The effect of minibars basalt fiber fraction on mechanical properties of high-performance concrete

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\textbf{Abstract:} Basalt fiber (BF) is one of the most important sustainable materials used to enhance high-performance concrete (HPC) in recent years. There are two types of BF, namely micro-BF and macro-BF. Despite that, macro-BF is a new material and there are few studies about it. A variety of standard material tests were carried out to examine the impact of MiniBars BF as well as its fractions (0.6–1.8\%) on the physical and mechanical properties of HPC, including compressive strength ($f_{cm}$), flexural strength ($f_i$), workability, and modulus of elasticity ($E_c$). The study applied the one variable at a time method by using an identical mix with different fractions of MiniBars BF to minimize the influence of other factors on the result of the test. Six different mixes were investigated. The experiment showed that the MiniBars BF fraction slightly affected the workability of the HPC mix. The results indicated that the small amount of MiniBars BF did not affect the $f_{cm}$ and the $E_c$ of HPC. But it has a negative effect after the dosage of MiniBars BF increased by more than 1.2\%. The MiniBars BF enhanced the $f_i$ significantly even with a small percentage until it reached the optimum effect at 0.9\% then drop slightly.

\textbf{Subjects:} Mechanics; Materials Science; Civil, Environmental and Geotechnical Engineering

\textbf{Keywords:} Basalt fiber reinforced concrete; high-performance concrete; compressive strength; flexure strength; minibars; modulus of elasticity

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The strength of concrete structures depends on many factors. Some of the factors considered in this paper are the properties of the Macro-BF (MiniBars) which serve as the strengthener (reinforcement material) of the concrete. The quantity of the MiniBars and the curing period of the concrete are also some of the factors. Extensive research and experiments were done to ascertain the effectiveness of MiniBars basalt fiber on high-performance concrete (HPC). The compressive and flexural strength of the concrete was derived experimentally while the modulus of elasticity was determined numerically. At the end of the analysis, it was confirmed that MiniBars basalt fiber improved the strength and modulus of elasticity of the HPC even at different curing periods.
1. Introduction
Concrete is one of the most used constructions and building materials. Engineers design new structures to meet the aspect of sustainable development in many countries. Therefore, there has been an increased recognition that more attention needs to be paid to enhancing the existing construction materials, especially concrete. Due to superior physical and chemical properties, High-Performance Concrete (HPC) is among the most important materials used to replace Plain Concrete (PC). By replacing the PC with HPC, you will reduce the volume of materials used, speed up the construction process, and increase the structure’s service life (Kosmatka & Wilson, 2011). However, HPC still provides better compressive strength ($f_{cm}$) and Flexure Strength ($f_f$) than PCs but it is still considered fragile low-tensile-strength material (Bharatkumar et al., 2005). The fiber has been introduced to overcome some of the inherent limitations of HPC and improve the $f_f$ and tensile strength ($f_t$) of HPC (Bharatkumar et al., 2005; Lam et al., 2021; Shafieifar et al., 2017; Smarzewski, 2019; Wei et al., 2019).

Commonly, the composite material theory and the fiber spacing theory are adopted to explain the reinforcement mechanism of fiber-reinforced concrete. The former is built on the mixing rule of composite materials and the latter is the perfect bond theory between fiber and matrix. They explain the reinforcement effect of fiber on concrete from different perspectives. The theory of composite materials (Kaw, 2005) regards the strength and elastic modulus of fiber, and concrete as a superposition, to improve the performance of concrete. The theory is based on that the matrix is isotropic and homogeneous. The fibers are distributed parallel to the direction of stress, and there is no relative slip between the fibers and the matrix. However, to get the result of the enhanced function, the elastic modulus and strength of the fiber must be greater than that of the matrix. Under this condition, the larger the volume content of the fiber is, the more obvious the reinforcement effect will be. But the ideal result conflicted with the existing research results (Arshad et al., 2020; Dias & Thaumaturgo, 2005; Jiang et al., 2014; Sun et al., 2019; Torres & Lantsoght, 2019).

There are a few types of fibers compatible with concrete like steel fiber (SF), polypropylene fiber, and basalt fiber (BF). BF is considered a new sustainable construction material. Recent research shows that BF can provide high-class mechanical, chemical, and thermal properties (Gencel et al., 2022; Yavuz Bayraktar et al., 2021). BF is also environmentally friendly, non-toxic, and non-flammable with lower production costs (Boccardi et al., 2019; Feng et al., 2018; Jumaa & Yousif, 2019; Khandelwal & Rhee, 2020; Koksal et al., 2021; Militky et al., 2018; Shafieifar et al., 2017). Fiber is primarily used in concrete to inhibit tensile cracks growth, thus significantly increasing the post-crack $f_t$ of the concrete. The addition of fiber to concrete significantly alters the mechanical properties of the concrete such as the increase in toughness (energy absorption), ductility, $f_t$, and $f_f$ (Yavuz Bayraktar et al., 2021).

BF is usually made by pulling and twisting strands from a solution extracted from natural basalt rock (Pastuk et al., 2020). BF is extruded from molten basalt rock at diameters between 18 µm and 20 µm. BF products are available from various sources around the world mainly from Russia, Ukraine, and China. Basalt fiber reinforced polymer (BFRP) products are available in various forms such as bars, mesh, cages, spirals, fabric, and chopped fiber, and are useful as internal or external reinforcement of concrete structures (Anil, Len et al., 2013). It possesses a variety of unique characteristics, including superior mechanical capabilities, excellent thermal performance, and high environmental corrosion resistance, as well as exceptional bonding strength with polymeric glue due to its rough surface (Afroz et al., 2017; Branston, 2015; Ferrara et al., 2017; Jumaa & Yousif, 2019; X Wang et al., 2014; Zhang et al., 2017). Also, it improves the toughness and cracks resistance performance of the concrete (Khan & Cao, 2021; Zhou et al., 2020).
BF serves as a composite material in nonreinforced concrete, polypropylene composites, geopolymer concrete, epoxy composites, inorganic binders such as phosphates, and polysiloxane-based matrices, using its binding ability (Ding et al., 2011; M Wang et al., 2014). The microstructure of BF-modified concrete reveals good bonding in the early stages as compared to the latter (Jiang et al., 2014; Tassew & Lubell, 2014). The $f_{cm}$, fracture energy, $f_t$, and abrasion resistance of nonreinforced concrete could be improved significantly on account of BF incorporation in the concrete (Kabay, 2014). A major attribute of cementitious composites like cement mortar and concrete is their poor fracture toughness and tensile strength. These shortcomings can be resolved by introducing dispersed chopped fibers into the concrete matrix. They do so by limiting crack width and controlling crack propagation (Khan, Cao, Chu et al., 2022), which improves the toughness of the concrete reinforced with fiber.

Several research studies have been conducted on the use of fibers and polymers in concrete to improve strength-ductility (Ferdous et al., 2018; Khan, Cao, Ai et al., 2022; Xie et al., 2020). The incorporation of fibers in concrete could improve the post-cracking behavior of the concrete under compression (Caggiano et al., 2016). The incorporation of BF in concrete enhanced the strength of concrete (Chiadighiakaobi et al., 2022).

There were two types of BF used to improve the characteristics of the concrete micro-BF and macro-BF. The most common type is the micro-BF which is also known as chopped BF or BF only. The new type is called macro-BF and it is also known as MiniBars BF. Several studies have investigated the effectiveness of chopped BF on the mechanical properties like $f_{cm}$, $f_t$, and fracture energy of both PC and HPC (Alskar et al., 2021; Algin & Ozen, 2018; Alyousef, 2018; Arslan, 2016; Ayub, Shafiq, Nuruddin et al., 2014a, 2014b; Fiore et al., 2015; Khan et al., 2018; H Li et al., 2022; Y Li et al., 2022; B Liu et al., 2020; H Liu et al., 2017; Rawat et al., 2020; Zhang et al., 2022; Zheng et al., 2022). Therefore, there are very few studies about the effect of MiniBars BF on the PC and HPC (Alnahhal & Aljidda, 2018; C Zhang et al., 2021).

In general, MiniBars BF is considered a great replacement for the SF to reinforce concrete. MiniBars BF has a quarter the density of steel, is ecologically friendly, easy to mix with concrete, easy to pump, and does not sink or float in the mix (ReforceTech, 2021). The shear properties of HPC beams and small slabs reinforced with BFRP bars and macro-BF were studied in the research (Khan, Cao, Ai et al., 2022; Xie et al., 2020). The researchers used seven concrete mixes with five-volume fractions of MiniBars BF. The length of MiniBars BF used in the study was 43 mm and the fraction percentages included were 0.5%, 1.0%, 1.33%, 1.68%, and 2.0%, respectively. The $f_{cm}$ was slightly affected, and it ranged between 92 and 96.2 MPa. The study also found that increasing the fiber content enhanced the punching shear capacity and ductility of the slabs marginally (Mohammadi Mohaghegh, Silferbrand, Årskog et al., 2018a, 2018b).

Sudeep et al. (Adhikari & Adhikari, 2013) tested the effect of different fiber volume fractions of basalt MiniBars on the mechanical properties of PC. Volume fractions of 2%, 6%, 8%, and 10% were used. No loss of workability had been reported for any of the concrete mixes. It was found that the modulus of rupture of concrete increased with the increase of fiber content. In addition, the basalt fiber reinforced concrete (BFRC) prisms showed higher ductility and better toughness than PC prisms. Fiber content was reported to not affect on the $f_{cm}$ of the tested concrete. However, the modes of failure of the concrete cylinders made of BFRC mixes became more ductile with the increased fiber content. BFRC cylinders with high fiber volume fractions were capable to sustain loading with larger deflections than those with low fiber content.

Anil et al. studied the effect of MiniBars dosages on fresh and cured concrete properties (Anil, Sudeep et al., 2013). The MiniBars dosages ranged from 0.35% to 4% by volume. Physical inspection showed no segregation or balling of fibers during mixing. All concrete mixes showed acceptable slump with values ranging from 125 to 200 mm. The modulus of rupture was enhanced by increasing the fiber content. The highest enhancement in the modulus was obtained in the BFRC mix with 3% of MiniBars BF. A 25-percentage increase in its modulus over PC was recorded. Adding
fibers prevented the brittle failure of the concrete cylinders proving the ability of MiniBars to increase the energy absorption of concrete (Anil, Sudeep et al., 2013).

The impact of the chopped BF on the mechanical characteristics of the PC pavement was investigated by Sarkar and Hajihosseini. Three fiber doses (4, 8, and 12 kg/m³), two mixes, and two aggregate gradations were examined. According to test results, BF increased the compressive strength of a Portland cement sample by 4.3% to 9.4%. Despite this, the mechanical properties of Portland cement concrete are significantly influenced by the length and weight of this fiber as well as the quality of the aggregate. BF may have negative impacts or, under ideal circumstances, may only slightly increase split tensile and compression strength. This fiber’s greatest impact is an up to 20% increase in the flexural strength of concrete. Additionally, these fibers are ineffective at reducing the impact of chloride (or chlorine) on cement concrete (Sarkar & Hajihosseini, 2020).

Moreover, as a multifunctional fiber, BF possesses comprehensive and outstanding qualities: acidic and alkaline resistance, low- and high-temperature resistance, and excellent wettability (Lee et al., 2014; Zx Li et al., 2017).

2. Research objective and scope
This research investigated the behavior of the mechanical properties of HPC with newly developed MiniBars BF (Abed & Alhafiz, 2019). Most previous research focused on the impact of BF on the mechanical properties of normal concrete (Attia et al., 2020; Dilbas & Ö, 2020; John & Dharmar, 2021; Khandelwal & Rhee, 2020; Singh et al., 2019), with less on HPC. This study compared the effect of six MiniBars BF dosages on HPC and investigated the material’s influence on the density, \( f_{cm}, f_t \), and modulus of elasticity. Furthermore, the research also determined the optimal BF fraction to enhance the concrete properties and the effect of the MiniBars BF fraction on the HPC workability. The study also proposed the formulas for predicting the strengths of HPC reinforced with different MiniBars BF fractions in it aimed to determine the optimum MiniBars BF contents that could significantly enhance the mechanical properties of HPC.

Because BF affected the cementitious matrix component of concrete, HPC is a concrete composite with BF as the cause of increased \( f_t \) (Ma & Zhu, 2017). The fraction of BF in the cementitious matrix modified the mechanical characteristics and crack behavior under compression and flexural load. For the main four characteristics component is the \( f_{cm}, f_t \), crack, and failure behavior of HPC, aggregates with strong mechanical characteristics, cementitious materials, superplasticizer, and varying percentages of MiniBars BF were applied. MiniBars BF implied to minimize the macro cracks and deformation of the concrete (C Zhang et al., 2021). Therefore, BF has a significant impact on concrete plastic behavior and fracture extension in both compression and flexural tests. As a result, the cementitious matrix with MiniBars BF was able to absorb more energy and was more resistant to pre-cracked damage.

3. Materials and test methods
In this study, all the materials were measured and tested carefully in the same conditions to minimize the differences nonetheless it cannot be claimed that all specimens were the same.

3.1. Materials
The purpose of this study is to experimentally drive conclusive remarks about the effect of the MiniBars BF fraction and curing period on density, modulus of elasticity, \( f_{cm} \), and \( f_t \) of HPC. To prepare the minibar-basalt-fiber HPC (MiniBars BF HPC) specimens. The following materials were used

- Portland Cement M500 D0 = 500 kg was the main binder;
- Microsilica type MK-85 = 125 kg was the binding materials and mineral additives;
- Quartz powder of 50 µm = 100 kg/m³ was the mineral filler;
- Superplasticizer = 12.5 L/m³;
- Quartz Sand with a fineness modulus of 0.8–2.7 mm = 585 kg/m³ was the fine aggregate;
- Crushed Granite with fractions of 5–20 mm = 1005 kg/m³ was the coarse aggregate;
- Tap Water = 187.5 L/m³;
- Water cement ratio = 0.3

A locally manufactured Portland Cement M500 D0 (CEM I 42.5 N) Cement by South Ural mining and processing company in Russia. While The Microsilika MK-85 was produced by Novolipetsk Steel company (NLMK). Table 1 shows the chemical composition and physical properties of the cement while

Table 2 displays the physical and chemical properties of Microsilica MK-85.

Quartz powder was produced by SIBELCO Russia company. The chemical properties are shown in Table 3. Quartz Sand with a fineness modulus of 0.8–2.7 mm and Crushed Granite with fractions of 5–20 mm were used in this experiment. Figure 1 shows the particle size distribution. Quartz sand and crushed granite were gotten from the Ryazan region and supplied by SUKHOGRUZ Company.

Furthermore, BASF Stroitelnye Sistemy produces a Super Plasticizing admixture based on Polycarboxylic Ether (Glenium 115) that is used as a water-reducing additive. Table 4 displays the physical characteristics of Glenium 115. MiniBars BF was obtained from the Kamennye Vek company. Figure 2 and Table 5 show the physical characteristics and shape of the MiniBars BF used in the experiment. MiniBars BF with 18 mm length and 1.2 mm diameter is implemented because it can improve the anti-cracking performance of the concrete (D Wang et al., 2019).

### 3.2. Specimen and testing

To test the mechanical properties of the HPC, specimens were produced from each mixture. The concrete specimens required for each test were cast with a 0.32 water–binder ratio and proportions of 1:1.1:1.608 by mass of binding materials (Cement and Micro silica), fine aggregate, and coarse aggregate. Table 6 shows the details of the six combinations utilized in this study. In this experiment, the control group (Mix No. HPC0) did not contain MiniBars BF. The five HPC mixes with different proportions of MiniBars BF are the mixed group, which includes 0.60%, 0.90%, 1.2%, 1.5%, and 1.8%. These mixes are denoted as HPC0, HPC06, HPC09, HPC12, HPC15, and HPC18, respectively. The percentage of BF utilization in the mixture is reflected by the numbers after HPC. Therefore, to improve the fluidity and properties of the samples, Glenium 115 Superplasticizer (SP) was added to the admixture with a constant percentage of 2.0%.

A simple setup is employed to comprehend the effect of MiniBars BF on the behavior of HPC. As shown in Table 6, all the specimens used in the experiments had identical material fractions except MiniBars BF. The reference mix used the same materials and curing conditions as the other mixes. The laboratory pan mixer capacity was 130 liters. The mixer has a constant speed of 48 rpm. The ingredients were accurately weighed before being used. In the beginning, the aggregates blended for 60–120 seconds. Then, the first quarter of water was added for 60 seconds, and the binders were added and mixed for 120–180 seconds. The remaining liquid (water and superplasticizer) was added gradually to the mix to achieve a homogenous mix. Finally, the MiniBars BF was manually added at a rate of 10 grams per second to achieve uniform distribution. The cube specimens with dimensions 100 mm × 100 mm × 100 mm are used to perform the compressive test. While the rectangular prism specimen with dimensions 100 mm × 100 mm × 400 mm was used to test the flexural test. The room temperature of the laboratory was kept at 21 ± 3 for mold samples. The mold samples for the $f_{cm}$ and $f_r$ were kept for 48 hours and 72 hours, respectively. Later, moist cabinet machines were used to cure the samples at a temperature of 21°C and 95% humidity for 7, 14, and 28 days. The MATEST concrete compression machine (C025A) was used to perform the $f_{cm}$ test for the samples at ages 7, 14, and 28 days. While the MATEST
Table 1. Physical and chemical properties of Cement M500 D0

| Oxide (%) | Fineness (m²/kg) | Relative density |
|-----------|------------------|------------------|
| SiO₂      | 19.52            | 387              |
| Fe₂O₃     | 4.04             |                  |
| MgO       | 4.36             |                  |
| SO₃       | 2.89             |                  |
| Al₂O₃     | 4.81             |                  |
| CaO       | 62.18            |                  |
| K₂O       | 0.6              |                  |
| LOI       | 1.62             |                  |

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| Name of indicator | 50 microns |
|-------------------|-----------|
| **Chemical composition** | **50 microns** |
| Mass fraction of silicon dioxide (SiO$_2$), not less than % | 99.48 |
| Mass fraction of iron oxide (Fe$_2$O$_3$), not more than % | 0.128 |
| Mass fraction of alumina (Al$_2$O$_3$), not more than % | 0.254 |
| Mass fraction of calcium oxide (CaO), not more than % | 0.015 |
| pH | 7 |
| Loss on ignition, % | 0.12 |
| Mass fraction of sieve residue, % | |
| No. 0.16 | 2 |
| No. 0.1 | 19 |
| No. 0.063 | 39 |
| No. 0.040 | 43 |
| **Median particle diameter, microns** | **Medium D50** |
| | 43 |
| Maximum D90 | 123 |
| Minimum D10 | 2 |
| Oil consumption, g/100 g | 17.8 |
| Specific surface, m$^2$/g | 0.8 |
| Mass fraction of moisture, no more than% | 0.2 |
| Density | 2.65 |
| Bulk density | 1 |
Figure 1. Particle size distribution of the aggregates.

Table 4. The physical characteristics of the Glenium 115

| INDEX                                      | Values                                      |
|--------------------------------------------|---------------------------------------------|
| Appearance                                 | Homogeneous liquid of light-yellow color    |
| Density, kg/m$^3$                          | 1050–1090                                   |
| Hydrogen exponent, pH                      | 5–8                                         |
| Content of CI-ion, in mass. %, no more     | 0.1                                         |
concrete flexural machine (C091) used to perform the \( f_t \) at 14 and 28 days. Figure 3 shows the MATEST machine used in the experiments. All the tests were performed according to ASTM (American Society for Testing and Materials (ASTM), 2015, American Society for Testing and Materials (ASTM), 2002) and GOST standards (Betony, 2013).

| Table 5. Mechanical properties of MiniBars BF |
|---------------------------------------------|
| Length (mm)       | Diameter (mm) | Tensile Strength (MPa) | Young’s Modulus (GPa) | Aspect ratio (L/D) | Specific gravity |
|-------------------|---------------|------------------------|-----------------------|--------------------|------------------|
| 18                | 1.2           | 1080                   | 44                    | 15                 | 1.9–2.1          |

4. Results and discussion

4.1. Compressive strength results

The cube samples (100 mm × 100 mm × 100 mm) are used to test the \( f_{cm} \) of the HPC. Nine samples were tested for each configuration of HPC. Figure 4 shows the results of the \( f_{cm} \) test for the different mixes of MiniBars BF HPC. The figure shows the development of the \( f_{cm} \) during the curing. The average bulk weight density, \( f_{cm} \) (cube and cylinder samples), and the Coefficients of Variation (CoV) are shown in Table 7. For the 7-day test, the \( f_{cm} \) of plain HPC was higher than that of specimens with MiniBars BF. Moreover, the \( f_{cm} \) of plain HPC was slightly higher than the MiniBars BF HSC with 0.6% and 0.9% MiniBars BF fractions. The reduction in the \( f_{cm} \) in the HPC06 and HPC09 were 5.3% and 1.6%, respectively. However, the \( f_{cm} \) of the other mixes with MiniBars BF higher than 1.2% MiniBars BF dropped significantly. The reduction in the \( f_{cm} \) in the HPC12, HPC15, and HPC18 was between 12% and 21%. Therefore, MiniBars BF fraction percentage does not affect the \( f_{cm} \) of HPC if it is fraction is less than 0.9% but after that, it increases the MiniBars BF leading to a decrease of the \( f_{cm} \) of HPC in the early ages.

For the 14-day test, the \( f_{cm} \) of plain HPC was higher than that of specimens with MiniBars BF. Moreover, the \( f_{cm} \) of plain HPC was slightly higher than the MiniBars BF HSC with 0.6% and 0.9% MiniBars BF fractions. The decrease in the \( f_{cm} \) in the HPC06 and HPC09 were 2.6% and 4.7%, respectively. However, the \( f_{cm} \) of the other mixes with MiniBars BF higher than 1.2%, MiniBars BF dropped significantly. The reduction in the \( f_{cm} \) in the HPC12, HPC15, and HPC18 were between 10% and 19%.

For the 28-day test, the \( f_{cm} \) of MiniBars BF mortar with a 0.9% volume fraction was higher than the plain HPC slightly by 3.9%. Also, the \( f_{cm} \) of both plain HPC and MiniBars BF mortar with 0.6% were equivalent. Therefore, the \( f_{cm} \) of the rest of the mixes was slightly lower. The decrease in the \( f_{cm} \) in the HPC12, HPC15, and HPC18 were 10.7%, 11.8%, and 4.7%, respectively, as compared to the plain samples. From these results, there is an optimum fraction of MiniBars BF that can improve the \( f_{cm} \) of HPC. Similar research on micro-BF on plain concretes found that the \( f_{cm} \) is increased with BF until the MiniBars BF percentage reaches 2% (Ma & Zhu, 2017; Ronad et al., 2016). Hence, it reduced the HPCs \( f_{cm} \) (Khurun & Koroteev, 2018; D Wang et al., 2019). The curing period has a significant influence on HPC \( f_{cm} \). Therefore, the samples after 7 days reached 75–85% of its \( f_{cm} \) on day 28. Figure 5 shows a sample of the failure pattern at 28 days. These findings are in line with results reported by other research (Mohammadi Mohaghegh, Silfwerbrand, Arskog et al., 2018a). When compared to plain specimens, the addition of BF can improve the failure mode of cement mortar specimens under compressive loading. During testing, HPC specimens were revealed to have brittle failure modes. A significant number of mortar fragments were chipped off the matrix when the specimen cracked. The MiniBars BF reinforced HPC mixes, on the other hand, demonstrate a plastic deformation. The specimens’ crack dimensions were finer, the number of cracks increased, and the specimens’ structure was maintained. The difference in failure mode...
| Specimen Code | Cement (kg/m³) | Micro Silica (kg/m³) | Granite (kg/m³) | Quartz Sand (kg/m³) | Quartz Powder (kg/m³) | Plasticizing (L/m³) | Water (L/m³) | MiniBars BF (kg/m³) |
|---------------|----------------|----------------------|----------------|---------------------|----------------------|---------------------|--------------|---------------------|
| HPC0          | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 0                   |
| HPC06         | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 12.6 (0.6%)         |
| HPC09         | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 18.9 (0.9%)         |
| HPC12         | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 25.2 (1.2%)         |
| HPC15         | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 31.5 (1.5%)         |
| HPC18         | 500            | 125                  | 1005           | 585                 | 100                  | 12.5               | 187.5        | 37.8 (1.8%)         |
became more ductile as the fiber concentration increased. It was because the addition of fibers effectively limits fracture propagation and reduces crack convergence, absorbing more destructive energy in the process (Khan & Cao, 2021).

Analysis of Variance (ANOVA) test was applied to evaluate the significance of the difference in some factors which include the weight of the sample, curing age, and the MiniBars BF percentage. All statistical analyses were performed using Minitab 19 software. These tests are also used to determine if there is any relationship between these variables and the $f_{cm}$ of HPC and MiniBars BF HPC. P values of 0.05 or less are considered statistically significant in the analysis. The analysis shows that the weight of the sample does not affect the $f_{cm}$ of the concrete therefore it was removed from further investigation. Since the concrete density was approximately equal for all mixtures, the sample weight did not affect the compressive strength. The curing age of the samples was statistically significant with a very small P-value. According to the experimental
Table 7. Physical properties and \( f_{cm} \) for cube and cylinder samples

| Mixture Code | Bulk Wet Density (kg/m\(^3\)) | MiniBars BF% | 7 day | 14 day | 28 day |
|--------------|-------------------------------|--------------|-------|--------|--------|
|              |                               |              | \( f_{cm} \) Cube (MPa) | CoV%  | \( f_{cm} \) Cube (MPa) | CoV%  | \( f_{cm} \) Cylinder (MPa) | CoV% |
| HPC0         | 2455.2                        | 0            | 86.38 | 5.4    | 93.31  | 0.5    | 101.43                        | 0.5  |
| HPC06        | 2460.8                        | 0.6          | 81.75 | 2.4    | 90.85  | 2.0    | 101.43                        | 3.8  |
| HPC09        | 2428.7                        | 0.9          | 85.01 | 2.6    | 88.92  | 3.0    | 105.39                        | 0.8  |
| HPC12        | 2433.4                        | 1.2          | 70.57 | 5.7    | 75.12  | 3.5    | 90.50                         | 1.3  |
| HPC15        | 2410.1                        | 1.5          | 67.55 | 3.1    | 80.13  | 2.7    | 89.51                         | 1.7  |
| HPC18        | 2421.2                        | 1.8          | 75.80 | 3.8    | 83.90  | 0.7    | 92.30                         | 0.6  |

*CoV = Coefficient of Variation.
data, Equation 1 was developed to calculate the $f_{cm}$ of MiniBars BF HPC depending on the age and MiniBars BF fraction. The coefficient of determination ($R^2$) was 79.23% for the equation.

$$f_{cm-MBF} = 79.8 - 8.213\rho + 0.9124\omega$$

where:

$f_{cm-MBF}$: the compressive strength of the MiniBars BF HPC in MPa.

$\rho$: the MiniBars BF volume fraction percentage and.

$\omega$: the age of the sample in days (7, 14, and 28 days).

Figure 5 shows the cubes $f_{cm}$ failure at 28-day test for MiniBars BF HPC. When the load was increased, the MiniBars BF HPC was crushed with a loud noise. The surrounding concrete was crushed and spalled after the maximum load due to the cyclo-hoop effect, and the concrete block was pyramidal, as illustrated in Figure 5.

### 4.2. Theoretical Modulus of Elasticity ($E_c$)

Young’s modulus or the modulus of elasticity ($E_c$) of concrete is defined as the ratio of the stress to strain. The bulk wet density of each sample was measured before the test with high accuracy scale. The results of the general linear model (ANOVA) test show that the MiniBars BF has only a negligible effect on the density of HPC. ACI-318 recommended calculating the modulus of elasticity ($E_c$) by using Equation 2 (318-19A. 318-19 Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, 2019):

$$E_c = 0.043\omega^{1.5} \sqrt{f_c}$$
where:

\( f_c \): 28-Day compressive strength of Concrete in MPa.

\( w_c \): Weight of Concrete (kg/m³).

Table 7 shows the bulk wet density and the cylinder \( f'_{cm} \) used to estimate the \( E_c \). The \( E_c \) values of HPC at different fiber volume fractions are shown in Figure 6. Compared to the PC, the \( E_c \) of fiber-reinforced concretes is insignificantly affected by increasing the dosage of fiber. MiniBars BF HPC has an \( E_c \) of 48,930–43,916 MPa according to ACI-318 (Zheng et al., 2022). While the \( E_c \) for the HPC was 48,633 MPa. Also, there is no effect in the \( E_c \) for the mixes with MiniBars BF fraction less or equal to 0.9%. The increase of the MiniBars BF fraction after 0.9% decreased in the \( E_c \) of HPC. \( E_c \) depends on stress–strain relation up to 0.4 \( f'_{cm} \) before occurring the cracks, while fibers action starts after that. These results are consistent with the results obtained from the use of chopped BF in previous studies (Kizilkanat et al., 2015).

4.3. Flexural Strength Result

The 100 mm × 100 mm × 400 mm specimen samples used to test the \( f_f \) of the HPC. The flexural test results were calculated automatically by the computer connected to the device test MATEST concrete flexural machine (C091). Figure 7 shows the \( f_f \) results obtained from the experiment. The effect of the MiniBars BF deviation of the samples tested in this experiment. The increase in the percentage of MiniBars BF will increase the \( f_f \) of the HPC mix until it reaches the maximum value then it decreases. For the 14-day test, the \( f_f \) for the HPC without MiniBars BF (control mix) was 12.54 MPa. All the mixes with MiniBars BF showed a significant improvement in the \( f_f \) test. The initial increments in flexural tests were 20.8%, 43.2%, 13.5%, 26.5%, and 33.9% with the inclusion of 0.6%, 0.9%, 1.2%, 1.5%, and 1.8%, respectively, compared with that of regular HPC. The ultimate value of the \( f_f \) recorded at the HPC09 mix is 18.0 MPa.

For the 28-day test, the \( f_f \) of the HPC mix was 14.09 MPa. All the mixes showed improvement in the \( f_f \) the test compared to plain HPC. The final increment of the \( f_f \) was 18.6%, 40.4%, 21.8%, 16.4%, and 21.3% respectively for the 0.6%, 0.9%, 1.2%, 1.5% and 1.8%, respectively. The maximum value of the \( f_f \) recorded at 0.9% MiniBars BF was 19.77 MPa. The results (see Table 8) showed
that the MiniBars BF started affecting the HPC from an early age and keeps improving to the late age of HPC. For all samples, \( f_f \) increased at first with MiniBars BF content and then peaks at 0.9% (18.9 kg/m\(^3\)) MiniBars BF. A further increase in MiniBars BF resulted in additional reductions in the \( f_f \) of the HPC. This suggests that there is an optimum BF dosage beyond which increasing the BF dosage reduces \( f_f \). The tangling of fibers and the cementitious matrix is the primary cause of increasing \( f_f \) in BF HPC.

The main effect of the MiniBars BF was the bridging effect inside the concrete mix which leads to providing extra strength and improving the \( f_f \) (Ganesh & Muthukannan, 2021). On one hand, even a small percentage of MiniBars BF such as 0.6% showed a significant impact on the \( f_f \) of HPC as it enhances it by 18.6%. On the other hand, a high percentage of MiniBars BF (more than 1.2% MiniBars BF) did not enhance the \( f_f \) much but it also decreases the \( f_{cm} \). The increase of the MiniBars BF by more than 0.9% might prevent the complete interlock of aggregates together in the mix which leads to a decrease in the compressive strength of the mix. In general, the experiment result showed that the \( f_f \) of samples tested at 14 days of age represents 91–95% of the 28-day test. The enhancement of the \( f_f \) started from 18.6% with 0.6% MiniBars BF until it reached 40.434% at 0.9% MiniBars BF.

The failure of plain HPC during the flexure test was very immediate and quick. After cracks appeared as the load increased, the specimen was broken into two sections as shown in Figure 8. However, there was a delay between the emergence of cracks and the withdrawal of MiniBars BF from the HPC matrix. Despite the short time frame, it was demonstrated that concrete toughness improved. The crack length and width of MiniBars BF HPC were bigger than that of PC in terms of crack width as shown in Figure 9. Zhou et al. noticed a similar effect for the chopped BF on the tensile failure but it is more noticeable with MiniBars BF (Zhou et al., 2020). In addition, MiniBars BF HPC showed failure without collapse of the sample, and it was hard to separate the two sections from each other.
Statistical analyses were performed by applying a significance level of 0.05. Additionally, relatively large statistical differences were identified in the cases of MiniBars BF fractions and the curing period. The P-value of both cases was statistically significant (less than 0.01). Equation 3 shows the relationship between the $f_f$ and the cube $f_{cm}$ and MiniBars BF fractions at the 28-day test. The $R^2$ of equation 3 is equal to 96.42%.

$$f_{f',MBF} = 194.7 - 3.316f_{cm} - 51.15\rho + 0.01513f_{cm}^2 + 0.5516f_{cm} \times \rho$$  \hspace{1cm} (3)

where $f_{f',MBF}$ is the $f_f$ of the MiniBars BF HPC (MPa), $f_{cm}$ is the $f_{cm}$ of the MiniBars BF HPC; and $\rho$ is the MiniBars BF volume fraction.

5. Summary and conclusion

The main mechanical properties of the MiniBars BF HPC and HPC include $f_{cm}$, $f_f$, crack extension, and failure modes are all discussed in this paper. The cementitious matrix of concrete developed against flexural stress when MiniBars BF was used in HPC, and this component of concrete also made basalt-reinforced HPC more durable than standard HPC. BF had
a favorable effect on enhancing $f_t$ but had a negative influence on $f_{cm}$, according to the results of the experiments.

- The $f_{cm}$ of BF HPC at the 7-day test represents 75–85% of the $f_{cm}$ of the 28-day test. Fiber addition had no significant effect on the $f_{cm}$ of HPC. However, the $f_{cm}$ of concrete slightly reduced when the dosage of MiniBars BF increased.
- MiniBars BF fraction improves the $f_t$ by 21.8%, 16.4%, and 21.3% but it decreases the $f_{cm}$ by 10.8%, 11.8%, and 9% for HPC12, HPC15, and HPC18, respectively, compared with regular HPC.
- The MiniBars BF can provide extra safety measures to the concrete as it delays and prevents sudden failure.
- The $f_t$ reached 91–95% of the concrete strength after the 14-day test in comparison to the 28-day test.
- The MiniBars BF has an insignificant effect on the workability of the concrete.
- Statistical analysis test shows that the MiniBars BF fraction had a significant effect on the mechanical properties of HPC.
- A small amount of MiniBars BF did not affect the HPC’s $E_c$. When the dosage of MiniBars BF increased by more than 1.2%, the $E_c$ of HPC was slightly reduced. Therefore, even a small amount of MiniBars BF could lead to a significant improvement to the $f_t$ of the HPC without a side effect on the $f_{cm}$ and $E_c$.
- HPC with 0.9% MiniBars BF represented the optimum MiniBars BF percentage to improve the mechanical properties of HPC.
- Two equations were developed in this research to estimate the $f_{cm}$ and $f_t$ of MiniBars BF HPC at 28-day age depending on the $f_{cm}$ of HPC, MiniBars BF fraction percentage, and other factors.

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