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# Sustainable basalt fibre reinforced alkali-activated geopolymer concrete for sustainable environments

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## ABSTRACT

A novel study on fibre-reinforced cement less geopolymer concrete with diverse molar concentrations has gained attention in recent years. The current study uniquely explores the combined influence of four distinct molar concentrations (6M, 8M, 10M, and 12M) and five fibre volume fractions (0%, 0.25%, 0.50%, 0.75%, and 1%) on the mechanical behaviour of GPC. An experimental investigation on 20 numbers of varied geopolymer concrete mixes was performed, and the mechanical properties were evaluated and reported. Also, A non-destructive test using ultrasonic pulse velocity was made, and the regression analysis with compressive strength is reported. The result indicates that 10M concentration provides the optimum results than other molar concentrations, with 0.75% as the optimum basalt fibre volume addition to the cementless geopolymer concrete. The basalt fibre addition improves the split tensile strength and flexural bending strengths considerably. Morphology studies indicate that the lower molar concentration gives a comparatively loose and voided concrete matrix with a loose packing of ingredients than the higher molar concentration. This research provides a comprehensive and optimised approach by simultaneous variation of Molar concentration and fibre volume to enhance geopolymer concrete, supported by both mechanical investigation and microstructural analysis.

**Keywords:** Geopolymer; Basalt fiber; Fiber reinforced geopolymer; Mechanical strength.

## 1. INTRODUCTION

As of this date, the major problem faced by the construction industry is higher carbon dioxide emissions [1]. In an estimate, 5% of total $CO_2$ emissions are released from cement-related processes [2]. The usage of cement is one of the main reasons for this issue [3]. The introduction of the geopolymer technique is a viable solution to address this problem [4]. Also, on today's date, sustainability is a rising concern and an alternative to the existing cement-based products, using geopolymers is a workable solution [5]. Based on the existing research, it is proven that with the use of flyash-based geopolymer, it is possible to effectively reduce the $CO_2$ emissions upto 9% than conventional cement products. With geopolymerization, the emission of greenhouse gases can be effectively reduced up to 40–60%. With the use of geopolymers, it can be proven that the mechanical strength and durability properties have improved compared to the conventional cement-based products. As reported by the existing research, it is possible to prepare geopolymer concrete of up to 80 MPa. Also, the flexural and split tensile strength can be improved up to 10 MPa and 8 MPa, respectively [6]. Geopolymers are composite materials in place and have the capability of strong resistance against heat. It can be a fast-curing material [7].

In today's higher infrastructure development and fast urbanisation process, the requirement for concrete is also huge in volume worldwide [8]. The use of cement offers a negative constraint towards the environment, necessitating the alternate geopolymer technique to emerge faster than before. Several base materials can be used to prepare the geopolymers. The popular materials are Fly ash, GGBS, Metakaolin, Cement kiln dust and slag, etc [9]. The nature of supplementary cementitious materials decides the performance of geopolymer-based final products [10]. The main issue associated with the fly ash-based geopolymers is the later age strength and the higher brittleness [11].

Fibre reinforcement to the concrete is the decade of prevailing research and which improves the strength of concrete by arresting and propagating the micro cracks [12]. There are several types of fibre reinforcement

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available in the market, which include steel fibre, glass fibre, carbon fibre and other synthetic-fibre like polyvinyl alcohol fibre, polyethene fibres and more [13]. Each fibre has its own merits and demerits when used in the concrete. These fibres have proven the ability to improve the split tensile strength, bending strength, resistance against frost and improve the bonding behaviours, etc [14]. Out of the above range of fibres, one of the natural fibres available in the market has higher proven abilities of higher strength, improved elastic modulus, and lower cost are Basalt fibres [15]. It is widely engaged in improving the technical characteristics of geopolymer concrete extensively. These types of fibres are manufactured with extremely fine fibres of basalt rock, and they contain the olivine and pyroxene minerals.

According to the earlier investigation of [2], the basalt fibres were fixed at 2% by weight of all the specimens and the nano $CaCO_3$ was introduced. It is reported that the the higher baslt fiber addition of 15–30% did not show any significant improvement in the compressive strength and hence, in the current study, the Basalt fiber were introduced at the five different lower volume (0–1%) to study the coupled effects of molarity change and fiber dosage in the GPC. Also, the study reported in [13], the digital image correlation technique was used to evaluate the mechanical attributes of the basalt fibre added geopolymer concrete. In the study reported in [15], the metakaolin-based geopolymer was researched with the addition of 12–24 mm basalt fibres with boron waste.

Due to their low carbon footprint and ability to integrate a variety of industrial by-products, geopolymers have garnered significant interest as environmentally friendly alternatives to conventional cement-based materials. The effect of cement and lime additives on the strength and heat resistance of Class F and C fly ash-based geopolymer mortars was investigated by Ozkul et al. Although results differed depending on the type of fly ash and the curing technique, they discovered that both additions increased compressive strength and high-temperature durability [16]. A thorough analysis of the durability of geopolymers derived from natural pozzolans, agricultural waste, and industrial byproducts was carried out by Ngui et al. They promoted the wider use of waste-based binders in the manufacturing of geopolymers by highlighting characteristics like sulfate resistance, acid attack resistance, and freeze-thaw stability [17].

The mechanical and durability characteristics of geopolymers based on metakaolin and red mud and reinforced with powdered limestone, marble, and basalt were examined by Chakkor et al. They found that under high temperatures and freeze-thaw cycles, basalt powder produced the best results in terms of strength and performance [18]. Sonali Sri Durga et al investigated how the characteristics of fly ash-based geopolymer aggregates were affected by the addition of GGBFS and oven drying. They promoted the use of GGBFS in the manufacturing of lightweight aggregates by observing improved mechanical strength and decreased water absorption with optimum GGBFS content [19]. Nis examined how alkali-activated fly ash/slag concrete's compressive strength changed as NaOH concentrations and silicate-to-hydroxide ratios changed. Both early and long-term strength development were significantly impacted by optimal ratios [20].

Tammam et al. emphasised the function of waste fillers and recycled aggregates in geopolymer composites. The feasibility of utilising waste materials to lessen environmental impact while preserving mechanical qualities was validated by their findings [21]. Mashifana suggested geopolymerisation as a successful technique for stabilising fly ash in the manufacturing of green building bricks. Significant gains in strength and environmental safety over unstabilized materials were shown in the study [22]. An appropriate geopolymer grout for structural restoration in reinforced concrete (RC) beams was created by Kantarcı and Maraş. Their findings supported its improved mechanical performance and bonding, suggesting that it be used for retrofitting [23]. Ma et al. introduced a novel 3D-printed short carbon fibre-reinforced geopolymer composite that exhibits superior mechanical qualities and structural soundness appropriate for sophisticated building methods [24]. In their design of fibre-reinforced geopolymer concrete pipes for infrastructure, Rihawi et al. prioritised structural performance and environmental sustainability. Their research confirmed that geopolymer pipes are a viable and environmentally benign alternative to traditional concrete systems [25]. Maras (2021) investigated hybrid fiber-reinforced geo-polymer composites' tensile and flexural performance. Significant improvements in cracking behaviour were demonstrated by the results, confirming its use in structural elements that need to be extremely tough [26].

In the present study, to improve the mechanical properties of the geopolymer concrete, basalt fibre reinforcement was introduced. The study focused on evaluating the coupled effects of the simultaneous addition of Molar concentration and the varying fibre dosages. The compressive strength, split tensile strength and flexural strength were studied by varying the volume fractions of the basalt fibres. Sodium Hydroxide is used as a chemical alkali activator in the study. The properties of geopolymer concrete with and without the basalt fibre reinforcement were evaluated. A morphology study of the optimum mix was reported.

## 2. EXPERIMENTAL STUDY

### 2.1. Materials & methods

An alkali-activated basalt fibre reinforced geopolymer was developed in the present investigations. A low calcium Fly ash obtained from the Mettur Thermal Power Station, Tamil Nadu, India, is used in the present investigations. The physical and chemical properties of the obtained fly ash are presented in Tables 1 and 2, respectively.

**Table 1:** Physical properties of fly ash.

| PROPERTY | VALUE |
|---|---|
| Particle size | 45 µm |
| Specific gravity | 2.07 |
| Fineness | 527 $m^2/kg$ |

A view of the sample is given in Figure 1. Basalt chopped fibre of 6 mm was used in the present study, as the higher fibre length may influence the workability characteristics of concrete. The characteristics of the obtained basalt fibre are presented in Table 3. Figure 2 shows a view of chopped basalt fibre used in the present investigations. The main geopolymer constituents, such as alkaline activators such as NaOH (Caustic Soda) flakes and $Na_2SiO_2$ solution, are used for the investigation. NaOH of 99% purity was used for the preparation of specimens. The alkaline solution, which conforms to BIS381 (1995), was used for the study. Aggregates of crushed sand and coarse aggregates used in the study conform to BIS383 (2016).

**Table 2:** Chemical properties of fly ash.

| CONSTITUENTS | PERCENTAGE |
|---|---|
| Silicon dioxide ($SiO_2$) | 59.08 |
| Calcium oxide (CaO) | 2.08 |
| Aluminum oxide ($Al_2O_3$) | 36.46 |
| Iron oxide ($Fe_2O_3$) | 2.38 |

**Figure 1:** Fly ash.

**Table 3:** Properties of basalt fibre (from manufacturer).

| CHARACTERISTICS | VALUE |
|---|---|
| Fiber length | 6 (mm) |
| Fiber diameter | 9–20 (µm) |
| Unit weight | 2720 (kg/cum) |
| Elastic modulus | 89000 (N/mm$^2$) |
| Tensile strength | 4.84 (GPa) |

**Figure 2:** Basalt fiber.

### 2.2. Mix proportioning

The molar concentration of Alkaline solutions was 6, 8, 10 and 12, in the investigation with $Na_2SiO_2$/NaOH ratio kept constant as 2. In each Molar concentration, 5 nos of concrete mixes with 0, 0.25,0.5, 0.75 and 1% volume of basalt fibre are added. The alkaline solution to binder ratio is fixed as 0.45. Table 4 presents the mix proportions for the 20 nos of diverse concrete mixes. A typical range of geopolymer mix considered in the present study is also presented.

With the concrete mixer in the laboratory setup, geopolymer concrete was prepared. The mixer machine is operated at a speed of 25 revolutions per minute. With the initial 120 seconds, the ingredients are fed into the mix and intimately mixed. After that, the alkaline solutions were added, and the machine was rotated for another 180 seconds. After that, they poured into the mould and provided a resting time of 24 hours.

The compressive strength Testing is carried out as per ASTM C39/C39M and IS 516 (Part 1/Section 1). The Split tensile strength followed ASTM C496/C496M and IS 5816. The Flexural strength was assessed in accordance with ASTM C78/C78M and IS 516 (Part 2/Section 2). The Ultrasonic Pulse Velocity was measured as per IS 13311 (Part 1).

## 3. RESULTS AND DISCUSSION

### 3.1. Test results on compressive strength

Figure 3 presents the test results on the basalt fibre reinforced diverse molar concentrated geopolymer concrete mixes. Accordingly, the increased Molar concentration invariably enhances the compressive strength of the concrete mixes up to a certain level, and it shows a decline in trend.

The compressive strength results for various basalt fiber volume fractions (0%, 0.25%, 0.5%, 0.75%, and 1%) and molar concentrations (6M, 8M, 10M, and 12M) provide important information about the combined

**Table 4:** Typical range of GPC mix ingredients considered in the study.

| MIX | FLY ASH | NAOH | $Na_2SiO_2$ | ALKALINE SOLUTION TO BINDER | SAND | COARSE AGGREGATE | BASALT FIBRE |
|---|---|---|---|---|---|---|---|
| | kg/m³ | | | | | | % |
| 6M0 | 489 | 55.13 | 110.25 | 0.45 | 647 | 1299 | 0.00 |
| 6M0.25 | 489 | 55.13 | 110.25 | 0.45 | 647 | 1299 | 0.25 |
| 6M0.5 | 489 | 55.13 | 110.25 | 0.45 | 647 | 1299 | 0.50 |
| 6M0.75 | 489 | 55.13 | 110.25 | 0.45 | 647 | 1299 | 0.75 |
| 6M1 | 489 | 55.13 | 110.25 | 0.45 | 647 | 1299 | 1.00 |
| 8M0 | 489 | 73.50 | 147.00 | 0.45 | 647 | 1299 | 0.00 |
| 8M0.25 | 489 | 73.50 | 147.00 | 0.45 | 647 | 1299 | 0.25 |
| 8M0.5 | 489 | 73.50 | 147.00 | 0.45 | 647 | 1299 | 0.50 |
| 8M0.75 | 489 | 73.50 | 147.00 | 0.45 | 647 | 1299 | 0.75 |
| 8M1 | 489 | 73.50 | 147.00 | 0.45 | 647 | 1299 | 1.00 |
| 10M0 | 489 | 91.88 | 183.75 | 0.45 | 647 | 1299 | 0.00 |
| 10M0.25 | 489 | 91.88 | 183.75 | 0.45 | 647 | 1299 | 0.25 |
| 10M0.5 | 489 | 91.88 | 183.75 | 0.45 | 647 | 1299 | 0.50 |
| 10M0.75 | 489 | 91.88 | 183.75 | 0.45 | 647 | 1299 | 0.75 |
| 10M1 | 489 | 91.88 | 183.75 | 0.45 | 647 | 1299 | 1.00 |
| 12M0 | 489 | 110.25 | 220.50 | 0.45 | 647 | 1299 | 0.00 |
| 12M0.25 | 489 | 110.25 | 220.50 | 0.45 | 647 | 1299 | 0.25 |
| 12M0.5 | 489 | 110.25 | 220.50 | 0.45 | 647 | 1299 | 0.50 |
| 12M0.75 | 489 | 110.25 | 220.50 | 0.45 | 647 | 1299 | 0.75 |
| 12M1 | 489 | 110.25 | 220.50 | 0.45 | 647 | 1299 | 1.00 |

effects of fiber reinforcement and alkaline activator concentration on geopolymer concrete (GPC): All fibre dosages saw a notable increase in compressive strength when the molarity was raised from 6M to 10M, with 10M blends showing the highest strengths. A denser alumino-silicate matrix is formed as a result of the enhanced geopolymerization reaction caused by the increase in molarity, which increases strength. A further increase to 12M, however, caused a decrease in strength, suggesting that extremely high alkalinity may result in an excessively quick setting, which could impact workability and cause incomplete bonding or microcracks because of the excessive heat of reaction. It negatively impacts the fibre–matrix interface at high pH levels.

- The inclusion of basalt fibre boosted compressive strength across all molarities up to 0.75%, after which there was a minor decrease at 1%. Regardless of molarity, peak performance was consistently attained at 0.75% fibre volume, emphasising its function in bridging microcracks, halting crack propagation, and enhancing post-peak load-carrying capacity. Fibre agglomeration, which results in uneven dispersion and the formation of weak interfacial zones as a result of inadequate bonding or clustering, may be the cause of the strength decrease at 1% fibre dose. Potential loss in matrix integrity and an increase in voids. The highest compressive strength (41.5 MPa) was obtained with a combination of 10M molarity and 0.75% basalt fibre, suggesting that chemical activation and fibre reinforcement work best together.
- Despite fibre reinforcement, lower molarity mixes such as 6M demonstrated relatively lower strength (25.5 MPa at 0.75%) because of insufficient geopolymer gel formation and higher porosity. This demonstrates that adequate alkaline activation is necessary to achieve the reinforcing benefits of basalt fibres.

### 3.2. Test results on split tensile strength

The split tensile test results on basalt fiber reinforced different molar concentrated geopolymer concrete mixes are given in Figure 4.

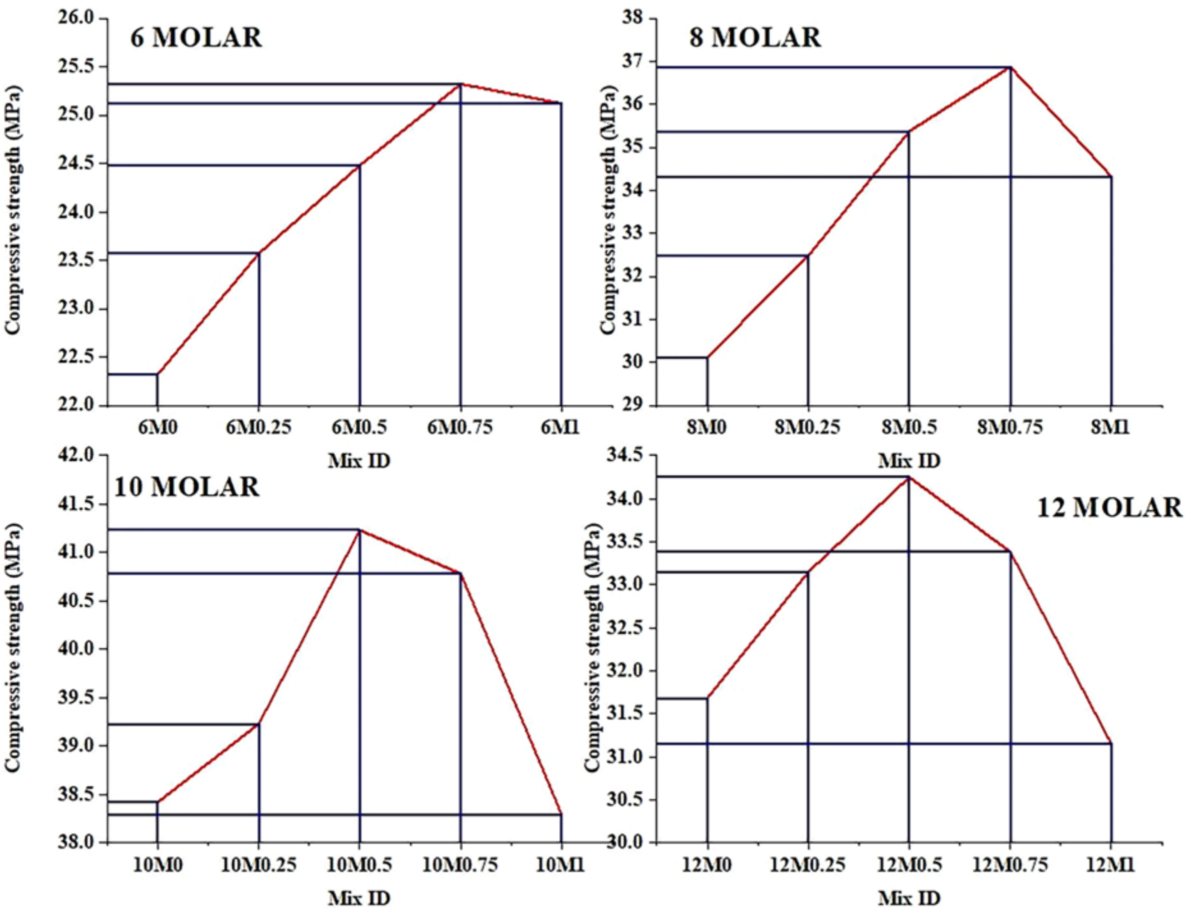


**Figure 3:** Compressive strength test results of various molar concentrations.

The split strength results for various basalt fiber volume fractions (0%, 0.25%, 0.5%, 0.75%, and 1%) and molar concentrations (6M, 8M, 10M, and 12M) provide important information about the combined effects of fiber reinforcement and alkaline activator concentration on geopolymer concrete (GPC):

Similar to compressive strength, split tensile strength is improved by increasing the molarity from 6M to 10M because of improved geopolymerization, which strengthens the link between paste and aggregates and enhances matrix integrity. Excessive alkalinity may weaken the fibre-matrix interface or cause microcracks due to shrinkage and quick setting, as seen by the peak strength at 10M (up to 5.7 MPa) and the minor drop at 12M. Across all molarities, the inclusion of basalt fibres greatly increased split tensile strength: Fibre content might boost strength by up to 0.75%. After this (at 1%), a modest plateau or drop is observed. Basalt fibres help by preventing cracks from spreading under tensile pressures and by bridging existing cracks. Improving post-peak load resistance and ductility. Fibre aggregation and insufficient dispersion may cause stress concentration zones, which could account for the 1% performance loss. reduction in the effective load transmission due to matrix continuity disruption. The combination of 10M molarity and 0.75% fibre yields the best tensile strength (~5.7 MPa), demonstrating its optimality. The inclusion of fibres significantly increases tensile strength (from around 2.5 MPa to about 3.6 MPa) even at lower molarity (e.g., 6M), demonstrating the beneficial effects of reinforcement even in less reactive matrices.

Figure 5. presents the regression analysis for the compressive strength and split tensile strength of the concrete mixes. The regression analysis is made for each molar concentration. The lower concentration of 6M and 8M proves the best-fit curves with R2 greater than 0.95 and 0.98. However, the higher concentration provides the R2 values greater than 0.83. The regression equations to are established for each molar concentration and is provided in Figure 5.

### 3.3. Test results on flexural strength

The flexural strength results of the basalt fibre added diverse molar concentrated geopolymer concrete mixes were presented in Figure 6. A similar trend of strength pattern is observed with the split tensile strength test

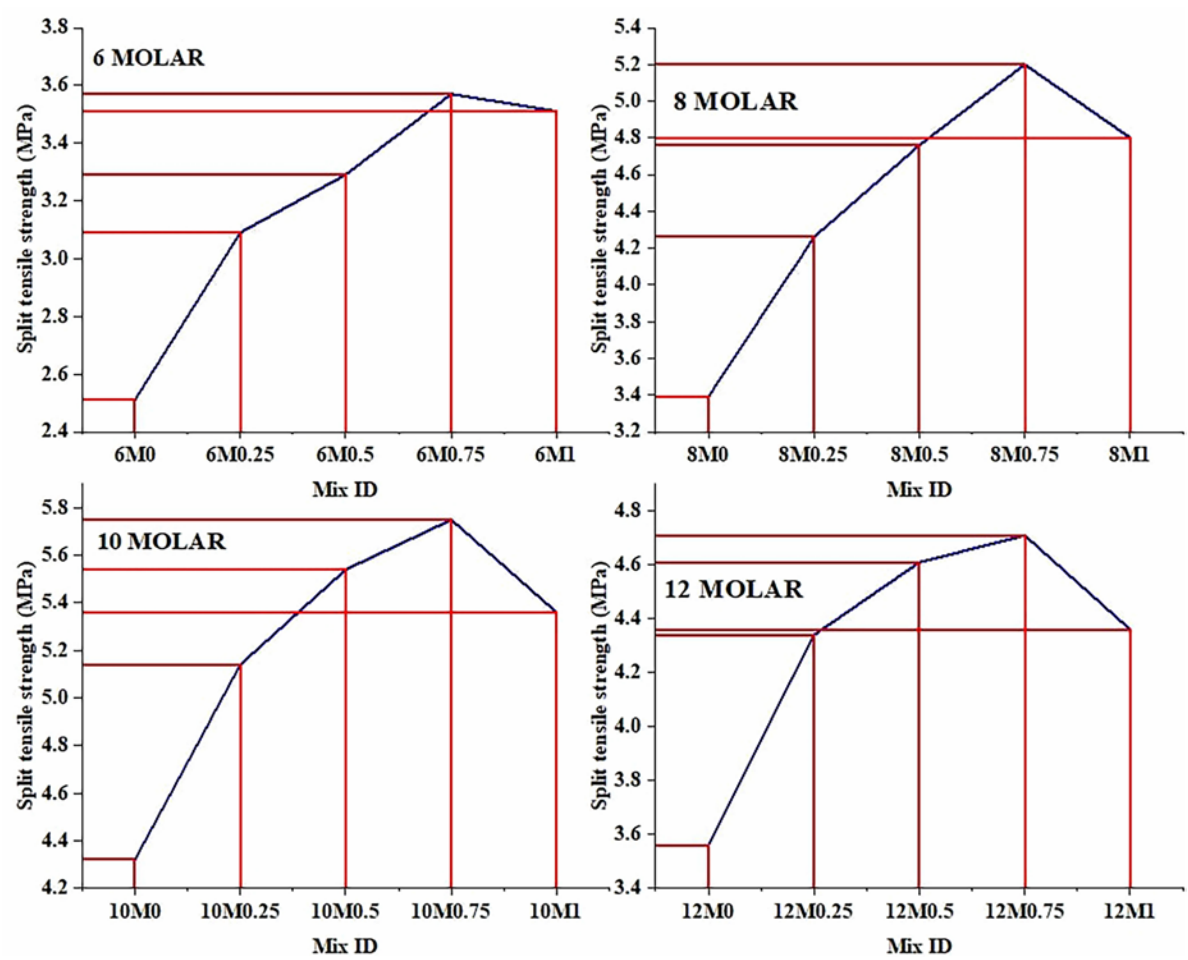


**Figure 4:** Split tensile strength test results of various molar concentrations.

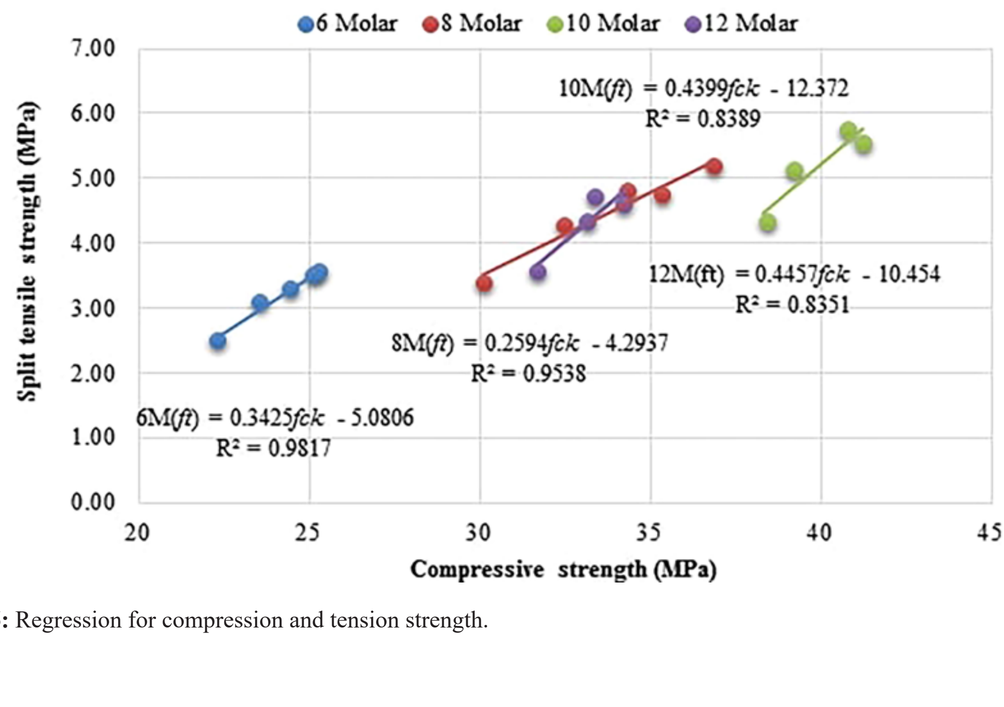


**Figure 5:** Regression for compression and tension strength.

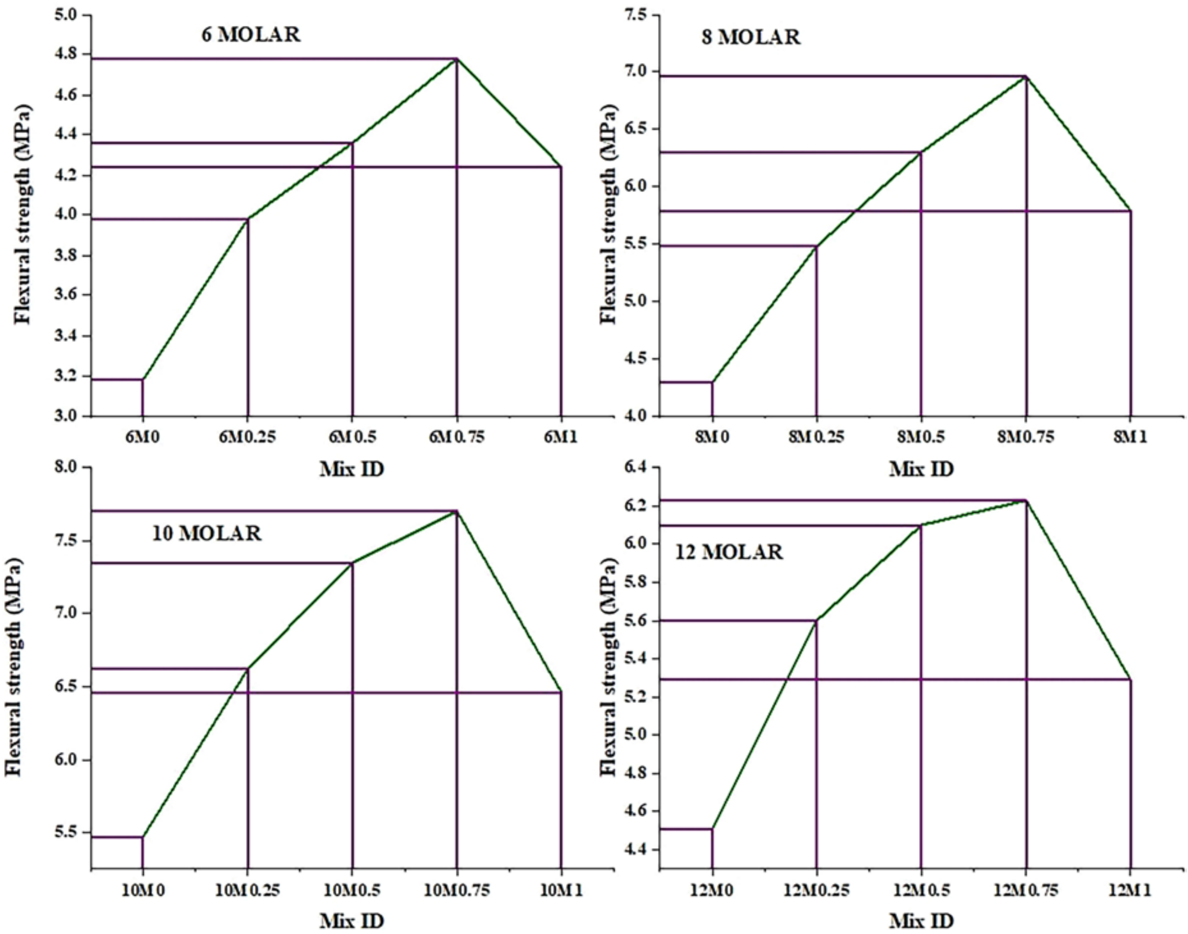


**Figure 6:** Flexural strength test results of various molar concentrations.

results. Based on the results, 0.75% of fibre incorporation provides the optimum strength values in all the 6M, 8M, 10M and 12M concentrations. The increased molar concentration increases the flexural strength up to 10M, and further increased concentration tends to decrease the flexural strength of the concrete mixes. The increased basalt fibre addition improves the flexural strength up to 0.75% and further addition decreases the strength of the concrete mixes. It is to noting that the excessive alkalinity at higher molarities (over 10M) can cause rapid geopolymerization, which can impact the fibre-matrix bond and overall flexural performance by causing micro-cracking and the creation of a brittle matrix. Geopolymeric gel structures that are coarse or uneven may also emerge as a result of high molar concentrations, thereby decreasing the matrix's homogeneity and continuity. If the fibre concentration is more than 0.75%, weak zones and disturbed stress transmission mechanisms may result from fibre aggregation and inadequate dispersion.  Fibre deterioration or inadequate interfacial bonding may also limit the efficiency of stress bridging at high alkalinity, especially for natural fibres like basalt.

### 3.4. Ultrasonic pulse velocity

The test results of Ultrasonic pulse velocity at the age of 28 days are given in Table 5. Based on the results, it is observed that the increased basalt fibre addition slightly improves the ultrasonic pulse velocity of the concrete mixes. The observation invariably holds good for the diverse molar concentration levels. A congruence observation of UPV and compressive strength is also noted, as shown in Figure 7. Four different Regression equations were observed for 6M,8M,10M and 12M molar concentrations. For 10M and 12 M concentrations, a best-fit equation of $R^2$ greater than 0.9 was observed.

## 4. MORPHOLOGY STUDIES

Under the Morphology studies, the samples of 6M0.5 and 10M0.75 were subjected to scanning electron microscope investigations. With the investigations, it is observed that in both the micrographs the fly ash particles are present along with the other constituents. Fiber particle is visible in Figure 8. There is a clear dense con-

**Table 5:** Ultrasonic pulse velocity test results.

| MIX ID | UPV (m/s) |
|---|---|
| 6M0 | 2972 |
| 6M0.25 | 2978 |
| 6M0.5 | 2982 |
| 6M0.75 | 2987 |
| 6M1 | 2981 |
| 8M0 | 3144 |
| 8M0.25 | 3152 |
| 8M0.5 | 3167 |
| 8M0.75 | 3183 |
| 8M1 | 3172 |
| 10M0 | 3212 |
| 10M0.25 | 3224 |
| 10M0.5 | 3268 |
| 10M0.75 | 3265 |
| 10M1 | 3212 |
| 12M0 | 31.68 |
| 12M0.25 | 33.15 |
| 12M0.5 | 34.25 |
| 12M0.75 | 33.38 |
| 12M1 | 31.15 |

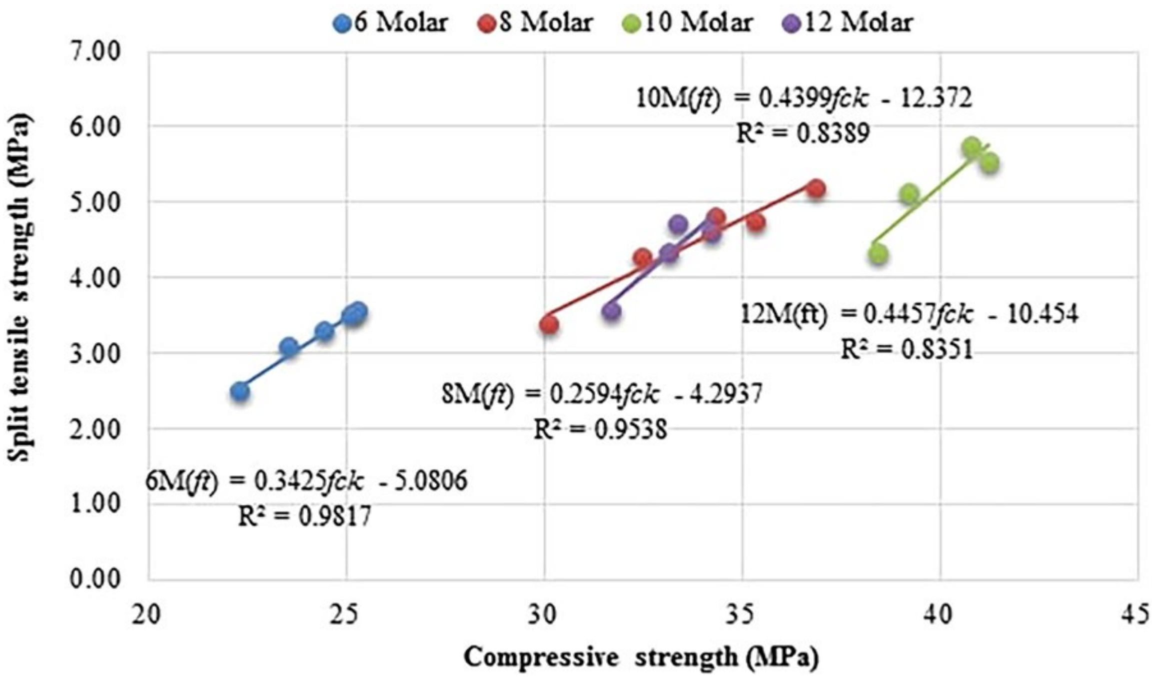


**Figure 7:** Regression analysis of UPV and compressive strength.

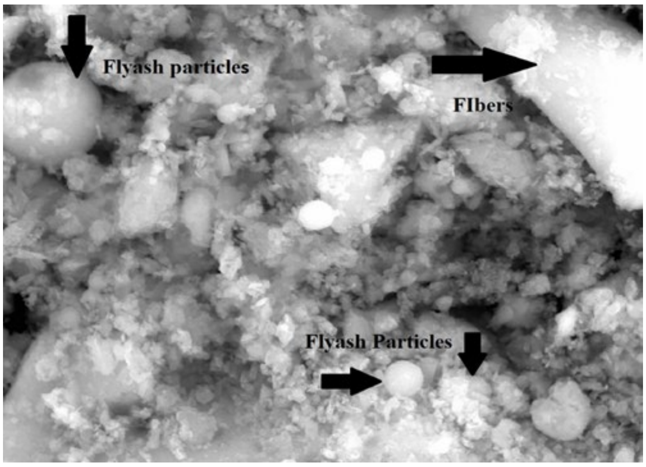


**Figure 8:** Micrograph of 10M0.75.

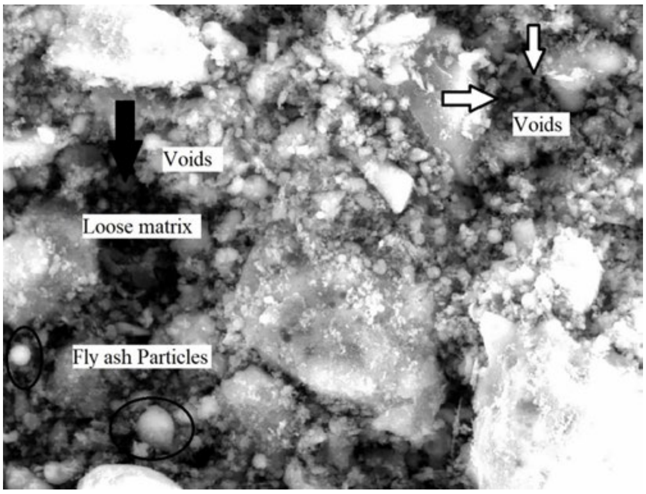


**Figure 9:** Micrograph of 6M0.5.

crete matrix is observed through Micrograph. However, in the case of the 6M0.5 Micrograph in Figure 9, it is observed that the very loose matrix can be noted. In several places, a lot of void spaces were observed. This correlates with the mechanical strength observations.

## 4. CONCLUSIONS

In this work, a completely cementless geopolymer concrete reinforced with chopped basalt fibers was the subject of a novel experiment. The alkaline activator solution's molar concentration (6M, 8M, 10M, and 12M) and the amount of basalt fiber (0%, 0.25%, 0.5%, 0.75%, and 1% by volume) were both changed during the experiment. The objective was to assess their combined impact on the microstructure and mechanical characteristics of the geopolymer concrete, and the following important findings were reached:

- Increasing molarity enhances the geopolymerization reaction, improving the compressive, split tensile, and flexural strength of the concrete up to 10M. However, further increase to 12M showed a slight decline, likely due to rapid setting and reduced workability.
- An optimal molarity of 10M was identified, beyond which the strength gains plateaued or slightly decreased, indicating a performance threshold under the specific mix and curing conditions used.

- Basalt fiber addition improves mechanical strength, particularly in split tensile and flexural strength, due to better crack-bridging and energy absorption. The optimal fiber volume fraction was found to be 0.75%, beyond which strength gains diminished, likely due to fiber clustering or dispersion issues.
- Similar strength trends were observed across all mechanical tests, validating the consistency and reliability of the results.
- Morphological (SEM) analysis confirmed the mechanical findings. Lower molarity mixes (e.g., 6M) exhibited a porous and loosely bonded matrix, while higher molarities (notably 10M) showed denser, more homogeneous matrices with improved fiber-matrix bonding.

This study fulfils the stated objectives by demonstrating how the simultaneous variation of molar concentration and fiber volume influences performance, identifying optimal mix parameters, and validating mechanical trends through microstructural evidence.

The Key limitation of the current study is the lack of the long-term durability assessment and the diverse environmental exposure assessment. Further research would explore the durability under aggressive environments(Sulphate, Chloride and freeze and thaw cycles), Scalability and field applications of optimized mixes and Life cycle assessment for sustainability bench marking.Also, the ststistical analysis of UPV and the mechanical behaviour of the GPC concrete to be considered in the future research.

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## DATA AVAILABILITY

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.