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Research Article

Influence of hybrid basalt fibre with varied length on the mechanical properties of normal and high strength concrete

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Abstract

Hybrid fibre-reinforced concrete combines different types of fibres or fibres of varying lengths to maximize their individual advantages, which can potentially lead to a synergistic enhancement in overall performance. The main aim of this study is to explore the feasibility of integrating a hybrid fibre system to enhance the efficiency and properties of basalt fibre-reinforced concrete. Specifically, the research focuses on evaluating the mechanical characteristics of basalt hybrid fibre-reinforced concrete across two concrete grades: normal strength M30 and high strength M60. Basalt fibres of 12 mm and 30 mm lengths are used to hybridize the concrete, with a total fibre volume fraction of 1.5%. By incorporating both short and long basalt fibres into the concrete matrix, this study aims to assess how these variations impact essential properties such as workability, compressive strength, flexural strength, and Modulus of Elasticity (MOE). The hybrid mix, comprising 25% of 12 mm fibres and 75% of 30 mm fibres at a volume content of 1.5%, demonstrates enhanced mechanical properties across all concrete grades. The addition of basalt fibres, particularly those with higher proportions of longer fibres, results in a decrease in workability. Notably, hybridizing fibres have no discernible effect on compressive strength or MOE in both concrete grades. From the results it was observed that the flexural strength of the optimal hybrid mixes is significantly higher, surpassing conventional concrete by 39% and 54.35% for M30 and M60 grades of concrete, respectively.

1. Introduction

Civil engineering encompasses construction, maintenance, planning, and rehabilitation activities aimed at improving the built environment for humanity. It entails redesigning and reshaping daily life via innovative infrastructure projects. Concrete, a versatile material, is widely used in the construction industry due to its ability to be cast into various shapes and its good workability. It plays a crucial role in numerous infrastructure projects, providing durability, strength, and longevity to structures ranging from foundations to skyscrapers and highways to airports.

On the other side, concrete possesses several undesirable traits such as brittleness, limited impact resistance, and high weight. While traditional concrete exhibits strength primarily in compression, it lacks resilience in tension; as a result, there is a necessity to enhance the tensile capacity of concrete [1-3]. New types of concrete, including High Performance Concrete (HPC), High Strength Concrete (HSC), Ultra High-Performance Concrete (UHPC), Fibre Reinforced Concrete (FRC), and Fibre Reinforced High Strength Concrete (FRHSC), offer enhanced characteristics such as increased strength, long-term mechanical properties, toughness, durability, low permeability, high modulus of elasticity and

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resilience. HSC integrates mineral admixtures like blast furnace slag, metakaolin, silica fume, fly ash and chemical admixtures such as superplasticizers. Integrating metakaolin as an additional cementitious material enhances both the mechanical properties and durability of concrete. Concrete mixtures incorporating metakaolin exhibit superior flexural and compressive strengths, along with increased resilience against adverse environmental factors such as sulphate and acid attacks. This substitution of some cement with metakaolin not only promotes sustainability but also reduces environmental impact. In applications demanding high-performance and high-strength concrete, the inclusion of metakaolin alters pore structure, chloride diffusivity, and other microstructural properties, thereby enhancing overall performance and longevity [4-8].

However, HSC suffers from brittleness and crack development. To address these shortcomings, fibres can be incorporated into concrete, resulting in FRC with improved tensile strength, ductility, toughness, and durability properties [9]. FRC can be produced by integrating various types of fibres, including steel, cellulose, asbestos, polypropylene, glass, polyvinyl alcohol, basalt, carbon, and aramid fibres [10]. Basalt fibre is increasingly favored in construction for its exceptional qualities. Its high tensile strength makes it perfect for reinforcing concrete, while its resistance to corrosion, chemical and biological damage ensures durability in harsh conditions. With low thermal conductivity and excellent fire resistance, it minimizes heat loss and is suitable for fire-resistant structures. Its low water absorption prevents damage from freeze-thaw cycles, and its resilience to weathering and UV radiation suits outdoor use. Additionally, its high modulus of elasticity enhances concrete stiffness and reduces cracking [11]. As a sustainable material derived from volcanic rock, basalt fibre production demands minimal energy [12,13].

In concrete applications, the percentage of basalt fibres typically ranges from around 0.1% to 3% by volume of concrete. However, the exact percentage deemed "optimum" can vary based on factors such as the desired increase in flexural strength, compressive strength, durability, and tensile strength. Similarly, the length of basalt fibres can vary depending on the composite materials' intended properties. According to research, the utilization of basalt fibres as reinforcement in composite materials, particularly in concrete and polymer mortars, offers significant potential for enhancing mechanical properties such as tensile strength, flexural strength, durability and the long-term performance of concrete, leading to increased resistance to cracking [3,14], abrasion, and environmental degradation. However, the workability of the concrete is reduced when basalt fibre is added to the plain concrete, especially long length fibres [15-17]. Certain studies have noticed that the compressive strength of basalt fibre reinforced concrete shows enhancement with lower amounts of basalt fibres, whereas higher dosages do not lead to further improvement in compressive strength [18-21].

In Hybrid Fibre-Reinforced Concrete (HFRC), the combination of two or more distinct fibre kinds allows for the creation of a composite material. This composite leverages the unique mechanical and physical properties of each type of fibre, resulting in improved overall performance. Additionally, the interaction between these different fibres can lead to a synergistic response, further enhancing the mechanical and physical characteristics of the concrete. By carefully selecting and combining various fibre types, HFRC offers the opportunity to optimize performance and achieve superior results compared to single-fibre reinforcement [22].

The hybridization of concrete can be achieved by using fibres of different moduli or combining the same fibres of different lengths (short and long fibres). Short fibres are typically utilized to improve attributes such as impact resistance and crack control. Their shorter length allows for more uniform dispersion within the concrete matrix, effectively bridging microcracks and mitigating crack propagation. On the other hand, longer fibres, primarily contribute to enhancing tensile and flexural strength. Their greater length enables them to span larger distances within the concrete, providing reinforcement against applied forces and improving the overall structural integrity. Recent studies have demonstrated the superiority of hybrid basalt fibre-reinforced concrete over formulations using single basalt fibres alone. This hybrid approach has shown remarkable performance improvements in various aspects, including compressive strength, flexural strength, tensile strength, and fracture resistance. The integration of a hybrid fibre system allows for a more comprehensive reinforcement strategy, addressing multiple structural requirements simultaneously [23-25]. Overall, the adoption of hybrid basalt fibre-reinforced concrete represents a promising advancement in construction materials, offering enhanced durability, resilience, and sustainability for a wide range of infrastructure projects.

The present research work is significant as it tackles two major concerns in the field of construction materials. The first concern is to explore the potential of using a hybrid fibre system to enhance the performance of basalt FRC. Traditional concrete, although strong in compression, lacks tensile strength and is susceptible to cracking. The goal of this study is to use the synergistic benefits of different types of fibres to improve the overall mechanical properties by combining a hybrid system of basalt fibres of different lengths. This approach could result in the creation of more resilient concrete structures.

The second concern is to examine the specific enhancements brought about by hybrid fibre reinforcement in concrete. Studies have demonstrated that incorporating basalt fibres leads to better performance compared to plain concrete. However, there is a need for further research to evaluate the specific impact of hybridizing short and long basalt fibres on the mechanical properties of both normal and high-strength concrete. This involves a detailed analysis of how the combination of fibres affects key performance metrics such as workability, compressive strength, flexural strength, and MOE. By investigating these parameters, the research seeks to identify the optimal fibre proportions and configurations that offer the best balance between improved mechanical properties and practical considerations like ease of mixing and application. Understanding these mechanical behaviors is crucial for determining whether hybrid fibre-reinforced concrete can offer superior performance over conventional concrete in structural applications. The findings from this study could provide valuable insights for the construction industry, paving the way for the adoption of hybrid fibre-reinforced concrete in a variety of applications and ultimately leading to stronger, more durable, and more cost-effective infrastructure.

1.1 Research Significance

In recent years, basalt fibres have gained increasing attention and application in the construction industry, leading to several advancements. Currently, two primary methods are employed for fibre mixing: (a) using fibres with different properties and (b) using fibres of the same type but in varying lengths. Numerous studies have investigated the effects of discrete basalt fibres on the fresh and mechanical properties of concrete. While researchers have explored the combination of basalt fibre with various types of cement, cementitious materials, and hybrid fibres, the hybridization of the basalt fibre with different lengths and contents remains largely unexamined. Therefore, the primary goal of the current study is to assess the impact of single and hybrid basalt fibre lengths on the workability and mechanical properties of normal and high strength concrete. Short fibres are more efficient in controlling micro-cracks propagation, while long fibres bridge macro-cracks [25]. The current study also attempted to develop meaningful and reliable models to predict the compressive strength and the flexural strength of concrete using Response Surface Methodology. The experimental investigation was carried out on M30 and M60 grade concrete utilising 12mm and 30 mm basalt fibres and a hybrid mix of the two lengths at 1.5% fibre content.

2. Experimental Work and Procedure

2.1 Materials

Ordinary Portland Cement (OPC) 53 grade conforming to IS: 12269-2013, was utilized for both normal and high-strength concrete. Metakaolin was incorporated as the binder material along with cement for high-strength concrete. The chemical constitution of cement and metakaolin provided by the manufacturers is given in Table 1.

Table 1. Chemical composition of cement and metakaolin

Chemical components	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	Loss on ignition	Insoluble Residue
OPC 53 grade cement (%)	19.56	4.10	6.08	-	60.75	1.50	0.35		1.65	6.55
Metakaolin (%)	52	46	0.6	0.65	0.09	0.03	0.10	0.03	0.50	-

High-quality locally available manufactured sand (M sand) conforming to Zone II standards is used as fine aggregate in both normal and high-strength concrete. For coarse aggregates, a maximum size of 20 mm is used in normal concrete, while a maximum size of 10 mm is utilized in high-strength concrete. Various laboratory tests were conducted on the fine and coarse aggregates to assess their different physical properties, all of which adhered to the specifications outlined in IS: 383 – 2016.

This research aims to enhance the flexural performance of basalt fibre reinforced concrete by combining fibres with varying lengths i.e., hybridization obtained using short and long length fibres. For this hybridization, basalt fibres measuring 12 mm and 30 mm in length were employed. The properties of basalt fibre given by the manufacturer are presented in Table 2.

Table 2. Properties of basalt fibres

Fibre	Length (mm)	Density (kg/m^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%)
Basalt	12	2750	3500-4500	95-115	2.4-3.0
Basalt	30	2750	3500-4500	95-115	2.4-3.0

2.2 Mix Proportions

In this study, concrete grades M30 and M60, representing normal strength and high strength concrete, respectively, were formulated in accordance with the guidelines outlined in IS 10262:2019, and details are given in Table 3.

The total fibre volume fraction was 1.5%, and proportions of basalt fibres were determined based on the pilot study and literature review [26, 27]. The proportions of basalt fibre are given in Table 4.

Superplasticizers utilized in M30 and M60 concrete mixes were "Classic Superflow – SP" and "Classic Superflow-PC," respectively. The former is a brown liquid based on Naphthalene formaldehyde condensates, while the latter is a yellowish-brown liquid based on Polycarboxylate condensates.

Table 3. Design mix details

Grade of concrete	Cement (kg/m^3)	Metakaolin (kg/m^3)	Water (lit/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)
M30	420	-	168	1210	665
M60	444	49.3	138	1100	777

Table 4. Proportion of basalt fibres

Mix Designation	Fibre volume fraction (%)	Basalt fibre content (%)	
		12mm	30mm
HBFO	0	0	0
HBF1	1.5	100	0
HBF2	1.5	75	25
HBF3	1.5	50	50
HBF4	1.5	25	75
HBF5	1.5	0	100

2.3 Casting and Testing Of Specimens

The concrete mixes were prepared using a tilting drum mixer equipped with revolving star blades. To prevent absorption, the interior of the drum was initially rinsed with water. The preparation process involved mixing fine and coarse aggregates, cement, mineral admixtures, and basalt fibres in the tilting drum mixer. Dry mixing was carried out for one minute, followed by the addition of water mixed with superplasticizers. Subsequently, mixing was continued for four minutes to achieve a homogeneous mixture. Standard moulds were prepared, oiled, and positioned on a vibration table set at a low speed while the concrete was poured. Firm steel moulds were utilized for retaining the freshly mixed concrete, and a table vibrator was used to compact it. After a 24-hour curing period, the specimens were demolded, and each one was labelled with the date of casting and the mix used. The specimens were put in the curing tank, and all the tests were done after 28 days of curing. The tests conducted are explained in the following sections.

2.3.1 Slump Cone Test

In the slump test, the freshly mixed concrete was placed in four layers, with each layer being tamped 25 times using a standard rod. Subsequently, the surface of the concrete was levelled. After raising the cone vertically, the difference in height between the concrete sample and the mould was measured. This test assesses the consistency and flowability of the concrete, which are crucial properties for ensuring proper placement and consolidation of the concrete within the formwork. The test was conducted in accordance with IS 1199:1959 specifications, and the test set up is shown in Fig.1(a).

2.3.2 Compressive Strength Test

The primary test frequently carried out on hardened concrete entails testing cubical specimens with dimensions of 150 mm × 150 mm × 150 mm in a Compression Testing Machine (CTM) with a capacity of 3000 kN. The test was conducted at a loading rate of 14 N/mm^2 per minute in accordance with IS: 516-1959 specifications. Compressive strength is found by dividing the ultimate load by the area of loading zone, typically after 28 days of curing. The strength of concrete is influenced by the proportions of its constituent materials. The water-cement ratio plays a crucial role in determining concrete strength, with lower ratios typically resulting in higher compressive strength. Fig. 1b illustrates a compression test being performed on a cube specimen.

2.3.3 Flexural Strength Test

The bending strength of concrete is estimated through a flexural test, which assesses the load at which cracking occurs. This test measures its ability to endure bending failure. The flexural strength of conventional concrete was determined using a two-point loading method. A plain concrete beam specimen measuring 100 mm × 100 mm × 500 mm was utilized for the test in accordance with IS: 516-1959. The specimen was positioned on steel rollers resting on the bed of the testing machine, spaced at a distance of 400 mm center to center. Two 38 mm diameter rollers were positioned at one-third points of the supporting span, spaced at 133 mm intervals. The load was applied at a rate of 1.8 kN per minute, and the maximum load at which the specimen failed under flexure was recorded. The average flexural strength of three samples of each mix was mentioned as the Modulus of Rupture (MOR). The flexural strength test was conducted after 28 days of curing. Fig.1c depicts the arrangement for the flexural strength test.

2.3.4 Modulus of Elasticity Test

The MOE was determined by subjecting cylindrical specimens to uniaxial compression, as outlined in IS 516-1959. The test involved measuring deformations using a dial gauge fixed between gauge lengths of 200 mm, as depicted in Fig. 1d. Cylindrical specimens with a standard size of 300 mm in height and 150 mm in diameter were placed on a CTM of 3000 kN capacity, ensuring uniform loading without eccentricity.

(a) (b) (c) (d)

Fig. 1. Test set-up a) slump cone test b) compressive strength test c) flexural strength test d) MOE test apparatus

The load was applied until the cylinder failed, and the target load and deflection were recorded. Deflection readings were converted to strain by calculating the change in length. Stress was calculated by dividing the applied load by the cylinder's cross-sectional area. A series of readings were taken, and stress-strain graphs were plotted. The MOE was obtained from the slope of the stress-strain graph, providing a measure of the material's stiffness.

3. Results and Discussion

3.1 Workability

The slump cone test with respect to IS 1199-1959 standards was conducted for all the basalt hybrid mixes and the values for M30 and M60 grades are reported in Table 5. The test was done for investigating the impact of basalt fibres on workability of the concrete.

The observed slump values are lower than those of conventional concrete. It's widely acknowledged that the addition of any fiber type typically decreases slump values, a trend consistently documented across various studies. A portion of the cement paste was employed to cover the basalt fibres as they were included in the mixture, leaving less paste for workability [28, 29].

It is easy to note that the inclusion of 30 mm length basalt fibre in cement concrete compromised the workability of the concrete compared to the 12 mm length basalt fibre. The concrete mix containing only 30 mm fibres exhibited the lowest slump values, measuring 40 mm for the M30 grade and 30 mm for the M60 grade. During the concrete mixing process, the higher volume fraction of fibres led to noticeable clustering of fibres, significantly reducing workability. This issue was particularly pronounced in mixes containing 30 mm fibres compared to those with 12 mm fibres due to their greater length. Incorporating 30 mm basalt fibres made it exceedingly difficult to achieve a uniform concrete mixture during mixing. The 30 mm basalt fibres have a greater surface area than 12 mm basalt fibres, which results in the high water absorption of 30 mm basalt fibres and hence low workability. The slump decreased with increasing fibre length due to the greater specific surface area, rough surface, and high coefficient of friction [18, 30]. The workability can be increased by the use of appropriate dosage of super plasticizers. In this study, the dosage of super plasticizers has been found out from trial and errors.

3.2 Compressive Strength (f_c)

The compressive strength values of different concrete mixes after 28 days of water curing were obtained by testing cubes of side 15 cm in the CTM and results were presented in Table 5. The results are presented in graphical form in Fig. 3. The accompanying graph depicts the f_c values of concrete cubes with varying proportions of basalt fibres (12 mm and 30 mm). Introducing basalt fibres into the concrete mix had a negligible impact on its compressive strength. The most significant enhancement in compressive strength, amounting to 1.29% and 4.48% for M30 and M60, respectively was observed when the concrete mix comprised 75% basalt fibres 30 mm and 25% basalt fibres 12 mm. An insignificant decrease of 3.63% in compressive strength was observed for normal grade concrete with only 12 mm basalt fibres, and a 6.22% decrease was noted for normal grade concrete with only 30 mm fibres, compared to conventional concrete specimens. Similarly, for high-strength grade concrete, a 2.81% decrease in compressive strength was observed with only 12 mm basalt fibres and a 5.231% decrease with only 30 mm fibres, when compared to conventional concrete specimens. This trend aligns with previous studies [21, 31], potentially due to the bunching effect of the fibres, compaction issues, and an increase in poor interface regions within the matrix [28, 32, 33]. Conversely, the compressive strength of M30 and M60 concrete reinforced with a hybrid of 12 mm and 30 mm basalt fibres at a volume content of 1.5% was higher than that of conventional concrete specimens. The compressive strength of the hybrid fibre concrete HBF4 mix showed an insignificant increase of 1.29% for M30 and 4.48% for M60, compared to conventional concrete. Hybrid fibre concrete mixes HBF2, HBF3, and HBF4 demonstrated better compressive strength than single-length fibre-reinforced specimens for both M30 and M60 grades. The variation in the average cube compressive strengths of normal and high-strength hybrid basalt fibre-reinforced concrete was within ±5% when compared to conventional concrete. These results align with the findings from previous literature [28, 33, 34].

The compressive strength of mixes containing 30 mm fibres is lower than that of mixes incorporating 12 mm basalt fibres for the same fibre volume. This discrepancy in strength can be ascribed to the greater length and higher volume content of long fibres in the concrete mixture, which may result in inadequate dispersion of fibres throughout the concrete matrix, which elevates the likelihood of pore concentration within the matrix and fosters the creation of a feeble interface between the fibres and the matrix, consequently leading to diminished compressive strengths when subjected to compressive forces [18]. The conventional concrete specimens experienced failure primarily through the crushing of the concrete under the applied load. In contrast, the cubes containing hybrid basalt fibre concrete failed differently, as fissures formed on their surfaces. This indicates the effectiveness of the adhesion between the basalt fibre and concrete. Fig. 2a illustrates the failure mode observed in hybrid basalt fibre concrete. Additionally, some of the M60 cube samples failed by splitting along one or more planes, which occurs when the tensile strength of the concrete is surpassed, resulting in cracks propagating perpendicular to the direction of loading.

3.3 Flexural Strength

The flexural strength of concrete refers to its ability to resist failure under bending forces. Four point bending tests were conducted on a beam specimen of 10cm x 10cm cross section and 50cm length. The failed specimens are shown in Fig. 2b. The results for the test are given in Table 5. The results are presented in graphical form in Fig. 4.

The flexural strength or MOR values showed an increase in the range of 24.2% to 39.6% for M30 and 14.35% to 54.35% for M60 grade concrete mixes when compared to conventional concrete mixes. Addition of basalt fibres particularly boosted the flexural strength, unlike the compressive strength.

According to Loh et al., [32] the flexural strength of normal strength concrete mixes with 12 mm basalt fibres increased by approximately 39.6% at a fibre volume content of 1.5% compared to conventional concrete. Similarly, Shoaib et al., [15] reported a 56% increase in flexural strength for normal strength concrete using 43 mm long basalt fibres at the same volume content. For high-strength concrete, Ayub et al., [31] observed a 43.5% increase in flexural strength with 25 mm basalt fibres at a volume content of 2%. In the current study, the M30 concrete mix containing only 12 mm basalt fibres exhibited 24.2% higher MOR values than conventional concrete, while the M60 mix showed a 14.35% increase. Additionally, the M30 mix with only 30 mm basalt fibres demonstrated a 27% higher MOR, and the M60 mix showed a 38.55% increase compared to conventional concrete. The present study's findings align well with previous research, confirming that basalt fibres, especially when used in optimal lengths and volumes, can markedly improve the mechanical properties of concrete. Concrete mixes with longer fibres demonstrated better MOR values than those with shorter fibres, regardless of the concrete grade. These findings are consistent with the previous studies [31, 35].

The MOR values for M30 concrete HBF2, HBF3, and HBF4 mixes were 34.6%, 35.2%, and 39.6% higher than conventional concrete, respectively. For the M60 mixes, the values were 20.8%, 41.45%, and 54.35% higher. The results from the flexural strength tests indicate that the hybridization of different basalt fibre length specimens demonstrates superior performance compared to conventional and single basalt fibre reinforced concrete mixes [34]. This enhancement may be attributed to the crack bridging properties inherent in the incorporated fibres. Short fibres are more effective in regulating micro-cracks proliferation, while long fibres bridge macro cracks. During the test, the conventional concrete mix experienced an abrupt brittle failure when a fracture formed, causing the beam to split into two separate pieces. In contrast, the fibre-reinforced specimen with single length and hybrid length basalt fibres exhibited ductile failure mechanisms. The crack was formed at the bottom, which then propagated towards the top of the specimen. Additionally, there was a delay observed in the propagation of cracks. The bridging function of the fibres successfully impeded the rapid propagation of fractures and longer fibres show a stronger anchorage and bridging effect [35].

The hybrid fibre concrete mixes, with 25% and 75% basalt 12 mm and 30 mm fibres respectively exhibited superior values for modulus of rupture compared to conventional concrete mixes for both M30 and M60 grades. Despite the lower flexural strength values observed for the concrete mix containing only 30 mm fibres when compared to optimum hybrid mix, it was surprising that the beam specimen did not split into two separate parts. The data suggests that as the proportion of 30 mm fibres increases, there is a significant rise in flexural strength values, indicating that longer fibres are more effective in bridging macro cracks. However, the lower flexural strength of concrete mix with 30 mm fibres only may be due to the poor fibre dispersion in the mix. The same trend was noted for both normal and high strength concrete.

3.4 Modulus of Elasticity

There wasn't a considerable increase in the MOE values with the addition of basalt fibres. Studies indicate that even with higher fibre volumes, the enhancement of MOE for both normal and high-strength concrete grades remains minimal. This is in line with the observation/s of a few investigators [36, 37].

(a) (b) (c)

Fig. 2. Failed specimens after testing a) prisms b) cube c) cylinder

The results are shown in graphical form in Fig. 5. The correlation between the MOE and compressive strength of concrete has been reported by many researchers. Given the absence of improvement in compressive strength values, it's reasonable to conclude that the change in MOE values is very minimal. The failed cylindrical specimen is shown in Fig. 2c.

Table 5. Mechanical properties for M30 and M60 grade of concrete

Specimen ID	M30				M60			
	Slump (mm)	f_c (MPa)	MOR (MPa)	MOE (GPa)	Slump (mm)	f_c (MPa)	MOR (MPa)	MOE (GPa)
HBFO	70	38.60	5.00	26.60	97	69.20	6.20	33.40
HBF1	64	37.26	6.21	27.53	75	67.25	7.09	36.05
HBF2	60	37.80	6.73	27.64	68	70.08	7.49	36.42
HBF3	56	38.21	6.76	27.90	62	71.26	8.77	36.81
HBF4	50	39.10	6.98	28.31	55	72.31	9.57	37.15
HBF5	40	36.20	6.35	28.12	30	65.58	8.59	36.86

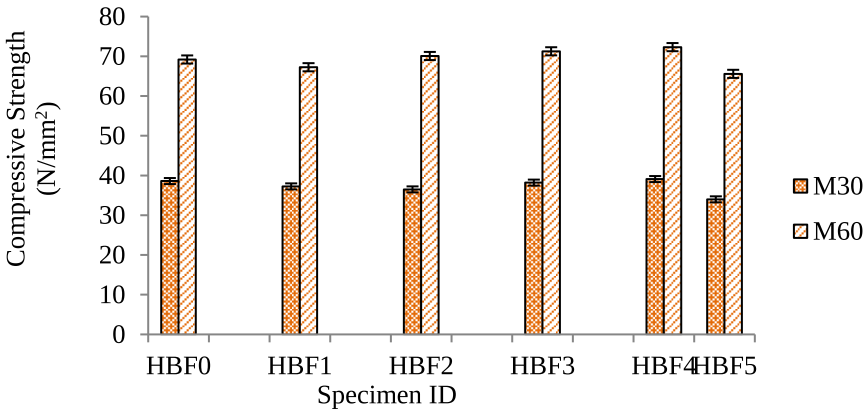


Fig. 3. Compressive strength of hybrid mixes

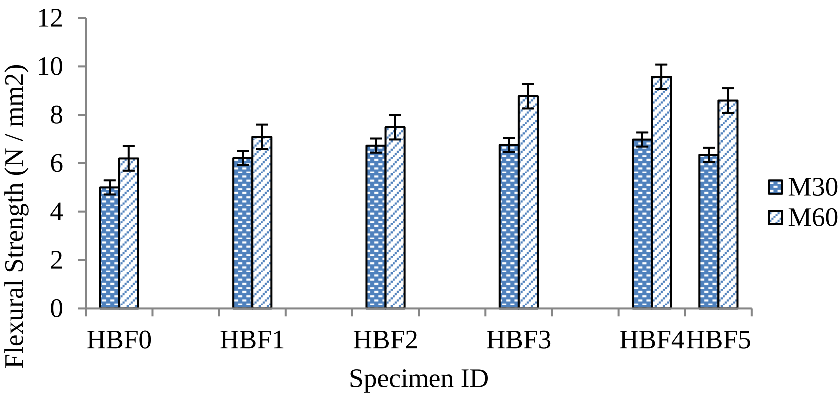


Fig. 4. Flexural strength/ MOR of hybrid mixes

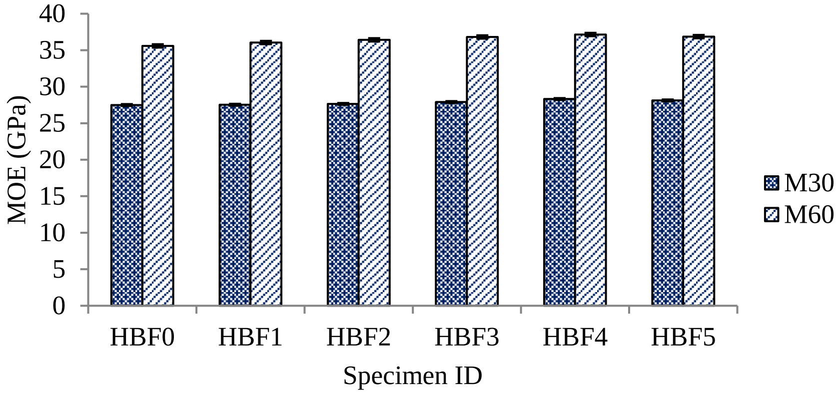
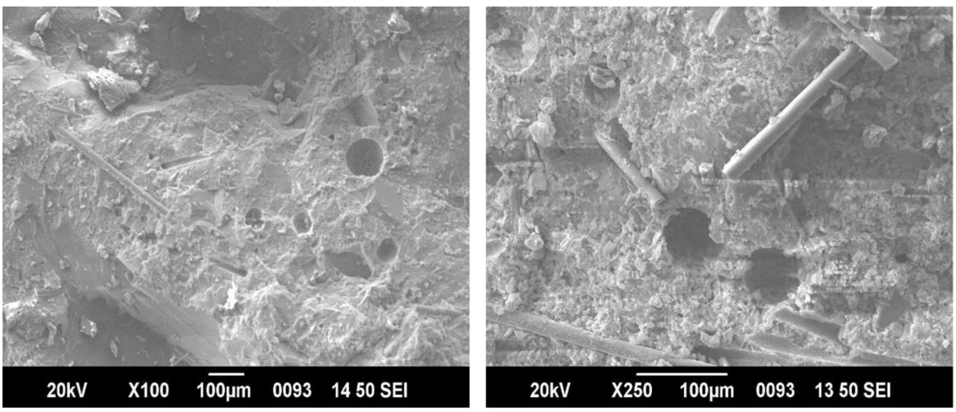


Fig. 5. MOE of hybrid mixes

3.5 Microstructural Characteristics

The Scanning Electron Microscopy (SEM) images of the optimum hybrid mixes are shown in Fig. 6. Both images depict the presence of voids within the concrete matrix, with M60 exhibiting a denser matrix compared to the other. The strong adhesion between the basalt fibres and the concrete matrix is evident from the fibre-concrete interphase observed in the images. Additionally, the basalt fibres were visibly embedded within the concrete matrix in both images. The images clearly display the slip trace of basalt fibres that have been pulled out from the concrete matrix. This phenomenon indicates that the fibres have been pulled out without rupturing, which contributes to increased energy dissipation during the post-cracking process. As a result, this behavior enhances the tensile strength of basalt hybrid fibre-reinforced concrete. The presence of slip traces suggests strong adhesion between the basalt fibres and the concrete matrix, allowing for effective load transfer and improved mechanical properties, particularly in tension [9].



(a) (b)

Fig. 6. SEM images of optimal hybrid mix HBF4 a) M30 b) M60

3.6 Statistical Analysis

In this section, a detailed descriptive statistical analysis was carried out on the selected parameters from the gathered dataset. To further analyze the data, Response Surface Methodology (RSM) was employed to develop predictive models. RSM is a sophisticated statistical technique used to explore the relationships between several input variables (also known as factors) and one or more response variables (output factors) [38]. This method helps in understanding the interaction effects of these input variables on the output and in constructing an ideal mathematical model that can predict the desired outcomes with high accuracy. The core concept of RSM is that the input variables can be visualized as the vertices of a geometric shape, typically a cuboid in multi-dimensional space. By analyzing how the response variable changes as the input variables are varied, RSM creates contour plots—lines that connect points of equal response. These contour lines, when analyzed collectively, provide a clear understanding of how different combinations of input variables influence the output**.** The RSM model can be represented using the mathematical expression given in Eq.1[39].

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i<j}^{n} \beta_{ij} X_i X_j \ldots + e(X_i, X_j, \ldots \ldots .., X_n) \tag{1}$$

where, X_i and Y denote independent factors and response, β_0 is the intercept, β_i , β_{ii} and β_{ij} are model coefficients that characterize the linear, squared and interaction effect of the model, respectively. A commercially available software with statistical design and analysis tool pack was used to develop the RSM models [45].

In this study, the selected input parameters include the water-to-binder ratio (w/b) and the amounts of basalt fibres of different lengths, specifically shorter length 12 mm and a longer length 30 mm, which are denoted as bfs and bfl respectively. The response variables being analyzed are the compressive strength (cs) and flexural strength (fs) of the concrete. The corresponding regression equations for cs and fs derived using RSM are provided in Eq. 2 and Eq. 3, respectively. The coefficients of determination R^2 values for these equations are 0.99 for cs and 0.95 for fs. This high R^2 value indicates an excellent fit, meaning the model is highly accurate in predicting the compressive strength and flexural strength based on the input parameters. The residual plots for cs and fs are plotted in Fig. 7 and Fig. 8 respectively.

$$cs = 142.18 - 259.6\ w/b + 2.1\ bfs - 1.15\ bfl - 1.84\ bfs*bfs - 2.2\ w/b*bfs - 1.5\ w/b*bfl \tag{2}$$

$$fs = 9.41 - 11.21\ w/b + 4.43\ bfs + 3.72\ bfl - 3.27\ bfs*bfs + 3.14\ w/b*bfs - 6.97\ w/b*bfl \tag{3}$$

By applying RSM, the study aims to develop a predictive model that can accurately estimate these mechanical properties based on the variations in the selected input parameters, thereby providing valuable insights for optimizing the composition of basalt fibre-reinforced concrete.

The accuracy of the prediction model was validated by comparing its predicted values for both compressive strength and flexural strength with experimental data from previous studies and is shown in graphical form in Fig. 9 and Fig. 10 respectively. The comparison revealed that all estimated values fell within ±6% and ±3.4% for compressive strength and flexural strength, respectively compared to the experimental results, indicating a high level of agreement and validating the model's performance.

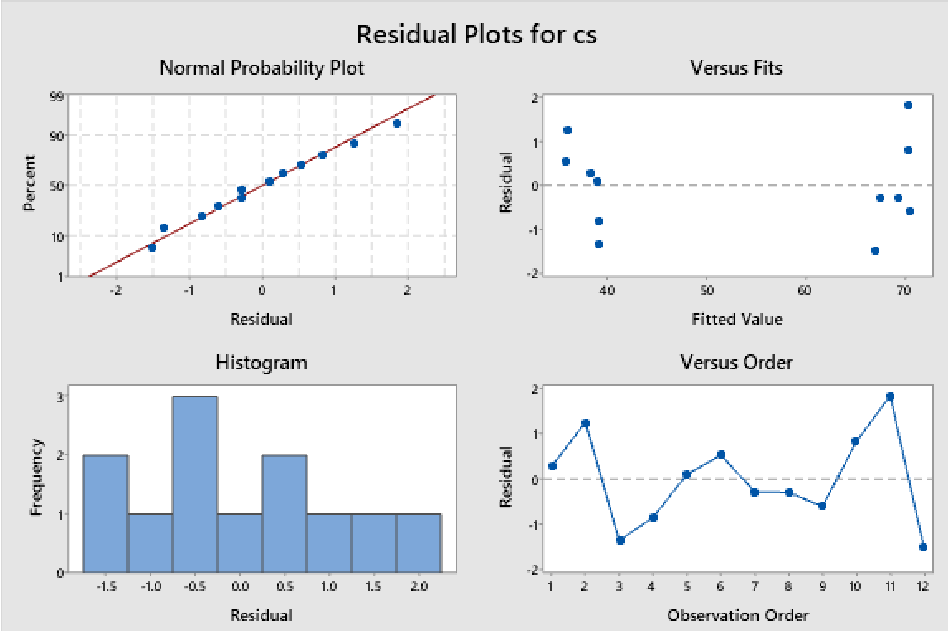


Fig. 7. Residual plot for cs

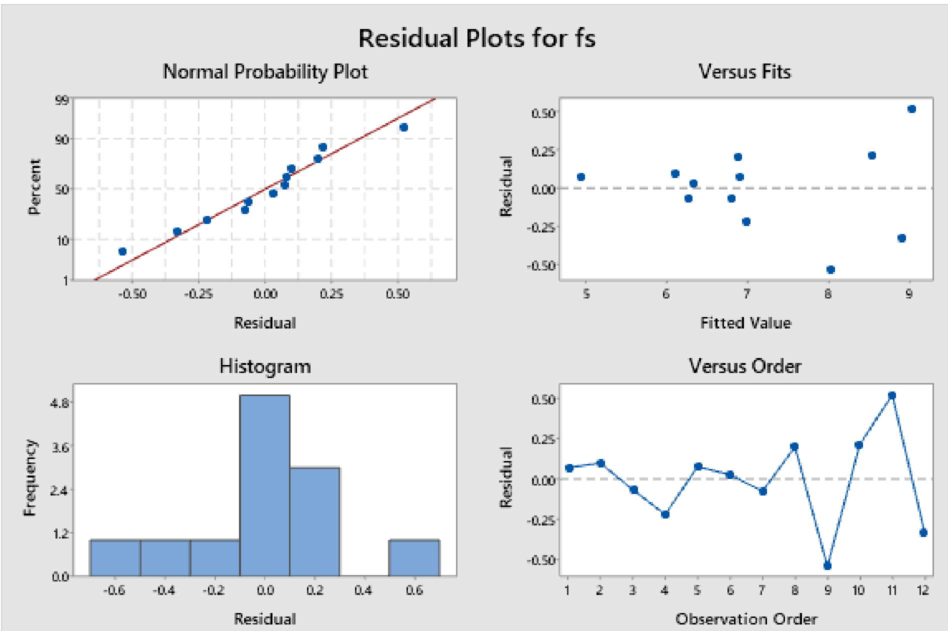


Fig. 8. Residual plot for fs

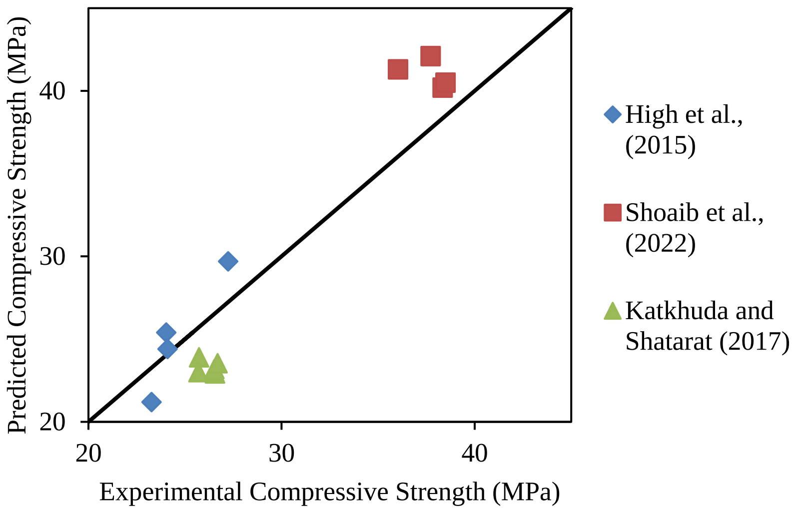


Fig.9. Comparison between compressive strength results of earlier researchers [13,15,29] and the predicted values by RSM model

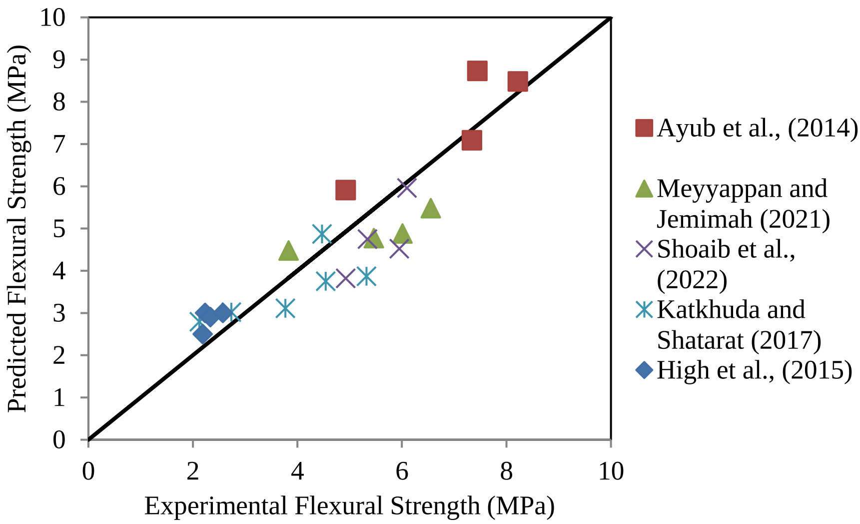


Fig.10. Comparison between flexural strength results of earlier researchers [13,15,29,31,33] and the predicted values by RSM model

4. Conclusions

The inclusion of fibres and pozzolanic materials helps in maximizing the mechanical and chemical attributes of concrete. In the present study, the influence of hybrid basalt fibre lengths on the workability and mechanical properties of normal and high-strength reinforced concrete were examined. Basalt fibres, measuring 12 mm and 30 mm in length and constituting 1.5% of the concrete volume, were integrated into the mixture. Various parameters were investigated; including workability assessed using the slump cone test, as well as compressive strength, flexural strength and MOE. Furthermore, SEM analysis was performed to examine the microstructural characteristics of basalt FRC. Based on the results obtained from lab experiments and discussions, the following conclusions are drawn,

- The hybrid fibre volume fraction of 1.5% with 25-75 basalt fibre 12 mm-30 mm combination (HBF4) significantly improves the general performance.
- Slump values decreased for hybrid mixes in comparison to conventional concrete, with a notable decrease observed in workability with the inclusion of 30 mm fibres. The slump decreased with increasing fibre length due to the greater specific surface area, rough surface, and high coefficient of friction. Specifically, in high strength concrete, there was a maximum reduction in slump value.
- The inclusion of basalt fibres did not lead to a significant enhancement in compressive strength values. However, the compressive strength of different length hybrid fibre reinforced specimens is better than that of single length fibre reinforced specimens for the same basalt fibre content.
- The maximum flexural strength in the HBF4 mix was found to be 39% and 54.35% higher than the control specimens for normal and high-strength concrete, respectively. This improvement could be attributed to the crack-bridging properties of the incorporated fibres.
- All the hybrid mixes showed no notable improvement in the Modulus of Elasticity (MOE) of the concrete.

Therefore, the positive results obtained from the enhanced properties of hybrid basalt fibre-reinforced concrete (FRC) utilizing 12 mm and 30 mm basalt fibres in both normal and high-strength concrete indicate its potential utility in structural applications.

5. Scope for Future Work

For future research on basalt hybrid FRC, it is essential to evaluate its ductility performance. This involves assessing the material's ability to undergo significant plastic deformation before failure, which is crucial for structures subject to dynamic loads and seismic activity. Studies should focus on how different fibre combinations influence ductility using tensile and bending tests to measure strain capacity and energy absorption. Additionally, investigating the failure modes of basalt hybrid FRC will provide insights into its structural integrity and weaknesses. A thorough study of crack patterns under various loading conditions is necessary to understand its stress response, including examining the spacing, width, distribution, and progression of cracks over time. Evaluating the long-term durability of basalt hybrid FRC, including resistance to environmental factors such as freeze-thaw cycles, chemical exposure, and UV radiation, will help determine its suitability for various applications. Research should also explore optimizing fibre proportions and lengths to balance workability, mechanical properties, and cost-effectiveness, potentially experimenting with fibre types and lengths beyond those used in current study.

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