Influence of Bacterial Strain Combination in Hybrid Fiber Reinforced Geopolymer Concrete subjected to Heavy and Very Heavy Traffic Condition

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Abstract

The effect of bacterial and fiber combination to enhance the properties of GGBS based geopolymer concrete to be used as paver block is investigated in this study. In this study, Bacterial combinations such as Bacillus Subtilis and Bacillus Sphaericus and high modulus glass fibers and low modulus polypropylene fibers were incorporated to produce hybrid fiber reinforced bacterial geopolymer concrete with increased energy absorption characteristics and better post cracking behavior under heavy loads. Combined and the discrete performance of bacteria and fiber over the mechanical properties of the geopolymer concrete were investigated. The influence of bacterial strain combination over self-healing of concrete is also studied by inducing artificial cracks of 1mm over concrete. The self-healed products were subjected to microstructural investigation such as SEM analysis and XRD analysis to understand the microstructure of precipitated products and the bio-remedial action exhibited by the bacteria. Finally, the paver blocks were produced for the optimum specimens of geopolymer concrete along with fiber and bacteria and its performance over compressive, split tensile, flexural and water absorption characteristics were assessed to determine its adaptability to sustain loading under heavy and very heavy traffic conditions as per Indian Standard 15658 (2006). This research work lays a path for the sustainable development of production of eco-friendly self-healing high strength paver blocks.

1. Introduction

Concrete serves as the most predominant building material owing to its adaptability in production. The primary material used to synthesis concrete is cement. Due to the expansions in infrastructure around the world, there has been a considerable increase in the production of cement every year. The production of cement liberates equal amounts of carbon dioxide (CO₂) into the atmosphere. This liberated CO₂ accounts up to 82% of the total greenhouse gas emission, which in turn leads to global warming (Mehta 2001; Roy 1999). Scientists are at an alarming threat to identify an alternate binding material that would replace the role of cement in concrete.

To overcome the environmental problem, Geopolymer Concrete (GPC) can be employed thereby eliminating the need of cement completely. Geopolymer is synthesized through the alkaline activation of industrial by-products such as fly ash and Ground Granulated Blast furnace Slag (GGBS). GPC yields high compressive strength, resistance to acid attack and fire attack and exhibits low shrinkage and creep (Ganesh and Muthukannan 2018; Castel et al. 2016; Sagoe-Crentsil 2013; Ariffin et al. 2013; Mehta and Siddique 2017). GPC exhibits better performance than cement concrete under elevated temperatures (Ganesh et al. 2018; Ganesh and Muthukannan 2019a). The limitation of GPC lies in its brittle behavior. Sarkar et al. (2013) investigated the brittleness of GPC and observed that the fracture planes are smoother in GPC than that of the Ordinary Portland Cement Concrete (OPC). Pan et al. (2011) claimed that the reduction in the fracture energy was due to the morphology of the base material, which altered the microstructure of the matrix. Efforts have to be made to reduce this brittleness to make geopolymer concrete a complete replacement for the OPC cement.

Geopolymer concrete finds its application in various precast elements such as boat ramps, tanks, girders, wall panels, bricks and paver blocks (Ganesh et al. 2020a; Aldred and Day 2012). Moreover, GPC paver blocks synthesized in various research works performed well under light and medium traffic condition as specified by Indian Standard 15658 (2006) (Tawalare et al. 2018; Kumutha et al. 2017), whereas the design of GPC paver blocks for heavy and very heavy traffic conditions remain baffled. Failure pattern analysis reveals that paver blocks fail with the development of micro and macro cracks due to their high brittleness and low energy absorption characteristics, thereby reducing their capability to withstand heavy loads (Pretorius and Logan 2003). Efforts have to be concentrated to synthesis GGBS based GPC paver blocks under ambient curing conditions with high impact energy to withstand heavy loads.
The presence of fibers in the concrete improves the structural integrity and enhances the impact resistance and brittleness (Ravikumar et al. 2015; Sutharsan et al. 2020). Different types of fibers improve different types of properties of the concrete. High modulus fibers tend to increase the mechanical properties and control the propagation of macro cracks, whereas the low modulus fibers increase the post cracking behavior of the concrete and control the formation of micro-cracks (Ganesh and Muthukannan 2019b, 2019c, 2019d; Muthukannan et al. 2019; Ganesh et al. 2020b). Some research works concentrate on the utilization of two fibers of different moduli inside the matrix in the hybrid form to enhance the mechanical, durability and post cracking behavior of concrete (Ganesan et al. 2013; Ganesh and Muthukannan 2019e; Ganesh et al. 2020c). The employing of hybrid fibers inside the geopolymer would increase its energy absorption characteristics with augmented post cracking behavior and pay the way for the development of GPC paver blocks under heavy and very heavy traffic conditions.

Incorporation of Self-healing property in the concrete would prove to be a substantial approach in the development of sustainable building material. Out of the many available techniques for inducing self-healing property such as utilizations of expansive cements, epoxy resins, chemical-based agents and bacteria, application of bacteria prove to be beneficial over other techniques (Thao et al. 2009; Dry and McMillan 1996; Dry 2000; Huang et al. 2011; Seifan et al. 2016). Jonkers (2011) reported that bacteria that exist in the matrix act as a catalyst and transform the precursor compound to filler material and fills the crack. Bacterial strain used in the concrete varies as Bacillus Pasteuri, Sporosarcina Pasteuri, Bacillus Subtillis, Bacillus Sphaericus, Bacillus Licheniformis and Bacillus Thurigiensis (Andalib et al. 2015; Wulandari et al. 2018; Jadhav et al. 2018; Chatterjee et al. 2019; Seifan et al. 2019; Morsali et al. 2019; Ganesh et al. 2019). Extensive studies have been concentrated on the application of a single type of bacterial strain inside cementation matrix and only a few focuses on co-culturing of two bacteria inside geopolymer matrix.

The study examines the effects of incorporation of fibers and bacteria over the alkalinity, compressive, split tensile and flexural strength of GPC. The self-healing ability of bacteria is investigated by inducing artificial cracks in GPC and observing its effectiveness in ceasing the cracks. Microstructural investigation through Scanning Electron Microscope (SEM) analysis and X-Ray Diffraction (XRD) analysis is carried out to determine the microstructure of sealed products. Finally, the Hybrid Fiber Reinforced Bacterial Geopolymer Concrete (HFRBGPC) is cast in the form of paver blocks and its performance was assessed over compressive, split tensile and flexural strength and water absorption properties to check for its competency in withstanding heavy and very traffic conditions as per Indian Standard 15658 (2006). This research paper focuses on the development of sustainable green paver blocks with self-healing property to perform under heavy and very heavy traffic conditions.

2. Materials

2.1 Geopolymer concrete

GGBS based GPC concrete was synthesized in this work. GGBS was procured from the Salem steel plant. From Scanning Electron Microscopy (SEM) Analysis it is determined that GGBS utilized in this work is angular in shape and is shown in Fig. 1. Specific gravity of GGBS was determined to be 2.9. The chemical compositions of GGBS utilized in this work are tabulated in Table 1 and it is explicit that GGBS sample possesses CaO content more than 20%. Concoction of Sodium hydroxide (NaOH) solution and Sodium silicate (Na2SiO3) solution was used as the alkaline solution. Specific gravity of sodium hydroxide solution was found to be 1.47 and sodium silicate solution to be 1.6. M-sand confirming to Zone 3 obtained from the local industry was utilized as the fine aggregate. Clean, dry and angular coarse aggregates of 20 mm size were utilized in this work. The physical properties of M-sand and Coarse aggregates are listed in Table 2 and the values are conforming to Indian Standard 383 (1970).

| Table 1 Chemical composition of GGBS. |
| S. No | Constituents | Percentage composition (%) |
| 1. | SiO2 | 31.25 |
| 2. | Al2O3 | 14.06 |
| 3. | Fe2O3 | 2.80 |
| 4. | CaO | 33.75 |
| 5. | MgO | 7.03 |

| Table 2 Physical properties of M-sand and coarse aggregate. |
| S. No | Physical Property | M-sand | Coarse Aggregate |
| 1. | Specific gravity | 2.60 | 2.62 |
| 2. | Fineness Modulus | 2.36 | 6.10 |
| 3. | Bulk density | 1702 Kg/m³ | 1456 Kg/m³ |

Fig. 1 SEM analysis of GGBS.
2.2 Hybrid fiber
Both high and low modulus fibers were utilized in this work to enhance the mechanical properties of Geopolymer concrete. Glass fiber was selected as the high modulus fiber and polypropylene fiber was selected as the low modulus fiber. Physical properties of both the fibers are tabulated in Table 3 and it is observed that the tensile strength and modulus of elasticity of glass fiber are much higher than that of the polypropylene fiber and the aspect ratio of both the fibers were kept below the permissible limits (Shetty 2006).

2.3 Bacterial strain
Two types of bacterial strains such as Bacillus Subtillis and Bacillus Sphaericus were utilized in this work. The microscopic images of Bacillus Subtillis and Bacillus Sphaericus are shown in Fig. 2. Both the bacterial strains are rod shaped and are capable of precipitating carbonaceous compounds. Bacterial Subtillis can withstand a temperature of about 80°C by forming endospersms (Piyush 2016). Bacillus Sphaericus can withstand temperature of about 53°C for years by forming endospores (Park et al. 2009).

3. Experimental methodology
3.1 Liquid bacterial culture
Bacteria to be added to the concrete were cultured separately in a liquid medium Luria Broth (LB) which was produced by dissolving LB agar powder in distilled water at 28°C. The Barth is centrifuged for 10 minutes in a conical flask covered at the top using aluminum foil. The medium was then subjected to autoclaving at 37°C. The medium was again kept in a shaking incubator for 12 hours at a temperature of about 37°C. Complete Bacterial growth formation was characterized by the appearance of whitish yellow color in the solution. The solution also becomes turbid. Calcium lactate was added to feed the bacteria when needed. The concentration of cells of both the bacteria was taken as 105 per one milliliter of solution.

3.2 Preparation of solution
Alkaline solution to be used as the activator solution was prepared one day prior to casting. Combination of NaOH and Na₂SiO₃ solution in the ratio of 1 : 2.5 was used as the alkaline solution. NaOH solution of 13 Molarity is prepared by dissolving 520 grams of sodium hydroxide pellets in 1 liter of distilled water. Na₂SiO₃ solution was obtained in the gel form from the local chemical industry. The required amount of NaOH and Na₂SiO₃ solution are mixed in a container 24 hours prior to casting and were utilized in the work.

3.3 Mix design and casting of specimens
The various ingredients such as GGBS, M-sand, Coarse Aggregate, Alkaline solution, Glass Fiber, Polypropylene fiber were proportioned based on the guidelines (Anuradha et al. 2012) for design of GPC in which the calculation of fine and coarse aggregate is in accordance with the Indian Standard 10262 (2009). The proportions of the various materials to be added are tabulated in Table 4. The proportioned materials were mixed in a pan mixer for about 3-5 minutes. GPC was cast in moulds of desired size and were subjected to ambient curing conditions with temperatures varied between 27 and 31°C.

3.4 Testing and characterization analysis
The alkalinity of GPC with and without fibers and bacteria was studied. Mechanical properties of GPC such as compressive, split tensile and flexural strength and self-healing capacity of the hybrid fiber reinforced geopolymer concrete was investigated. Compressive strength was determined as per Indian Standard 516 (1959) over cubical specimens of size 150 x 150 x 150 mm. Split

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Table 3 Physical properties of glass fiber and polypropylene fiber.

| S. No | Physical Property | Glass fiber | Polypropylene fiber |
|-------|------------------|-------------|---------------------|
| 1.    | Length (mm)      | 6.0         | 20                  |
| 2.    | Diameter (mm)    | 0.1         | 0.2                 |
| 3.    | Aspect ratio     | 60          | 100                 |
| 4.    | Tensile strength (MPa) | 1700     | 400                 |
| 5.    | Modulus of Elasticity (GPa) | 72       | 3.5                 |
| 6.    | Specific Gravity | 2.5         | 0.98                |

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Fig. 2 Microscopic image of bacteria.
tensile strength was determined as per Indian Standard 5816 (1999) over cylindrical specimens of size 300 x 150 mm. Flexural strength was determined as per Indian Standard 516 (1959) over prismatic specimens of size 500 x 100 x 100 mm. Further, the self-healed products were subjected to microstructural analysis such as SEM and XRD to identify the bond formation involved in the products. The performance of hybrid fiber reinforced geopolymer paver blocks of size 200 x 100 x 100 mm, over compressive, split tensile and flexural strength and water absorption characteristics were investigated in accordance with Indian Standard 15658 (2006).

4. Results and discussions

4.1 Alkalinity

The Alkalinity of the GPC with and without fibers and bacteria was determined using pH meter and the results are tabulated in Table 5. From the results, it is explicit that all the Geopolymer concrete samples exhibited very high alkaline natures as pH level is more than 7 and very near to 14. The presence of fibers tends to decrease the alkalinity due to its comparatively less alkaline nature. The presence of bacteria had no significant effect on the alkalinity of the concrete.

4.2 Compressive strength

The average values of compressive, split tensile and flexural strength of the GPC specimens are tabulated in Table 6. The effect of incorporation of fibers and bacteria over compressive strength GPC at 7 and 28 days is depicted in Fig. 3. With the addition of glass fibers, compressive strength increased about 19.90% and 22.71% over conventional GPC at 7 and 28 days. By the addition of bacteria along with the glass fiber, compressive strength increased about 26.02% and 27.75% over conventional GPC at 7 and 28 days. With the addition of bacteria along with the hybrid fiber, compressive strength augmented about 20.66% and 23.39%.

4.3 Split tensile strength

The effect of incorporation of fibers and bacteria over split tensile strength GPC at 7 and 28 days is depicted in Fig. 4. With the addition of glass fibers, tensile strength increased about 34.29% and 38.46% over conventional GPC at 7 and 28 days. By the addition of hybrid fibers, tensile strength increased about 25.71% and 28.21% over conventional GPC at 7 and 28 days. With the incorporation of bacteria along with the glass fiber, tensile strength increased about 40.00% and 46.15% over conventional GPC at 7 and 28 days. With the addition of bacteria along with the hybrid fiber, tensile strength augmented about 34.29% and 33.33% at 7 and 28 days.

4.4 Flexural strength

The effect of incorporation of fibers and bacteria over

| Mix ID | pH value |
|--------|----------|
| GPC    | 13.5     |
| GPCGF  | 13.2     |
| GPCHF  | 13.1     |
| BGPCGF | 13.2     |
| BGPCHF | 13.1     |

Table 5 Alkalinity of geopolymer concrete.

Table 4 Mix proportions.

| Mix ID  | M  | GGBS | M-sand | CA | SH | SS  | GF (%) | PF (%) | Bacteria       |
|---------|----|------|--------|----|----|-----|--------|--------|----------------|
| GPC     | 13 | 550  | 481.21 | 1030.2 | 95.86 | 239.64 | 0 | 0 |                |
| GPCGF   | 13 | 550  | 481.21 | 1030.2 | 95.86 | 239.64 | 1 | 0 |                |
| GPCHF   | 13 | 550  | 481.21 | 1030.2 | 95.86 | 239.64 | 0.75 | 0.25 | 10<sup>5</sup> Cells/ml |
| BGPCGF  | 13 | 550  | 481.21 | 1030.2 | 95.86 | 239.64 | 1 | 0 | 10<sup>5</sup> Cells/ml |

Table 6 Mechanical properties of GPC with and without fibers and bacteria.

| Mix ID  | Compressive Strength (MPa) 7 days | SD | 28 days | SD | Split Tensile Strength (MPa) 7 days | SD | 28 days | SD | Flexural Strength (MPa) 7 days | SD | 28 days | SD |
|---------|-----------------------------------|----|---------|----|------------------------------------|----|---------|----|-------------------------------|----|---------|----|
| GPC     | 39.20                            | 2.4 | 43.60   | 2.7 | 3.50                               | 0.2 | 3.90   | 0.4 | 4.80                          | 0.4 | 5.40   | 0.5 |
| GPCGF   | 47.00                            | 2.3 | 53.50   | 2.6 | 4.70                               | 0.3 | 5.40   | 0.4 | 6.90                          | 0.5 | 7.80   | 0.6 |
| GPCHF   | 44.50                            | 2.3 | 50.50   | 2.7 | 4.40                               | 0.2 | 5.00   | 0.5 | 7.00                          | 0.6 | 8.05   | 0.7 |
| BGPCGF  | 49.40                            | 2.4 | 55.70   | 2.6 | 4.90                               | 0.3 | 5.70   | 0.4 | 7.10                          | 0.5 | 8.10   | 0.7 |
| BGPCHF  | 47.30                            | 2.5 | 53.80   | 2.7 | 4.70                               | 0.3 | 5.20   | 0.4 | 7.20                          | 0.5 | 8.30   | 0.7 |
flexural strength GPC at 7 and 28 days is depicted in Fig. 5. With the addition of glass fibers, flexural strength increased about 43.75% and 44.44% over conventional GPC at 7 and 28 days. By the addition of hybrid fibers, flexural strength increased about 45.83% and 49.07% over conventional GPC at 7 and 28 days. With the incorporation of bacteria along with the glass fiber, flexural strength increased about 47.92% and 50.00% over conventional GPC at 7 and 28 days. By the addition of bacteria along with the hybrid fiber, flexural strength augmented about 50.00% and 53.70% at 7 and 28 days.

4.5 Self-healing
Self-healing ability of the Bacterial GPC with and without the fibers was investigated by introducing artificial cracks over the concrete specimen. The specimens were subjected to loading at a rate of about 3 MPa per minute till the specimen exhibits a crack of width 1 mm. Crack width of the specimen varies from 400 micron meter to 1 mm. Efforts were made to maintain the same damage in all the specimens to maintain uniformity. The specimens were then sprayed with water and were kept under observation at room temperature (24 to 29°C) to witness the progress of sealing of cracks. Frequent photographs were taken to witness the healing of cracks. Figure 6 depicts the picture showing the process of healing of cracks through bacterial action. At the fifth day, precipitations were observed at the corners of the crack. Half of the cracks were sealed after fourteen days and the cracks were completely sealed at the 28 day. Also, these specimens were subjected to compressive strength test as per Indian Standard 516 (1959) after 28 days to identify the strength gain due to the bacterial action. The results are tabulated in Table 7.

4.5.1 Characterization of self-healed products through SEM analysis
SEM analysis was conducted over the self-healed products and is as shown in Fig. 7. Figures 7a) and 7b) reveal that the complete deposition of calcium carbonate over
the cracks without any void space. SEM images depict the closely packed structure of calcite over the cracks and mark the absence of unreacted particles in the cracks. GPC is already highly alkaline and this has enabled the amicable environment for the precipitation of calcite with the closely spaced system over the cracks.

4.5.2 Characterization of self-healed products through XRD analysis

XRD analysis was conducted over the self-healed products to confirm the observations through SEM analysis and the results are depicted in Fig. 8. The obtained peak of the precipitated material was similar to the calcite peak and has been checked using the Match software. JCPSDS number was also identified and included in Fig. 8. This reports the evidence for the formation of calcite compound in the GGBS based geopolymer concrete due to the bacterial action.

4.6 Performance of paver blocks

Bacterial geopolymer concrete with glass fiber (BGPCGF) and the bacterial geopolymer concrete with hybrid fiber (BGPCCHF) were cast as paver blocks of size 200 x 100 x 100 mm and are compared with conventional geopolymer paver blocks without fiber and bacteria. The average values of properties of paver blocks determined as per Indian Standard 15658 (2006) are tabulated in Table 8.

4.6.1 Compressive strength

Figure 9 depicts the compressive strength of the paver blocks at 7 days and 28 days for different samples calculated as per Indian Standard 15658 (2006). BGPCGF exhibited about 25.87% and BGPCCHF reported about 21.30% increase in compressive strength than the conventional geopolymer paver block. The increase in strength was maximum with the BGPCGF due to the presence of high modulus glass fibers. Presence of bacteria also enhanced the compressive strength due to the reduction in the void space by the bacterial action inside the matrix. Both BGPCGF and BGPCCHF were observed to possess the required amount of compressive strength to sustain load under heavy and very heavy traffic conditions.

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**Table 7 Self-healing performance.**

| Mix ID   | No of Specimens Tested | Original strength (MPa) | Strength at the inception of Crack (MPa) | Strength after 14 days of healing (MPa) | Strength after 28 days of healing (MPa) |
|----------|------------------------|-------------------------|------------------------------------------|----------------------------------------|----------------------------------------|
| BGPC     | 3                      | 46.70                   | 32.50                                    | 34.60                                   | 40.60                                   |
| BGPCGF   | 3                      | 55.70                   | 38.20                                    | 41.20                                   | 48.50                                   |
| BGPCCHF  | 3                      | 53.80                   | 36.80                                    | 38.50                                   | 45.70                                   |

With the incorporation of bacteria, the compressive strength increased about 87% over the glass fiber reinforced GPC and about 85% over the hybrid fiber reinforced GPC. Table 8. shows the initial and final crack width of the different mixes.

**Table 8 Crack width before and after self healing.**

| Mix ID   | Initial Width of Crack (μm) | Final Width of Crack (μm) | Healing (in %) |
|----------|-----------------------------|---------------------------|----------------|
| GPCGF    | 800                         | 700                       | 12.50          |
| GPCHF    | 830                         | 710                       | 14.46          |
| BGPC     | 970                         | 70                        | 92.78          |
| BGPCGF   | 870                         | 50                        | 94.25          |
| BGPCCHF  | 1000                        | 50                        | 95.00          |

From Table 8., it is explicit that the self healing action in ceasing the crack width, exhibited by bacterial strain is more than 90% in all the cases (ie. BGPC, BGPCGF, BGPCCHF).

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**Table 8.** shows the initial and final crack width of the different mixes.

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**Fig. 7** SEM analysis of self-healed products of GPC sample.
4.6.2 Split tensile strength

Figure 10 shows the tensile strength of the paver blocks at 7 and 28 days for different samples calculated as per Indian Standard 15658 (2006). BGPCGF exhibited about 45.45% and BGPCHF reported about 40.90% increase in tensile strength than the conventional geopolymer paver block. Presence of fibers enhanced the tensile strength due to the greater tensile strength of both the fibers that are used inside the matrix. The maximum increase in tensile strength witnessed in BGPCGF was due to the greater tensile strength of the glass fibers than the polypropylene fibers. Addition of bacteria also reduced the void content inside the matrix thereby enhancing its integrity and tensile strength.

4.6.3 Flexural strength

Figure 11 shows the flexural strength of the paver blocks at 7 and 28 days for different samples calculated as per Indian Standard 15658 (2006). BGPCGF exhibited about 53.66% and BGPCHF reported about 57.32% increase in flexural strength than the conventional geopolymer paver block. Presence of fibers enhanced the flexural strength due to the bridging effect exhibited by the fibers. The maximum increase of flexural strength reported in BGPCHF was due to the presence of polypropylene fiber with increased aspect ratio. This increased the post cracking performance of the paver block by arresting the crack formation and increasing the load carrying capacity of the paver block.

| Mix ID | Compressive strength (MPa) | Split tensile strength (MPa) | Flexural strength at 28 days (MPa) | Water absorption (%) |
|--------|-----------------------------|-----------------------------|-----------------------------------|----------------------|
|        | 7 days | 28 days | 7 days | 28 days | Flexural strength at 28 days | Flexural strength at 28 days | Water absorption | Water absorption |
| GPC    | 40.8   | 46.0    | 3.9    | 4.4    | 8.2                             | 12.9                             | 4.2               | 3.1               |
| BGPCHF | 49.3   | 55.8    | 5.6    | 6.2    | 12.9                             | 12.9                             | 3.1               | 3.2               |
| BGPCGF | 51.4   | 57.9    | 5.76   | 6.4    | 12.6                             | 12.6                             | 3.2               | 3.2               |

Table 9 Properties of paver block specimens.
4.6.4 Water absorption

Figure 12 shows the water absorption capacity of the paver blocks for different samples calculated as per Indian Standard 15658 (2006). BGPCGF exhibited about 23.80% and BGPCHF reported about 26.19% decrease in water absorption capacity than the conventional geopolymer paver block. Presence of fibers attenuated the water absorption capacity due to the increased structural integrity provided by both fibers. Maximum reduction in capacity was witnessed in BGPCHF due to the presence of polypropylene fibers that are hydrophobic in nature. Incorporation of Bacteria also reduced the water absorption capacity by reducing the amount of pores present inside the matrix. Reduction of pores presenting inside the matrix is obtained due to the precipitation of calcium carbonate inside the voids by the microbial action. All the paver blocks exhibited water absorption capacity less than 6% which is the permissible standard as per Indian Standard 15658 (2006).

5. Discussion

The presence of fibers tends to decrease the alkalinity and the presence of bacteria had no significant effect on the alkalinity of the concrete.

The presence of fibers increases the structural integrity which leads to an increase in the compressive strength of the concrete. The increase was more with the utilization of glass fibers owing to its high stiffness compared to the polypropylene fibers. Seithi et al. (2019) claimed that the incorporation of glass powder increases the compressive strength. A significant increase in compressive strength with the utilization of high modulus fibers was observed in other research works in different composites (Sukontasukkul et al. 2018; Alrefaei and Dai 2018; Sivakumar and Santhanam 2007). With the incorporation of bacteria, nano-pores presenting in the matrix are occupied by the calcium silicate precipitated by the bacteria. This increases the homogeneity of the matrix, which enhances the compressive strength of GPC.

The existence of fibers increased the tensile strength of the fiber owing to the increased tensile strength of the fibers compared to that of the matrix. Enhancement in tensile strength was more with the utilization of glass fibers due to the high modulus of elasticity and tensile strength of the glass fiber than the polypropylene fiber. Experimental works conducted by Sachitanandam and Meikandaan (2015) and Vijai et al. (2012) also reported an increase in tensile strength with the utilization of glass fibers. A similar trend has been witnessed in the hybrid fiber medium reported by other researchers (Sivakumar and Santhanam 2007; Sachitanandam and Meikandaan 2015; Nia et al. 2018). The addition of bacteria enhances the tensile strength by increasing the homogeneity through the precipitation of calcium carbonate inside the matrix.

There was a considerable regain of strength with the incorporation of bacteria. The regain in strength observed was due to the leaching of nano carbon silica compounds present inside the GPC matrix. This originates the bio remedial action of self-healing of cracks. Through the microbial action, calcium carbonate gets precipitated in the cracks when added with water under the presence of sunlight. This has been verified by the conductance of microstructural investigation over the self-healed products. Chatterjee et al. (2019) reported the formation of calcite and gehlenite compounds due to the bacterial action by bacillus subtillius inside fly ash based GPC mortar. Studies by Jadhav et al. (2018) over meta-
kaolin based GPC were also found to be in accordance with the observed behavior.

Bacterial fiber reinforced paver blocks were found to exhibit compressive strength greater than 55 MPa and water absorption capacity less than 6%, which makes them suitable to be utilized as paver blocks to sustain heavy and very heavy traffic conditions as per Indian Standard 15658 (2006). The reason for the increase in the properties was due to the combined performance of fibers and Bacteria, which reduced the number of pores inside the matrix and enhanced the homogeneity and structural integrity of the matrix.

6. Conclusion

The development of self-healing paver blocks for heavy and very heavy traffic conditions was investigated in this paper. Incorporation of fibers and bacteria tends to increase the mechanical properties of geopolymer concrete. Incorporation of 1% glass fiber and Bacillus Subtillis and Bacillus Sphaericus increased the compressive strength about 27.75% and split tensile strength about 46.15% than conventional geopolymer concrete without fiber and Bacteria. Incorporation of 0.75% of glass fiber and 0.25% of polypropylene fiber, along with the bacteria increased the flexural strength 53.70% than the conventional geopolymer concrete without fiber and Bacteria. Further with the incorporation of the Bacillus Subtillis and Bacillus Sphaericus inside the geopolymer matrix complete healing of cracks was reported at 28 days with about 85% of regaining of strength. Self-healing eco-friendly geopolymer paver blocks with strength more than 55 MPa could be synthesized using glass and polypropylene fiber and Bacillus Subtillis and Bacillus Sphaericus bacteria to serve the purpose of handling heavy and very traffic conditions.

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