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Mechanical Properties of Steel and Polypropylene Fiber Reinforced Alkali-Activated Cement

Brijbhushan S.[1*], Veeresh B. Karikatti [2], Basavaraj Gudadappanavar[3]

[1*]Assistant Professor, Department of Civil Engineering (Construction Technology), Visvesvaraya Technological University, Centre for Postgraduate Studies, Kalaburagi - 585105, Karnataka Kalaburagi

[2]Associate Professor Department of Civil Engineering, K. L. E. Institute of Technology, Hubballi

[3]Assistant Professor, Civil Engineering, SDM College of Engineering & Technology, Dharwad, Karnataka- 580 002

Abstract

This study investigates the usage of Fiber Reinforced Alkali-activated cement combined with granulated blast furnace slag and activated with alkali solution as a viable construction material. This research distinguishes itself by conducting a thorough analysis of the impact of two different types of fibers, namely Polypropylene Fiber (PF) and Steel Fiber (SF), on the mechanical characteristics of the concrete matrix. In order to improve the workability of the material without sacrificing its structural strength, we utilized the capabilities of a naphthalene-based superplasticizer. This allowed for easier handling during the preparation process. Control mixtures without fibers were used as a reference point for comparison. Subsequent batches included different amounts of PF and SF (ranging from 0.5% to 1.5%) to understand how they affected the material's performance. The results of our research, namely in tests measuring compressive strength, revealed fascinating discoveries. Significantly, the incorporation of steel fibers at a volume percentage of 1.5% resulted in the greatest compressive strength, surpassing all other compositions. In contrast, polypropylene fibers, although they improve ductility by changing the failure mode from brittle to ductile, demonstrated lower strength in comparison to steel fibers. However, this increase in ductility was accompanied by a decrease in the capacity to work with the mixture as the fiber concentration increased. This phenomenon highlights the intricate equilibrium between mechanical durability and practical functionality, The micro-morphological analysis provided a clear understanding of the bonding processes present in the composite matrix. It visually depicted how the material's structure behaves when subjected to stress. Nevertheless, it is important to mention that the addition of polypropylene fibers did not have a substantial impact on the elastic modulus. This indicates that there may be trapped empty spaces, which could be a result of the fibers clumping together during the mixing process. Tackling this difficulty provides an opportunity for future improvement and optimization of FRGC formulations. This research highlights the significant capacity to serve as a long-lasting substitute in construction materials. Through a thorough analysis of the interaction between components and their physical characteristics, we create a foundation for well-informed engineering choices and groundbreaking progress in the field of infrastructure construction.

Keywords: *Steel Fiber, Polypropylene Fiber, GGBS, Alkali-activated cement, SEM Analysis, Alkali Activator*

1. Introduction

The production of conventional cement has historically been linked to substantial greenhouse gas emissions, which have contributed to widespread environmental deterioration. According to reports, an astonishing 7.35% of global carbon dioxide emissions are attributed to the production of cement. This grim reality emphasizes the pressing necessity for solutions that not only provide superior mechanical characteristics but also alleviate environmental and economic consequences. Geopolymers are a type of inorganic polymers that have the potential to greatly transform the construction sector. Geopolymers are created by dissolving aluminum and silicon source materials in an alkaline solution. This process leads to polymerization reactions, resulting in the development of complex ring structures that consist of silicon-oxygen-aluminum-oxygen links. Geopolymers are a chemical combination made up of repeating molecular units that provide a sustainable alternative to traditional Portland cement.

Researchers have studied the impact of different amounts of polyethylene fiber and water-to-binder ratios on fracture qualities in high-toughness Alkali-activated cement. The findings uncovered a complex relationship, where more fiber concentration resulted in a bell-shaped curve in fracture toughness. Significantly, formulations with a water-to-binder ratio of 0.35 demonstrated higher fracture toughness in comparison to those with a ratio of 0.38, highlighting the crucial role of careful formulation. Simultaneously, research on steel fibers revealed their substantial influence on the properties of concrete. Gradual increases in the amount of fiber, up to 2%, were found to be directly connected to improved compressive strength. The highest levels of tensile and flexural strength were seen when the fiber content reached 2.5% of the total volume. By adding small amounts of basalt fiber to fly ash Alkali-activated cement, researchers observed enhanced fracture toughness and crack propagation mechanisms. This suggests that combining these materials could lead to synergistic improvements in their properties. Additional inquiries into hybrid combinations incorporating both steel and polypropylene fibers highlighted the importance of achieving a careful equilibrium between longevity and mechanical characteristics. Although hybrid formulations showed improved durability, there was a noticeable compromise in mechanical performance, emphasizing the importance of careful material selection. Furthermore, research examining the effectiveness of Alkali-activated cement has revealed the complex relationship between the amount of fibers used and the characteristics of the freshly mixed concrete. An increase in fiber content led to a decrease in workability, which requires careful attention when formulating and applying the material.
Finally, impact tests conducted on fiber-reinforced Alkali-activated cement demonstrated the effectiveness of crimpled stainless-steel fibers in improving the ability to withstand impact loads. Specimens containing 0.75% of these fibers demonstrated exceptional performance when subjected to dynamic loading conditions, suggesting their potential for use in challenging structural applications. These groundbreaking research highlight the significant impact that geopolymers and fiber-reinforced composites may have on promoting sustainable construction methods. Researchers are exploring the intricate relationship between the composition of materials, their mechanical qualities, and their impact on the environment to create a more environmentally friendly and durable constructed environment.

1. Material Characteristics

2.1 Alkali-activated cement

In the realm of industrial production, byproducts such as silica fume and GGBS (Ground Granulated Blast Furnace Slag) emerge as significant waste streams. Remarkably, both of these materials boast a geopolymer base rich in silicon and aluminum. Through activation with a basic solution, a fascinating reaction called polymerization ensues, ultimately giving rise to a binder material with immense potential in construction applications.

Alkali-activated cement – a revolutionary composite material poised to redefine the norms of traditional concrete production. The manufacturing process involves blending the aforementioned binder material with coarse aggregates, typically comprised of crushed stones with a nominal size of 20mm. To complement this mix, fine aggregates in the form of manufactured sand are introduced, facilitating optimal cohesion and strength.

The chemical characteristics of silica fume and GGBS play a pivotal role in shaping the properties of Alkali-activated cement. Table 1 provides a detailed illustration of these characteristics, offering insights into key parameters such as particle size distribution, chemical composition, and reactive potential.

Table 1: Chemical Characteristics of Silica Fume and GGBS

Compound	GGBS (%)	Silica Fume (%)
Silicon Dioxide	35.8	94.9

Ferric Oxide	1.52	0.948
Aluminum Oxide	10.8	1.19
Magnesium Oxide	11.98	0.948
Calcium Oxide	38.7	0.588
Sodium Oxide	0.718	0.418
Potassium oxide	0.759	1.118
Manganese Oxide	1.677	-

These chemical nuances not only influence the material's performance but also dictate its suitability for specific applications within the construction domain. By harnessing the unique properties of silica fume and GGBS, engineers and researchers alike can unlock a myriad of possibilities in sustainable infrastructure development.

In essence, the synergy between industrial waste streams and innovative material science paves the way for a more sustainable future. Through the utilization of geopolymer-based materials like Alkali-activated cement, we not only mitigate waste generation but also propel towards a greener, more efficient construction industry.

2.2 Steel Fiber and Polypropylene Fiber

In this groundbreaking study, we delve into the realm of advanced construction materials, leveraging the unique properties of crimped steel fibers and monofilament polypropylene fibers. Figure 1 showcases the distinctive morphology of crimped steel fibers, characterized by a length of 30mm, diameter of 0.6mm, and an impressive aspect ratio of 50. With a nominal tensile strength of 1100N/mm2, these steel fibers represent a formidable addition to the composite material matrix. Figure 2 introduces us to the monofilament polypropylene fibers, distinguished by their natural white color, with a diameter of 0.5mm and a length of 12mm. Despite their seemingly modest dimensions, these polypropylene fibers pack a punch when it comes to enhancing the material's mechanical properties and durability. The juxtaposition of these two fiber types in our study opens up a realm of possibilities in material design and engineering. While crimped steel fibers offer unparalleled tensile strength and reinforcement capabilities, monofilament polypropylene fibers contribute to enhanced ductility and crack resistance. Together, they form a synergistic blend that transcends the limitations of traditional construction materials, paving the way for innovative and sustainable infrastructure solutions.

Figure 1. Crimped Steel Fibers

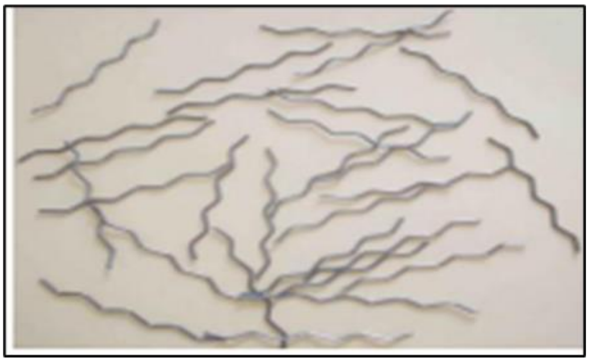

Figure 2. Monofilament Polypropylene Fibers

2.3 Design Mix

In our pioneering research, we embarked on a journey to explore the intricate relationship between sodium silicate/sodium hydroxide ratios and the mechanical properties of Alkali-activated cement. Through meticulous experimentation, we sought to optimize mix compositions and alkali activator solutions to achieve superior performance.

Our methodology began with the investigation of various sodium silicate/sodium hydroxide ratios, coupled with a meticulous evaluation of the volume of sodium hydroxide solution. Additionally, we introduced a control mix, meticulously crafted to exhibit maximum compressive strength, serving as a benchmark for subsequent investigations. Building upon this foundation, a second batch of mix ratios was meticulously examined to discern the influence of both fibers on the mechanical properties of Alkali-activated cement. Notably, the quantity proportion of silica fume was fixed at 30% of the binder weight, with the remaining composition constituted by GGBS. The alkali activator to binder ratio was standardized at 0.4, ensuring consistency across experiments.

The preparation of alkali activator solutions followed a precise protocol, involving the gradual dilution of NaOH flakes with water, followed by a resting period at room temperature for optimal activation. Subsequently, Na2SiO3 solution was meticulously added to the prepared activator solution to complete the formulation. The dry components, comprising GGBS, micro silica, and manufactured sand, were meticulously blended in a high-speed blender until a uniform, light gray-colored mixture was achieved. The prepared activator solution was then gradually introduced to the dry blend, ensuring thorough incorporation and homogenization. To mitigate the risk of fiber balling or lump formation, fibers were progressively added to the mixture, ensuring uniform dispersion and consistency. Finally, the prepared mix was carefully placed into molds and subjected to rigorous testing as per established standards and requirements. The culmination of our efforts resulted in the formulation of finalized mix ratios, meticulously tabulated in Table 3, offering valuable insights into the volume content of the optimized Alkali-activated cement mixes. Through our meticulous methodology and rigorous experimentation, we aim to contribute to the advancement of Alkali-activated cement technology, paving the way for sustainable and resilient construction practices.

Table 2. Mix Ratio-Batch 1

Micro silica (kg per cubic meter)	GGBS (kg per cubic meter)	Na_2SiO_3 /NaOH ratio	Molarity of Sodium Hydroxide	Manufactured Sand (kg per cubic meter)

285	860	1.5	6	832
285	860	1.5	10	832
285	860	2.5	6	845
285	860	2.5	10	845
285	860	3.5	6	850
285	860	3.5	10	850

Table 3. Mix Ratio- Batch 2

Mixture Volume Percentage (% SF or %PF)	Micro silica (kg per cubic meter)	GGBS (kg per cubic meter)	Na_2SiO_3/ NaOH ratio	NaOH (M)	Manufactured Sand (kg per cubic meter)
0.5% Steel Fiber	285	860	3.5	10	832
0.5% Polypropylene Fiber	285	860	3.5	10	832
1.0% Steel Fiber	285	860	3.5	10	845
1.0% Polypropylene Fiber	285	860	3.5	10	845
1.5% Steel Fiber	285	860	3.5	10	850
1.5% Polypropylene Fiber	285	860	3.5	10	850

3. Methods of Testing

The impact of addition of fiber on the fresh concrete property that is workability was measured using flow test as per IS 1199-1959 immediately after mixing every batch.

Figure 3. Flexural Strength Test Specimen

4 Results and Discussions

4.1 Workability

As the volume fraction of steel fibers (SF) increased, a noticeable trend emerged – a decrease in flow diameter was observed. This intriguing phenomenon shed light on the intricate dynamics at play within the concrete matrix. Upon closer inspection, it became apparent that the introduction of higher volumes of SF resulted in the production of harsher mixes. This observation raised questions about the underlying mechanisms driving this behavior. Further analysis revealed a compelling explanation: the density of steel fibers is relatively low. Consequently, even for very low volume fractions, a larger quantity of fibers was incorporated into the mix. This phenomenon, in turn, intensified the interaction between the fibers and the matrix, leading to heightened resistance to flow. In essence, the increase in SF volume fraction not only impacted the physical properties of the concrete mix but also influenced the overall flow behavior. This newfound understanding opens up avenues for further exploration and optimization in the realm of concrete mix design.

4.2 Compressive Strength

In Table 2, we present the results obtained from the first batch of mix ratios, shedding light on the fascinating interplay between alkali dissolution rates, polymerization kinetics, and compressive strength in Alkali-activated cement. Aluminates and silicates, key constituents of the binder material, dissolve in the alkaline solution at a specific rate, with polymerization dynamics hinging upon this dissolution rate.

Across all mix variations, a common observation emerged: the emergence of a new gel product indicative of polymerization progression. Notably, as the quantity of sodium hydroxide (NaOH) increased, there was a corresponding increase in compressive strength. This phenomenon can be attributed to enhanced polymerization kinetics, which augment the dissolution rate of aluminosilicates, leading to greater binder cohesion and strength. Further analysis revealed a fascinating correlation between the Na2SiO3/NaOH ratio and water-to-binder ratio, with an increase in the former resulting in a reduction in the latter. This reduction in water-to-binder ratio, in turn, contributed to a notable increase in compressive strength, underscoring the pivotal role of molarity and Na2SiO3/NaOH ratio in determining compressive strength at 28 days. Of particular significance was the mix incorporating an SS/SH option of 3.5 and 10 molar sodium hydroxide, which exhibited the highest compressive strength among all variants. This mix was subsequently selected as the control mix for batch 2, serving as a reference point for further experimentation. Furthermore, it was observed that the inclusion of fibers resulted in an overall increase in compressive strength across all mixes in batch 2. Interestingly, the maximum compressive strength among all percentage volume content mixes was consistently associated with steel fibers. This trend highlighted a progressive enhancement in mix strength with increasing volume percentage of steel fibers, whereas polypropylene fibers exhibited a contrasting trend, with a progressive decrease in compressive strength. To provide a visual representation of these findings, the 28-day compressive strength values are graphically depicted in Figure 6, offering a comprehensive overview of the observed trends and correlations. In summary, the results from this study offer valuable insights into the complex interactions governing the mechanical properties of Alkali-activated cement, paving the way for informed material design and optimization strategies.

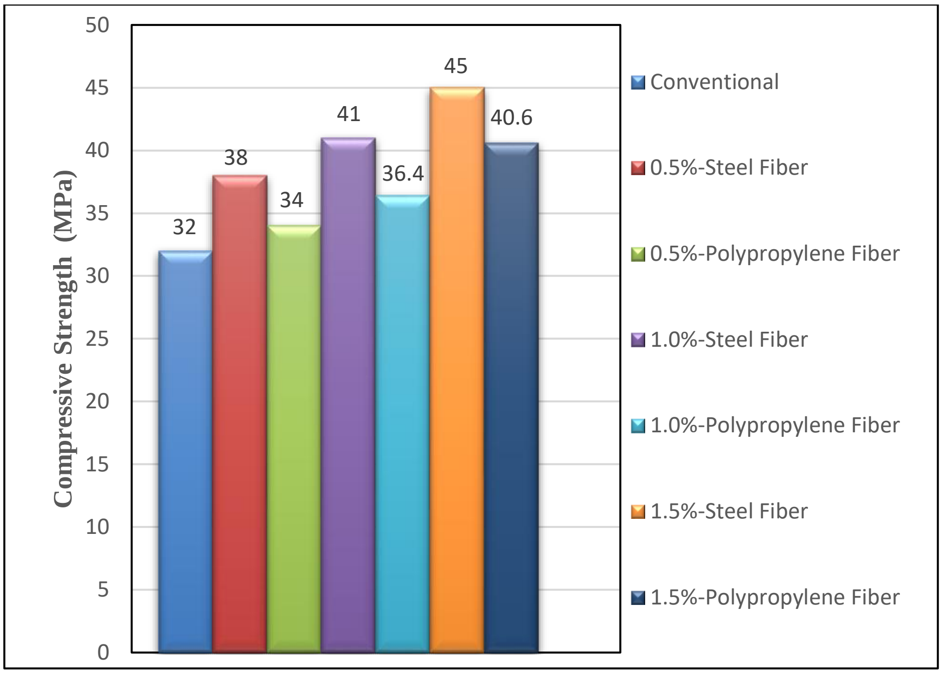

Figure 6. Compressive Strength

4.3 Splitting Tensile Strength

Upon meticulous observation, distinct behaviors in crack propagation were discerned across various mix compositions. In the control mix, crack propagation occurred abruptly, manifesting as a straight crack upon specimen failure – a characteristic indicative of brittle mode failure, as anticipated. However, with the incorporation of steel fibers (SF) and polypropylene fibers (PF), a notable shift in crack propagation dynamics was observed. Interestingly, mixes containing SF and PF exhibited slower crack propagation, accompanied by the emergence of numerous micro split cracks adjacent to the main crack, suggestive of a more ductile mode of failure. Initially, during the elastic deformation phase, the specimen remained crack-free. However, as the loading increased, cracks gradually formed, with a subsequent expansion observed. Upon reaching peak stress, the crack width increased exponentially, ultimately leading to failure by longitudinal splitting. Remarkably, following the initiation of cracks in the concrete matrix, the fibers assumed load-bearing responsibilities, accompanied by a slight decrease in load-carrying capacity before rapidly increasing. Notably, the quantity of PF used per unit volume of concrete was approximately one-tenth that of SF, with minimal fiber gaps between PF within the matrix. This characteristic ensured effective crack suppression, particularly against shrinkage or bleeding-induced crack formation. While PF exhibited effective crack suppression initially, SF demonstrated superior crack arresting capabilities under higher loading conditions, owing to their higher elastic properties. This nuanced interplay between fiber types and loading conditions underscores the importance of material selection and mix design in optimizing crack resistance and structural integrity. To visually depict the split tensile strength values of the tested mixes, Figure 7 provides a graphical representation, offering insights into the comparative performance of different mix compositions under tensile loading conditions.

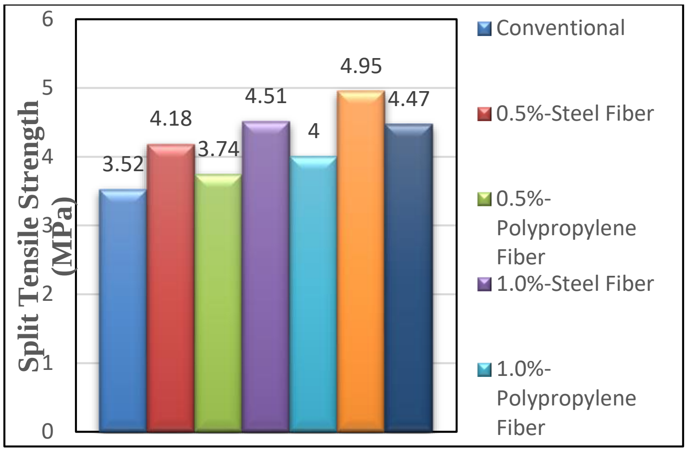

Figure 7. Split Tensile Strength

4.4 Flexural Strength

The findings of our study unveil compelling insights into the performance of fiber-reinforced Alkali-activated cement (FRGPC), shedding light on the critical role played by steel fibers (SF) and polypropylene fibers (PF) in enhancing mechanical properties. Notably, the mix containing 1.5% SF exhibited the highest flexural strength, reaching an impressive 11.8 MPa. Upon closer examination, it was observed that during tensile pull-out, tiny cracks formed at the contact area between the binder and SF, highlighting the robust bond between the fibers and the matrix. In contrast, PF exhibited lesser abrasion, attributed to their susceptibility to breakage. Remarkably, PF could be easily withdrawn from the binder without causing cracks or abrasions to the surface, underscoring their distinct characteristics and performance. Furthermore, the incorporation of fibers resulted in increased ductility and flexural strength, corroborating previous research findings. The tough texture of steel fiber surfaces fosters strong binding with the binder, enhancing overall stiffness and mechanical integrity. Moreover, the gel-like nature of geopolymers, characterized by numerous gaps and crystallized aluminum and silicate elements, further reinforces the composite matrix, contributing to enhanced strength properties. The fibers, acting as reinforcement elements, effectively distribute loads across the matrix, leading to improved splitting tensile strength and flexural strength compared to the control mix. However, the presence of microfractures suggests a nuanced interplay between fiber length, size, and mechanical behavior, highlighting the need for careful consideration in mix design and fiber selection. To provide a visual representation of these findings, the 28-day flexural strength of the specimens is graphically depicted in Figure 8, offering a comprehensive overview of the observed trends and performance metrics.

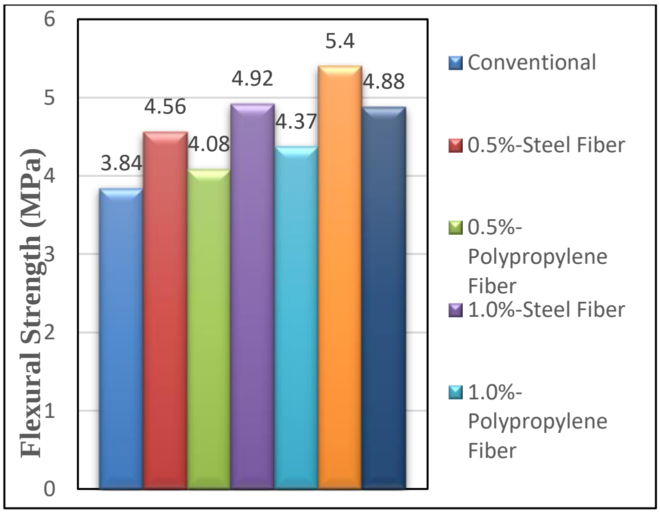

Figure 8. Flexural Strength

5. Conclusion

In our comprehensive study on fiber-reinforced Alkali-activated cement (FRGPC), we uncovered intriguing findings regarding the impact of fiber inclusion on mix workability and mechanical properties. Regardless of the volume content, the addition of fibers led to a reduction in mix workability. Moreover, further increases in fiber content exacerbated this effect, resulting in harsher and less workable mixes.

A notable contrast emerged between steel fibers and polypropylene fibers in terms of their mechanical performance. Steel fibers exhibited a substantial increase in mechanical properties and demonstrated a broader range of benefits compared to polypropylene fibers. Specifically, the incorporation of 1.5% steel fibers resulted in a remarkable 40% increase in flexural strength, while polypropylene fibers contributed to a commendable 27% increase compared to conventional mixes. Further analysis revealed that mixes incorporating 10M solution GPC with steel fibers exhibited the highest 28-day compressive strength values. This underscores the significant enhancement in compressive strength achieved through the synergistic combination of geopolymers and steel fibers. Moreover, the inclusion of fibers, particularly steel fibers, led to higher split tensile strength values in FRGPC. This observation indicates reduced crack propagation and the formation of microcracks, highlighting the effectiveness of fiber reinforcement in enhancing the structural integrity and durability of the concrete.

In summary, our study demonstrates the pivotal role of fiber reinforcement in augmenting the mechanical properties and performance of Alkali-activated cement. By uncovering these insights, we contribute to the advancement of sustainable construction practices and the development of resilient infrastructure solutions.

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