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Predictive models for mechanical properties of hybrid fibres reinforced concrete containing bamboo and basalt fibres

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ABSTRACT

The aim of this study was to investigate hybrid fibre reinforced concrete containing natural Bamboo and basalt fibres and forecasting the effect of these fibres on Mechanical properties. The contents of Basalt fibres were (0%, 0.25%, 0.50%, 0.75% and 1.00%). The mechanical performance of the hybrid fibre-reinforced concrete was studied in terms of compressive, splitting tensile and flexural strengths. All the samples were tested at the ages of 7, 14, and 28 days. The results showed that an increase in fibre percentages led to a reduction in the concrete slump. It was also found that 0.75% Basalt fibres with 1% bamboo fibres resulted in the optimum performance of the mechanical properties of the concrete. Based on regression models, it was found that bamboo fibres have negative impact on the compressive and splitting tensile strength while basalt fibres enhanced this strength, however, the negative effect of bamboo fibres reduces with the age of concrete. While the effect of bamboo fibres on flexural strength was positive and basalt fibres have negative impact on it. It was concluded that the bamboo and basalt fibre have good relation in overall improving the mechanical properties of hybrid fibre reinforced concrete.

1. Introduction

Hybrid fibre-reinforced concrete is defined as a combination of more than one type of fibre in concrete. Green and sustainable concrete materials have been the main concern in the construction industry. Concrete is the most widely used man-made construction material in the world [1]. Fibres are usually added in concrete mixes to control cracking due to plastic and drying shrinkage. Fibres used in concrete mixes are available in different materials as well as sizes and shapes [2]. The main factors affecting the characteristics of fibre-reinforced concrete are water-cement ratio, percentages of fibres used, their diameters and lengths [3]. Cracking, earthquakes, high temperatures, and fires are among the issues which may lead to a reduction in the durability [4]. Common fibres added in concrete mixes include steel, polypropylene, glass fibre, polyester, and carbon. Some characteristics may be enhanced, and some would be diminished since each fibre has its different properties [5]. However, fibres can enhance the durability of concrete [6]. The use of synthetic fibres can be costly, and the production process of the fibres may also consume high energy and may be harmful to the environment and human health [7].

Basalt is a type of igneous rock produced by the rapid cooling of lava. It is a type of mineral fibre present in volcanic rocks [8]. Basalt fibres are available in various forms such as chopped and fibre strands. Many investigations have been conducted on Basalt fibres as an ingredient for improving the properties of concrete [9–12]. Basalt fibres in concrete provide a lot of advantages such as high strength, high elastic modulus, good thermal and chemical stability as well as effective sound insulation and electrical characteristics [13].

Bamboo is available abundantly in Asia Pacific countries. Bamboo fibres are natural and are harvested from Bamboo plants. These plant-based natural fibres have many advantages such as low cost, low density, environment friendly, and are sustainable [14]. The Bamboo achieves its maturity within three to four years and consumes little energy to harvest [15]. Due to its outstanding properties such as low

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weight-to-strength ratio, high tensile strength, and affordability, it has received attention from scientists and engineers for utilization in construction [15].

2. Literature review

Zhou et al. [16] studied the mechanical performance of Basalt rock fibres in concrete with a volume content of 0%, 0.1%, 0.2%, 0.3%, 0.4% 0.5% and 0.6%. The compressive strength, tensile strength, flexural strength, toughness index, fracture energy, flexural-compressive ratio, and reinforcement coefficient of concrete were all significantly improved.

Kavitha and Kala [14] reported that 1% Bamboo fibre is the optimum percentage with the corresponding fibre aspect ratio of 40. Their study revealed that Bamboo fibre reinforced concrete leads to significant enhancement in early as well as long-term compressive strength and split tensile strength of concrete. Kumarasamy et al. [17] studied the compressive strength, split tensile and flexural properties of Bamboo fibre reinforced concrete by incorporating 0%, 0.5%, 1%, 1.5%, 2% and 2.5%. It was reported that the mechanical properties were enhanced up to 2%. Gupta and Singh [15] revealed that the workability of Bamboo fibre concrete decreases with the increase in fibre length and percentages up to 1.5%.

From the above mechanical properties of concrete were enhanced by using Basalt fibre reinforcement [18,19] ductility [20], concrete pre-cracking strength has been improved by using basalt fibre [21] and possess good impact resistance [12]. Single fibre using Bamboo in concrete showed that Bamboo fibres could control crack propagation and showed improved crack-bridging effects [22], improve ductility [15], as well as enhanced cubic compressive strength and remarkably improved splitting tensile strength of concrete [23].

Some efforts have been made by previous researchers to develop composite structure using bamboo and basalt fibre. Lv et al. [24] reported a bonding behaviour of basalt fibre-reinforced polymer and laminated bamboo. They found that the effective bond length is 100 mm when the specimen is affixed using epoxy resin. Lv and Liu [25] studied the mechanical behaviour of laminated bamboo beam strengthen by basalt fibre-reinforced plastic sheet. They reported an increase about 24% in ultimate load capacity of the bamboo laminated beam when affixed with two layer of basalt fibre-reinforced plastic sheet.

The performance of a mixture of fibres together in hybrid fibre-reinforced concrete can provide better mechanical properties than that of single length fibre reinforced concrete [26]. Chetia and Samanta [27] studied the sliding wear of bamboo/basalt hybrid composite. Their findings show that the addition of basalt reduced the wear loss of the hybrid composite. This was the only cited previous study on the combined effect of bamboo and basalt fibre concrete.

There are several models to forecast the mechanical properties of fibre reinforced concrete [28–31]. But, none of the researcher proposed the predictive models for hybrid fibre reinforced concrete Hence, the properties of this hybrid containing natural fibres (Bamboo) and mineral fibres (Basalt) was further investigated in order to optimise these fibres content and develop the predictive models for mechanical properties.

3. Significance and research aim

Bamboo fibres could significantly improve the toughness of concrete, especially when combined with Basalt fibre to decrease its inherent brittleness and stiffness. The current research suggests that merging these two distinct fibre types in concrete has the potential for a broad spectrum of uses, both in structural and non-structural elements, in compliance with the increasing demand for environmentally friendly and sustainable materials in the construction sector.

The work primarily concentrates on the mechanical properties of fibre-reinforced concrete using either bamboo or basalt fibre or hybridization of these fibres with other types.

In this research, two sets of hybrid fibre concrete were produced by incorporating 1% (Group I) and 1.5% (Group II) Bamboo fibres by weight of cement with varying percentages of Basalt fibres (0.25%, 0.5%, 0.75%, and 1%) to identify the best percentage mix that could efficiently serve as a crack arrester, thereby enabling the concrete to withstand higher loads than its non-reinforced counterpart. The mechanical properties such as compressive strength, splitting tensile strength, and flexural strength were then measured and analysed.

4. Experimental programme

4.1. Materials

Ordinary Portland cement (OPC) ASTM Type I was used in this investigation. Natural Coarse aggregates were between 70–80% of the weight of concrete. The size of coarse aggregate used was made passing 10 mm and retained 5 mm sieve. Fine aggregate, natural sand, with a size of 2.36 mm and below was considered in this study. The source of fine aggregate was flint shingle obtained from a river near Universiti Malaysia Pahang. Fine aggregate was dried in the open air before usage.

4.2. Bamboo Fibres

In this study, *Gigantochloa Scortechinii* species of Bamboo fibres were extracted using a mechanical method. The dried Bamboo undergoes chemical treatment before use. The Bamboo was first split into strips before being immersed in an aqueous NaOH solution at 10% concentration which was 10% in mass over volume. The Bamboo splints were soaked for 48 h at ambient temperature to decompose ligneous content [32]. Thereafter, the treated Bamboo strips were washed with distilled water to reduce brittleness and air-dried before the mill rolling process using a sugar cane machine. To eliminate the alkaline content on the fibre surface, the extracted fibres were rinsed with distilled water until they reached a neutral pH [33]. In the last stage, the fibres were subjected to a drying process through autoclaving in an oven at 60 °C for 24 h [34] as shown in Fig. 1. The dried Bamboo had been placed in a storage box with silica gel to avoid moisture absorption that could damage the outcome. The final yield of Bamboo fibres was cut into the size of 1 in. which is 2.54 cm in length [35]. It should be noted that bamboo fibre may be processed using tap water, industrial grade NaOH and sun-dried to reduce the production cost for a practical application to below $1000 per ton. Table 1 shows the mechanical properties of Bamboo and Basalt rock fibres.

4.3. Basalt Fibres

Basalt fibres used for this research are from Dingqiao Town. Haining City, Zhejiang Province, China. The physical appearance of Basalt fibres is golden in colour and has a smooth surface as shown in Fig. 2. The chopped Basalt fibres were coated with a special surface treatment agent. The measurement of Basalt fibres used in this research was 6 mm. Table 2 presents the physical properties of Basalt fibres.

4.4. Mix Proportions

Concrete mix design of characteristic strength 30 MPa using Ordinary Portland Cement Type I was considered in this study. The control mix is made of cement, water, and coarse, and fine aggregates without fibres and admixtures. The water-cement ratio was kept constant at 0.55 for all the design mixes throughout this investigation. Superplasticizer of dosage 0.25% and 2% was added to the control mix and mixes with hybrid fibres, respectively to improve the concrete workability. The mix proportions of the control mix and hybrid concrete mixes are presented in Table 3. In this study, the percentages of 1% and 1.5% bamboo fibre were chosen based on the recommendation by Ahmad et al. [36], who suggested that the optimal proportion of bamboo fibre typically falls

Fig. 1. Dried Bamboo fibres.

Table 1
Mechanical properties of Bamboo and Basalt fibres.

Mechanical fibres properties	Type/variety used in this study	
	Bamboo	Basalt
Density (g/cm^3)	1.2	2.67
Elasticity modulus (GPa)	21 – 38	84
Elongation at break (%)	1-4	2.8
Melting point °C	1000 (Fire)	1350
Tensile strength (MPa)	390 – 730	> 1000

Fig. 2. Basalt fibre.

within the range of 1–1.5% of the binder's weight.

5. Experimental Procedure

5.1. Fresh Properties

Slump test performed in this study is according to BS EN 12350–2:2009 [37]. Concrete mixes were preserved, and vibration was carried out to make air bubbles grow in the mixture after placement in the mould and even to liquefy mixtures containing less water. These specimens were permitted to stay in the steel mould for the first 24 h in atmospheric conditions [38].

5.2. Hardened Properties

The compressive strength test performed in this study is according to BS 1881: Part 1 16:1983 [39]. Concrete cube samples with the size of 100 mm × 100 mm × 100 mm were considered in this study. Nine specimens were prepared for the ages, of 7, 14, and 28 days. After 24 h of casting, the concrete specimens were demoulded and placed in the curing tank for water curing. The specimens were tested at 7, 14 and 28 days after the water curing process.

Splitting tensile strength conducted in this study is according to ASTM C 496 [40]. This test was performed using a Universal Testing Machine of 50 kN. The size of the cylindrical samples was 100 mm in diameter and 200 mm in height. The samples were tested after 7, 14 and 28 days of water curing.

Flexural strength conducted in this study is according to ASTM C 293 [41]. The size of the concrete beam specimens used for flexural strength was 100 mm in width, 100 mm in height and 500 mm in length. Two beams were cast for each hybrid fibre percentage and tested at 7, 14 and 28 days. The average results were recorded.

Table 2
Physical properties of Basalt fibre.

Length	Nominal diameter of filaments	Density	Tensile strength	Moisture content	Elongation	Combustible matter content
Control	16 μm	2.6-2.8 g/cm^3	2000 – 2400 MPa	0.1-0.2%	2.6-3.0%	0.3-0.6%

Table 3
Mix design proportions used for studied specimens (per m^3).

Specimen / Group	Sample code	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Bamboo (%)	Basalt (%)	Sp.	
								%	L/m^3
Control	C0	1112.2	681.6	388	213.3	0	0	0.25	0.97
Hybrid / Group I	A1	1112.2	681.6	388	213.3	1	0.25	2	7.76
	A2						0.5		
	A3						0.75		
	A4						1.0		
Hybrid / Group II	B1	1112.2	681.6	388	213.3	1.5	0.25		
	B2						0.5		
	B3						0.75		
	B4						1.0		

6. Experimental results and discussion

6.1. Workability

Fig. 3 and Table 4 show the slump test results for Group I specimens containing 1% Bamboo fibres and Group II specimens which contain 1.5% Bamboo fibres. Both Group specimens contain 0.25%, 0.5%, 0.75% and 1% Basalt fibres. Both control and hybrid fibre mixes exhibited shear slump in the fresh properties test due to the addition of 0.25% and 2% superplasticizer respectively. The use of a superplasticizer (SP) increases workability without altering the water/cement ratio [42]. Hybrid fibre inclusions in Group I and Group II mix normally absorbed water which resulted in a honeycomb in concrete [43] which is not the case for the control mix without any fibres. The superplasticizer gave the cement particles a strong negative charge, which causes them to repel one another hence, extra water is provided by deflocculating the cement particles [42].

It can be seen from Fig. 3 and Table 4 that the slump values decreased with increasing Basalt fibre content (0.25%> 0.5%>0.75%>1%) in both Group I (1%) and Group II (1.5%) Bamboo fibres. Although the slump decreased with the increase in fibre percentage, the difference in slump values was small, up to 3% for Group I, and 4% for Group II. This shows that adding both Bamboo and Basalt fibres to the concrete leads to a reduction in the concrete workability. This can be explained by several factors. First is due to the fact that fibres typically have a large specific surface area, which increases the consumption of water making the mixing, pouring, and compacting processes more complex [44] as more cement paste was needed to fully coat the fibres which increase the mix viscosity [45]. Besides, fibres cause the aggregates, paste, and fibres to interlock, which lessens the cement paste's lubricating impact on the movement of the aggregates during placement and compacting [44]. Other factors include clumps or balling phenomenon of fibres associated with greater fibre volume fractions [46]. Similarly, Bamboo fibre in concrete also reduces the slump and workability [16,47]. This is because of the water affinity of Bamboo as it absorbs the water. Previous studies also reported that an increase in Bamboo fibre content could enhance the cohesiveness and internal resistance of the fresh mix, thereby reducing the workability of the mix [48].

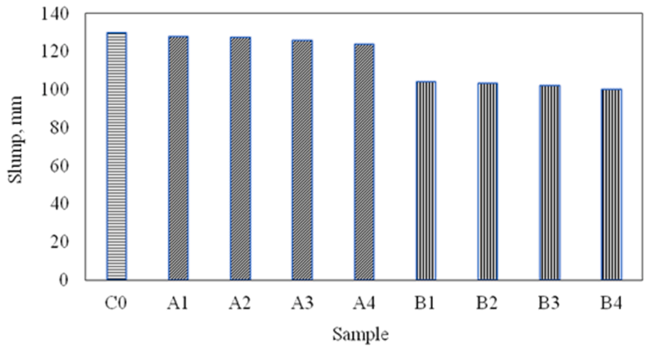

Fig. 3. Slump test results for control and hybrid fibre concrete.

6.2. Compressive Strength

Fig. 4 shows the results of the compressive strength of Group I (1% Bamboo fibre) and Group II (1.5% Bamboo fibre) hybrid specimens compared to the control concrete at 7, 14 and 28 days. As can be observed, all specimens showed an improvement in strength from 7 to 28 days of age.

The Group II samples exhibited higher compressive strength than the Group 1 at all ages of testing. This indicates that higher bamboo fibre content had more fibre fibrillation which was induced by the alkalinisation treatment hence promoting the precipitation of calcium silicate hydrate (CSH) gel of the cement into the fibre cavities [49]. The addition of 0.25% and 0.5% basalt fibre in the hybrid samples led to a reduction in compressive strength than the control sample at all curing ages except for the B2 sample which managed to slightly surpass the control concrete at 28 days but there has not been much difference in contribution to compressive strength. However, by adding 0.75% of basalt fibre, the compressive strength of all hybrid samples was improved by more than 5% in comparison with the control mix at 28 days. The control samples achieved an average 28-day compressive strength of 40.05 MPa.

The highest strengths recorded from Group I and Group II were 43.6 MPa and 45.8 MPa respectively which was 8.87% and 14.36% higher than the control concrete. This indicates that for this mix, Basalt fibre of 0.75% content is the optimum mix combination for the hybrid fibre concrete. The improvement in the compressive strength of 1% Bamboo fibre with 0.75% Basalt fibre mix may be due to the surface roughness induced by the alkali treatment of the bamboo fibre [47]. Basalt fibres' bridging action might also increase compressive strength [50]. In their study, they reported that the higher incorporations ($0.15 < 0.3 < 0.45 < 0.6$) % of shorter ($12 > 25 > 37 > 50$) mm of basalt fibre increases the compressive strength of hybrid steel-basalt fibre reinforced concrete under normal conditions due to the homogeneity of the concrete mix. This is closely in line with the results gained in this study where 0.75% of 6 mm basalt fibre was utilized.

Increasing the Basalt fibre content to 1% in both hybrid groups resulted in a decrease in the compressive strength of all specimens, in comparison to the hybrid concrete containing 0.75% basalt fibre. As the volume of the basalt fibres increases, the voids increase, causing a reduction in the compressive strength of concrete [9]. Excessive inclusion of basalt fibre causes poor fibre dispersion leading to a weak spot within the cement matrix [51]. This trend agrees with the findings of Kirthika and Singh [52] and Manibalan and Baskar [53] who reported that a 1% addition of Basalt fibres in concrete reduced the compressive strength. Moreover, hybridization with bamboo fibre again as well increased the porosity of concrete resulting in segregated and honeycombed concrete [54]. This causes the initiation and propagation of micro-cracks leading to premature failure of the specimen [48]. In general, the improvement in compressive strength with the addition of

Table 4
Slump result for various concrete mixes.

Specimen	Sample Code	Bamboo (%)	Basalt (%)	Sp. (%)	Water-Cement Ratio	Slump (mm)	Slump type
Control	C0	-	-	0.25	0.55	130	Shear Slump
Hybrid/ Group I	A1	1	0.25	2		128	Shear Slump
	A2		0.5			127.5	
	A3		0.75			126	
	A4		1.0			124	
Hybrid/ Group II	B1	1.5	0.25			104	
	B2		0.5			103.5	
	B3		0.75			102	
	B4		1.0			100	

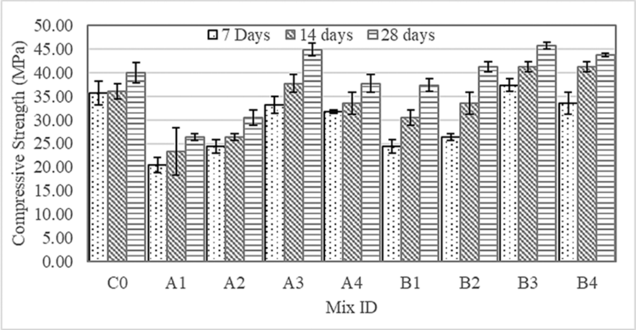

Fig. 4. Compressive strength of Concrete with Age.

1% and 1.5% bamboo fibres with 0.75% basalt fibres is rather slight, as both types only have about 5% difference. Both type A3 and B3 showed slight increase compared to the control, C0, about 8% and 12%, respectively.

6.3. *Splitting tensile strength*

Fig. 5 presented the splitting tensile strength of various volume percentages of basalt fibres concerning curing ages for both Group I and Group II respectively compared to the plain concrete with no fibres. At early age between 7 and 14 days, all of the hybrid specimens were shown to possess lower splitting tensile strength than the control specimens. In contrast to the compressive strength results, the Group I specimens mainly exhibited higher splitting tensile strength than the Group II specimens. Besides, Group II shows a slower strength increment than Group I specimens where the A3 sample with 0.75% basalt fibre had already surpassed the control concrete by 4.54% at 14 days. The strength drop that was noticed in Group II was probably caused by the voids and air pockets that were created by natural fibres [55].

From the findings in this study, the higher percentage of bamboo fibre was seen to be the major contributor to the porosity of the concrete. In the splitting tensile test, the fibre-matrix bond becomes more important as the fibres were subjected to tension force and are directly pulled apart, which is vice versa from the compression test [51]. Therefore, a higher percentage of bamboo fibre may cause a weak layer to exist in the interfacial transition zone (ITZ) between the matrix and fibre and consequently lead to a reduction in strength [55].

At 28 days, there is a positive enhancement in tensile strength possessed by the Group II samples with the highest strength recorded by the B3 samples containing 0.75% basalt fibre with the strength achieved of 3.29 MPa which was 8.68% higher than the control sample. The higher content of bamboo fibre caused a considerably denser accumulation of hydration products which reduce the porosity to some extent which will effectively transferring the stress [49]. Besides, the improved surface roughness of the bamboo fibre as a result of the chemical treatment process is the additional factor contributing to the observed improvement in splitting tensile strength. Thus, a higher amount of bamboo fibre in Group II contributed to greater surface roughness which enable the formation of a stronger fibre-matrix bond, resulting in stronger anchoring and improved adhesion [51,56]. Furthermore, the bridging action of basalt fibre was effective at 0.75% of incorporation compared to other fibre percentages which led to the best performance in terms of the splitting tensile strength. The basalt fibre microscopically reinforces the concrete by bridging the cracks due to its high elastic modulus and tensile strength [14].

However, similar to the compressive strength result, there is a declination in splitting tensile strength with an increment of basalt fibre of 1% for all specimens compared to the hybrid concrete with 0.75% basalt fibre. This may be attributed to the high percentage of fibre content which may cause improper dispersion of fibre in the mix [52]. A similar trend was reported by Manibalan and Baskar [53] that the addition of 1% Basalt fibres showed signs of reduction in splitting tensile strength at 28 days. When a substantially higher volume percentage is utilised, this reduction could once more be the result of fibres clustering together during mixing.

6.4. *Flexural strength*

Fig. 6 shows the results of flexural strength concerning Group I and Group II hybrid concrete tested at 7, 14 and 28 days. Unlike the

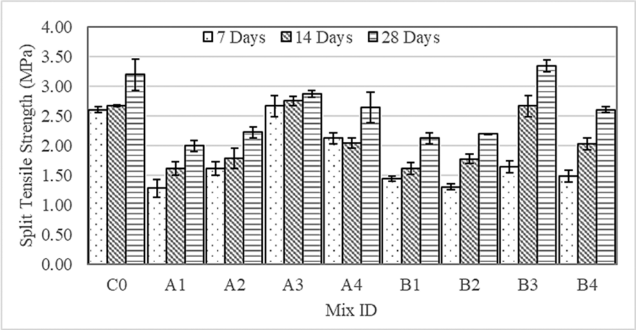

Fig. 5. Splitting tensile of strength of Concrete with Age.

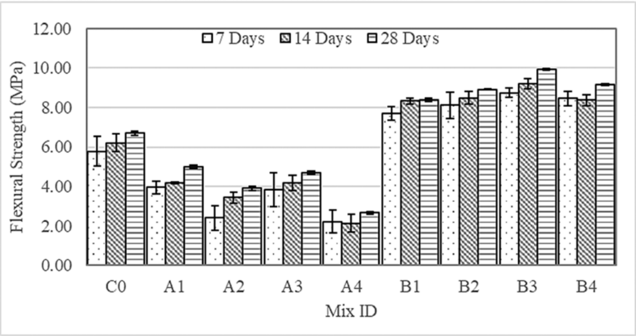

Fig. 6. Flexural strength of Concrete with Age.

performance of hybrid concrete in compressive and splitting tensile tests, all Group I specimens exhibited lower flexural strength than the control concrete. The addition of 0.25% Basalt fibres led to the highest flexural strength among the other Basalt fibre percentages in Group I. It was noticed that there is a drop in the flexural strength for the 0.5% addition of basalt fibre and then an increase of strength when increasing the fibre dosage to 0.75%. The inconsistency of results may be possible due to the dispersion of fibre during mixing.

However, in the case of Group II, all samples revealed remarkable improvements in flexural strength. The hybrid samples managed to surpass the flexural strength of the control concrete by 28.55%, 34.58%, 46.9% and 36.93% for each increment of basalt fibre percentage respectively. It can be seen from the figure that specimens containing 0.75% Basalt fibres exhibited the highest flexural strength of 9.81 MPa at 28 days of curing among the other Basalt fibre percentages. The cement matrix can transfer some amounts of the applied external load to bamboo fibre when the stress is originally applied to the cement matrix. This high flexural strength was achieved due to enhanced bonding and interlocking of the alkali-treated bamboo fibre with the cement matrix which provides a larger fibre failure surface area and considerable energy dissipation during composite failure [49].

Furthermore, the high tensile strength of Basalt fibre restricted the micro-cracks and increases the load-bearing capacity of the hybrid fibre concrete samples [52]. The bridging action of the fibres also raises the demand for energy needed to propagate the crack [44]. However, when the percentage of Basalt fibre increases to 1%, the flexural strength decreases slightly compared to 0.75% Basalt fibre. This may be due to difficulties in fibre dispersion with mixtures of high percentages, 1.5% Bamboo fibre and 1% Basalt fibre [45].

7. Predictive Models by Linear Regression

Following expressions have been proposed based on the correlation of variables with the properties of Concrete:

$$f_{CU} = af_{cup} + bf_{cup}W_{f1} + cf_{cup}W_{f2} \tag{1}$$

$$f_{sp} = d\sqrt{f_{cup}} + e\sqrt{f_{cup}}W_{f1} - f \quad \sqrt{f_{cup}}W_{f2} \tag{2}$$

$$f_{fl} = g\sqrt{f_{cup}} + h^2\sqrt{f_{cup}}W_{f1}^2 - j^2\sqrt{f_{cup}}W_{f2}^2 \tag{3}$$

Where,

$f_{CU} = Cube \quad compressive \quad strength \quad of \quad concrete, (MPa)$

$f_{sp} = Splitting \quad tensile \quad strength \quad of \quad concrete, (MPa)$

$f_{fl} = Flexural \quad Strength \quad of \quad concrete, (MPa)$

$a, b, c, d, e, g, h, j = Coefficients \quad of \quad corresponding \quad variable$

$depending \quad on \quad age \quad of \quad concrete$

$f_{cup} = Cube \quad strength \quad of \quad plain \quad concrete$

$\boldsymbol{W_{f1} = Weight \quad Fraction \quad of \quad Bamboo}$

$\boldsymbol{W_{f2} = Weight \quad Fraction \quad of \quad Basalt}$

Predictive models for Concrete have been proposed similar to the model of steel fibre reinforced concrete by (Thomas and Ramaswamy 2007) [28]; however, the independent variables and dependent variable required to be correlated to verify the effect of these variables on the corresponding dependent variable. The results have been mentioned in Table 5.

As it is evident that $\boldsymbol{f_{cup}W_{f2}}$ has the highest positive correlation with the cube compressive strength, splitting tensile strength and Flexural strength. Multiple linear regressions analysis through least square error has been used to determine the coefficients of independent variables. The significance level p-value 0.05 has been considered in this study that means there is a 5% or less probability that the predicted values will deviate from the true value due to unseen factors. In other words, maximum five (05) predicted values out of (50) will not follow the model. The results of regression models in terms of values of coefficients are mentioned in Table 6.

Table 5

Correlation between Dependent and Independent Variables.

Variables for Cube strength	f_{cup}	$f_{cup}W_{f1}$	$f_{cup}W_{f2}$	f_{CU}
f_{cup}	1			
$f_{cup}W_{f1}$	-	1		
$f_{cup}W_{f2}$	0	0.512	1	
f_{CU}	0.2	-0.193	0.375	1
Variables for Splitting Tensile strength	$\sqrt{f_{cup}}$	$\sqrt{f_{cup}}W_{f1}$	$\sqrt{f_{cup}}W_{f2}$	f_{sp}
$\sqrt{f_{cup}}$	1			
$\sqrt{f_{cup}}W_{f1}$	-	1		
$\sqrt{f_{cup}}W_{f2}$	0	0	1	
f_{sp}	0.111434	0.111434	0.685986	1
Variables for Flexural Strength	$\sqrt{f_{cup}}$	$\sqrt{f_{cup}}W_{f1}^2$	$\sqrt{f_{cup}}W_{f2}^2$	f_{fl}
$\sqrt{f_{cup}}$	1			
$\sqrt{f_{cup}}W_{f1}^2$	-	1		
$\sqrt{f_{cup}}W_{f2}^2$	0	0.26	1	
f_{fl}	0.3	0.714	-0.02	1

In Fig. 7, predicted and experimental compressive strength has been plotted. The value of R^2 is 0.97 which shows that the equation is well fitted to the experimental value. All of the p-values are less or equal to 0.05; however, the p-value is relatively higher for the term $\boldsymbol{f_{cup}W_{f1}}$. The higher p-value suggests that the term $\boldsymbol{f_{cup}W_{f1}}$ is not as significant as in the case of cube compressive strength. The coefficient of the term $\boldsymbol{f_{cup}W_{f2}}$ suggest that basalt fibres have major contribution in the gain of compressive strength, and it gradually decreases with the increase with age. The fibres in terms of weight fraction of basalt fibres have positive effect on the strength opposite to the bamboo fibres. However, the negative effect of bamboo fibres gradually decreases with the age of concrete (refer to Table 6). This regression model is very promising and the terms and order of expression suggested by (Thomas and Ramaswamy 2007) [28] is adequate for the expression of compressive strength of hybrid fibre reinforced concrete.

In Fig. 8, predicted and experimental splitting tensile strength has been plotted. The value of R^2 is 0.97 which shows that the equation is well fitted to the experimental value. All of the p-values are less or equal to 0.05; however, the p-value is relatively higher for the term $\boldsymbol{\sqrt{f_{cup}}W_{f1}}$. The higher p-value suggests that the term $\boldsymbol{\sqrt{f_{cup}}W_{f1}}$ is not as significant as in the case of splitting tensile strength as well (refer to Table 6). The coefficient of the term $\boldsymbol{\sqrt{f_{cup}}W_{f2}}$ suggest that basalt fibres have major contribution in the gain of splitting tensile strength as well and it gradually decreases with the increase with age. The fibres in terms of weight fraction of basalt fibres have positive effect on the strength opposite to the bamboo fibres. However, the negative effect of bamboo fibres gradually decreases with the age of concrete.

In Fig. 9, predicted and experimental flexural strength has been plotted. The value of R^2 is 0.95 which shows that the equation is well fitted to the experimental value. All of the p-values are less or equal to 0.05; however, the p-value is relatively higher for the term $\sqrt{f_{cup}}W_{f2}^2$. The higher p-value suggests that the term $\sqrt{f_{cup}}W_{f2}^2$ is not as significant as in the case of compressive and splitting tensile strength (refer to Table 6). In fact, term $\sqrt{f_{cup}}W_{f1}^2$ is more significant suggesting the better role of bamboo fibres in pre-cracking response of beams. While basalt fibres have least effect on it. The fibres in terms of weight fraction have minimal effect on the flexural strength with the age which was observed in the compressive and splitting tensile strength.

Table 6
Coefficients Calculated through Regression.

Age (Days)	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*j*
7	0.860	-18.20	31.2	0.426	-17.64	12.60	0.454	65.0	51.92
14	0.837	-5.60	29.10	0.40	-10.44	10.72	0.545	65.4	60.81
28	0.854	-0.59	21.39	0.451	-9.57	10.99	0.598	63.06	55.55

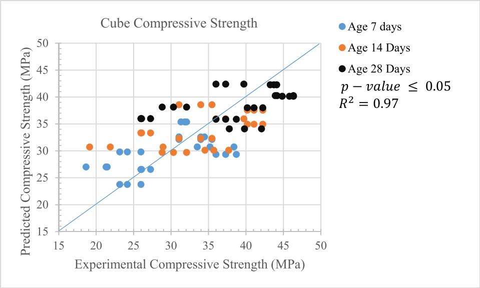

Fig. 7. Cube Compressive Strength Model of Hybrid Fibre Reinforced Concrete.

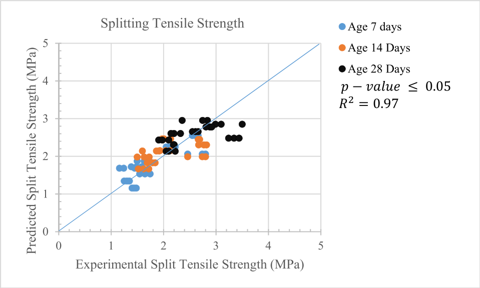

Fig. 8. Splitting Tensile Strength Model of Hybrid Fibre Reinforced Concrete.

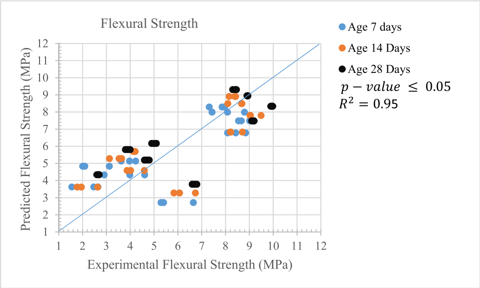

Fig. 9. Flexural Strength Model of Hybrid Fibre Reinforced Concrete.

8. Conclusions

The mechanical properties of the hybrid concrete elements containing natural fibres, namely Bamboo and Basalt were experimentally conducted and evaluated in this investigation. Based on the results of the compressive strength, splitting tensile strength, and flexural strength, the following conclusions can be drawn:

Hybrid fibre-reinforced concrete containing 1% and 1.5% Bamboo with different Basalt fibre percentages showed that the higher percentage of hybrid fibres added, the lower the slump was achieved. Low workability was observed in hybrid fibre-reinforced concrete.

Hybrid fibre-reinforced concrete containing 1% Bamboo and 0.75% Basalt fibre improved the compressive strength by 8.87% compared to the control concrete. On the other hand, 1.5% Bamboo fibres with 0.75% Basalt fibres exhibited the best performance in compressive strength, splitting tensile strength and flexural strength by 14.36%, 8.68% and 46.9% respectively. This is due to the confining and crack arresting behaviour of fibres causes increase in compressive, splitting and flexural strength.

Both 1% and 1.5% Bamboo fibre and 0.75% Basalt fibre were identified as the optimum mix design in hybrid fibre-reinforced concrete. Hence, this implies that hybrid fibre concrete incorporating Bamboo and Basalt fibre can be used as natural fibres towards green concrete production.

Based on the results of the current study, Basalt fibres incorporated together with treated natural Bamboo fibres in concrete mixes could enhance the mechanical properties of the concrete. The concrete strength was dependent upon the dosage of the fibres. In this work, both 1% and 1.5% Bamboo with 0.75% Basalt fibres showed excellent results and 1% Basalt fibre exhibited slight reduction in splitting and flexural strengths due to uneven dispersion of fibres. The model proposed based on regression analysis are well fitted to the experimental results and provide baseline for further research towards the development of predictive models for hybrid fibre reinforced concrete containing different fibres.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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