO₃ Lit. | NaOH Lit. | Slump (mm) | Flow test (mm) | Initial setting time (Min) | Final setting time (Min) | Compressive strength for 7 days (MPa) | Strength for 28 days (MPa) |
|-------------|--------------|--------------|-----------|------------|----------------|----------------------------|--------------------------|-------------------------------------|---------------------------|
| GPC-1       | 250          | 83.33        | 41.67     | 80         | 180            | 70                         | 233                       | 32.6                                | 38.5                      |
| GPC-2       | 400          | 133.33       | 66.67     | 85         | 200            | 63                         | 212                       | 34.3                                | 43.6                      |
| GPC-3       | 550          | 183.33       | 91.67     | 97         | 210            | 56                         | 195                       | 37.3                                | 46.6                      |

### Table 3. Slump test resulting from the effect of different steel fiber proportions

| Steel fiber ratio Vf % | Slump end hooked (L = 50 mm) | Slump end hooked (L=30 mm) | Slump crimped (L = 50 mm) | Slump crimped (L = 30 mm) |
|------------------------|------------------------------|-----------------------------|---------------------------|----------------------------|
| 0%                     | 80                           | 80                          | 80                        | 80                         |
| 0.50%                  | 73                           | 76                          | 74                        | 77                         |
| 1.00%                  | 67                           | 72                          | 70                        | 73                         |
| 1.50%                  | 59                           | 65                          | 62                        | 67                         |

### Table 4. OPC results for corrosion rate at (OPC content = 500 Kg/m³)

| Aggressive media | 7 days | 28 days | 60 days | 90 days | 180 days |
|------------------|--------|---------|---------|---------|----------|
| Tap Water        | 25.49  | 260     | 13.01   | 130     | 2.12     |
| Qarun Lake water | 62.89  | 635     | 75.93   | 760     | 100      |
| 5% HCL           | 70.57  | 706     | 82.7    | 827     | 108      |

### Table 5. GGBS results of corrosion rate (GGBS content = 500 Kg/m³)

| Aggressive media | 7 days | 28 days | 60 days | 90 days | 180 days |
|------------------|--------|---------|---------|---------|----------|
| Tap Water        | 0.141  | 1.5     | 0.1     | 1.1     | 0.07     |
| Qarun Lake Water | 44.67  | 450     | 15.85   | 155     | 7.84     |
| 5% HCL           | 56.77  | 570     | 22.8    | 228     | 9.65     |
Fig. 5. Fresh concrete properties as a consequence of GGBS content

Fig. 6. Slump test as a result of various steel fibre ratios
5.2 Fresh and Hardened Concrete Characteristics with Steel Fibres

5.2.1 Workability

Based on the experiments, it was demonstrated that the workability values decreased gradually from geopolymer concrete (GPC) without steel fibre to reinforced geopolymer concrete SFGPC. Moreover, adding steel fibres to geopolymer concrete resulted in reduced workability as proved in reference [23].

Particularly, long steel fibres with different types such as (End- Hooked (L=50 mm), Crimped (L=50 mm)) decreased slump values more than the other short steel fibre types as depicted in reference [24]. The reason was that SFRGPC tended to hang together compared to the short ones, long steel fibres facilitated this behaviour more. According to results of the slump test are depicted in Table 3 and Fig. 6. The aspect ratio increased, the slump values of the mixtures decreased. The increase of steel fibre content in the concrete mix decreased the slump values of concrete.

5.3 Effect on Mechanical Properties of Two Various Kinds of Steel Fibres

- It was found that the increase in the mechanical properties with increased fibre content was dependent on the type and length of fibre.
- Furthermore, it was found that both end-hooked and crimped (corrugated round) steel fibre at the length of 5 cm improved the mechanical properties of geopolymer concrete. Adding end-hooked steel fibres on geopolymer concrete was determined to improve mechanical properties better than corrugated Round steel fibres.
- It was depicted from the experiments that end-hooked steel fibre at length of 5 cm improved the mechanical properties more than the other steel fibre types.
- The splitting tensile strength, flexural strength and elasticity modulus enhanced as the steel fibre content increased.
- It was proved from the experimental studies that the optimum fibre content for the maximum strengths of steel fibres for geopolymer concrete (GPC) was 1.50% as depicted in Figs. 7-10.
- The compressive strength of Steel fibre reinforced geopolymer concrete increased up to 1.50% of steel fibres.
- Compressive, Split tensile, flexural and modulus of elasticity were directly proportional to the steel fibre content.
- Long-length fibers improved these mechanical properties more than the short ones. The reason was that long steel fibres tended to hang together compared to the short ones.
- Based on the experiments, it was found that Poisson’s ratio ranged from 0.2 to 0.22.
5.4 Effect of Different Types of Concrete on Corrosion Rate

5.4.1 OPC samples

- The results of the corrosion rate test on OPC samples were shown in Table 4 and Fig. 11.
- It was depicted that the corrosion rate of all OPC samples increased with time.
- It was provided from the experimental studies that tap water as aggressive media decreased the corrosion rate more than the other aggressive medias at different ages as shown in Figs. 12 and 13.
- It was noticed that the corrosion rate of GGBS samples reduced over time.

5.4.2 GGBS samples

- The results of the corrosion test on GGBS samples at different ages were shown in Table 5 and Fig. 12.
- Based on the results obtained it was found that the GGBS content was inversely proportional to the corrosion rate.
- It was provided from the experimental studies that tap water as aggressive media decreased the corrosion rate more than the other aggressive medias at different ages as shown in Figs. 12 and 13.
- It was noticed that the corrosion rate of GGBS samples reduced over time.

5.4.3 Comparison between OPC and GGBS samples

- From the experimental studies, it was depicted that the use of geopolymer concrete (GPC) decreased the corrosion rate more than normal concrete (OPC) did.
- Moreover, it was proved that geopolymer concrete resisted the corrosion better than normal concrete over time.
6. SUMMARY AND CONCLUSIONS

Based on the experimental studies conducted to investigate the mechanical and physical properties of fibre reinforced geopolymer concrete including both end-hooked and crimped (Corrugated round) steel fibres used in volume ratios 0.5, 1 and 1.5% at different length, the following conclusions were obtained:

- It was demonstrated that the workability values decreased gradually from geopolymer concrete (GPC) without steel fibre to reinforced geopolymer concrete (SFGPC). Moreover, adding steel fibres to geopolymer concrete resulted in reduced workability as stated in reference [23].
- The GGBS content increased the slump value of geopolymer concrete. It was proved that the addition of steel fibre decreased the workability of SFRGPC, moreover long fibres reduced the workability more than short fibers.
- After 28th day curing, end-hooked fibres increased the compressive strength by 19% with the addition of steel fibres and it was found that 1.5% of steel fibre was the optimum ratio to improve the mechanical properties generally.
- Long length fibers have improved mechanical properties more than the short ones. The reason for this was concluded to be the fact that long steel fibres tended to hang together compared to the short ones.
- The splitting tensile strength, flexural strength and elasticity modulus enhanced as the steel fibre content increased.
- It was depicted that end hooked steel fibres achieved better efficiency compared to crimped (corrugated round) steel fibres.
- Based on the results obtained, it was noticed that the addition of hooked steel
fibre with length of 50 mm improved mechanical properties better than the other steel fibres.

- According to experimental investigation, Poisson's ratio ranged from 0.2 to 0.22.
- Inclusion of steel fibres led to enhanced early-age compressive and flexural strengths and subsequently enhanced tensile splitting strength.
- The increase in geopolymer concrete content decreased the corrosion rate over time.
- Furthermore, it was demonstrated that when the GGBS content was increased, the corrosion rate was decreased.
- Additionally, it was proved that the corrosion rate was inversely proportional to GGBS content.
- By the course of time, the rate of corrosion of all OPC samples increased while that of samples of geopolymer concrete declined.
- Moreover, it was found that geopolymer concrete (GPC) resisted the corrosion better than normal concrete (OPC).
- It was provided from the experimental studies that tap water as aggressive media decreased the corrosion rate more than the other aggressive media at different ages.

ACKNOWLEDGEMENTS

The author wishes to express gratitude to all members of the Concrete Research and Material Properties Laboratory of the “Faculty of Engineering, Fayoum University.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. McCaffrey R. Climate change and cement industry. Global Cement and Lime Magazine (Environmental Special Issue). 2002;15-19.
2. Ellis Gartner. Industrially interesting approaches to low-CO2 cements. Cement and Concrete Research. 2004;34(9):1489–1498.
3. Ashok Kumar K. Study on strength and durability properties of fly ash based hand mixed geopolymer concrete. International Journal of Administration and Governance. 2015;1(5):10-17.
4. Duxson P, Ferna´ndez-Jime´nez A, Provis JL, Lukey GC, Palomo A and van Deventer JSJ. Geopolymer technology: The current state of the art. J Mater Sci. 2006;42(9):2917–2933.
5. Ng TS, Voo YL, Foster SJ. Sustainability with ultrahigh-performance and geopolymer concrete construction. In: Fardis MN Innovative materials and techniques in concrete construction: ACES workshop” Springer, Dordrecht. 2010;81–100.
6. Ng TS, Foster SJ. Development of a mix design methodology for high-performance geopolymer mortars. Structure Concrete. 2013;14(2):148–156.
7. Job Thomas, Ananth Ramaswamy. Mechanical properties of steel fibre-reinforced concrete. Journal of Materials in Civil Engineering. 2007;19(5).
8. Mahmoud N, Afroughsabet V. Combined effect of silica fume and steel fibres on the impact resistance and mechanical properties of concrete. International Journal of Impact Engineering. 2010;37:879-886.
9. Alavi Nia A, Hedayatian M, Nili M, Afrough Sabet V. An experimental and numerical study on how steel and polypropylene fibres affect the impact resistance in fibre-reinforced concrete. International Journal of Impact Engineering 2012;46:62-73.
10. Taner Yildirim S, Cevdet E, Fehim Findik E. Properties of hybrid fibre reinforced concrete under repeated impact loads. Russian Journal of Nondestructive Testing. 2010;46(7):538-546.
11. Mohammadi Y, Carlon-Azad R, Singh SP, Kaushik SK. Impact resistance of steel fibrous concrete containing fibres of mixed aspect ratio. Construction and Building Materials. 2009;23:183-189.
12. Chen XY, Ding YN, Azevedo C. Combined effect of steel fibres and steel rebars on impact resistance of high performance concrete. J Cent South Univ Technol. 2011;18:1677-1684.
13. Bernal S, De Gutierrez R, Delvasto S, Rodriguez E. Performance of an alkali activated slag concrete reinforced with steel fibres. Construct. Build. Mater. 2010; 24(2):208–214.
14. Aldadhoor MAA, Muhamad Bunnori N, Megat Johari MA. Development of green ultra-high performance fibre reinforced concrete containing ultra fine palm oil fuel
ash, Construct. Build. Mater. 2013;48:379–389.

15. Puertas F, Amat T, Fernández-Jiménez A, Vázquez T. Mechanical and durable behaviour of alkaline cement mortars reinforced with polypropylene fibres. Cem. Concrr. Res. 2003;33(12):2031–2036.

16. Shaikh FUA, Hosan A. Mechanical properties of steel fibre reinforced geopolymer concretes at elevated temperatures. Construct. Build. Mater. 2016;114:15–28.

17. Ranjbar N, Mehrali M, Mehrali M, Alengaram UJ, Jumaat MZ. High tensile strength fly ash based geopolymer composite using copper coated micro steel fibre. Construct. Build. Mater. 2016;112:629-638.

18. Yu R, van Beers L, Spiesz P, Brouwers HJH. Impact resistance of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under pendulum impact loadings. Construct. Build. Mater. 2016;107:203–215.

19. Mo KH, Alengaram UJ, Jumaat MZ, Liu MYJ, Lim J. Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand. J. Clean. Prod. 2016;112 (Part 1):763–770.

20. Ahmmad R, Jumaat MZ, Alengaram UJ, Bahri S, Rehman MA, Hashim HB. Performance evaluation of palm oil clinker as coarse aggregate in high strength lightweight concrete. J. Clean. Prod. 2016;112(Part 1):566–574.

21. Bernal S, De Gutierrez R, Delvasto S, Rodriguez E. Performance of an alkali-activated slag concrete reinforced with steel fibers. Construction Building Material. 2010:24:208–214.

22. Henki Wibowo Ashadi, Boy Ahmad Aprilando, Sotya Astutinsih. Effects of steel slag substitution in geopolymer concrete on compressive strength and corrosion rate of steel reinforcement in seawater and an acid rain environment. International Journal of Technology. 2015;2:227-235.

23. Kharde AM, Yadav PV, Dhage BS, Murade VB. Effects of steel fibres on various properties of geopolymer concrete. IJARIIE. 2017;3(3).

24. Merve Acikgenc, Kursat Esat Alyamac, Zulfu Cinar Ulucan. Fresh and hardened properties of steel fiber reinforced concrete produced with fibers of different lengths and diameters. 2nd International Balkans Conference on Challenges of Civil Engineering, BCCCE, EPOKA University, Turkey; 2013.