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Strength properties of coated E-glass fibres in concrete

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Scientific paper - Preliminary note

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Strength properties of coated E-glass fibres in concrete

Test results obtained by studying the influence of epoxy coated E-glass fibre composites on the compressive and splitting tensile strengths of concrete are reported in the paper. Three grades of concrete and varying fibre volume fractions (0.5 %, 1 %, 1.5 % and 2 %) were used as test variables. It was observed that the maximum compressive strength was attained for the fibre volume fraction of 1.5%, whereas the splitting tensile strength was found to increase with an increase in the fibre volume fraction. Based on the test results, a mathematical model was developed using regression analysis.

Ključne riječi:

coated glass fibres, fibre reinforced concrete, fibre volume fraction, compressive strength, splitting tensile strength

Prethodno priopćenje

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Utjecaj obloženih E-staklenih vlakana na svojstva čvrstoće betona

U radu su prikazani rezultati ispitivanja o utjecaju E-staklenih vlakana obloženih epoksidom na tlačnu i vlačnu čvrstoću betona. Kao parametri ispitivanja su odabrana tri različita razreda betona s varirajućim volumnim udjelima vlakana (0,5 %, 1 %, 1,5 % i 2 %). Uočeno je da se najveća tlačna čvrstoća postiže pri volumnom udjelu vlakana od 1,5 %, a vlačna čvrstoća cijepanjem povećava se kako se povećava volumni udio vlakana. Na temelju rezultata ispitivanja razvijen je matematički model primjenom metode regresijske analize.

Ključne riječi:

obložena staklena vlakna, beton ojačan vlaknima, volumni udio vlakana, tlačna čvrstoća, vlačna čvrstoća cijepanjem

Vorherige Mitteilung

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Einfluss beschichteter E-Glassfasern auf die Festigkeitseigenschaften von Beton

In dieser Arbeit werden Resultate von Untersuchungen zum Einfluss mit Epoxid beschichteter Glasfasern auf die Druck- und Zugfestigkeit von Beton dargestellt. Als Untersuchungsparameter wurden drei verschiedene Betonklassen mit verschiedenen Faservolumenanteilen (0,5 %, 1 %, 1,5 % und 2 %) gewählt. Es wurde festgestellt, dass die größte Druckfestigkeit bei einem Faservolumenanteil von 1,5% erzielt wird, während die Spaltzugfestigkeit mit dem Faservolumenanteil ansteigt. Aufgrund der experimentellen Resultate wurde aufgrund Methoden der Regressionsanalyse ein mathematisches Modell entwickelt.

Ključne riječi:

beschichtete Glasfasern, faserverstärker Beton, Faservolumenanteil, Druckfestigkeit, Spaltzugfestigkeit

1. Introduction

It has been well established that the use of fibres in concrete reduces the width of cracks developed due to external loads. Apart from reducing the crack width in concrete, the fibres also increase the ductility of concrete, improve the post-cracking behaviour of concrete, and resist high impact loads. Earlier researchers have reported that the behaviour of fibre reinforced concrete depends on factors such as the fibre shape, fibre geometry, aspect ratio, volume of fibres, curing method and curing time, use of superplasticisers, etc. (Trottier, J. F., and Banthia N., 1994 [1], Jianming Gao et al., 1997 [2], K. Ramesh et al., 2003 [3], A. Sivakumar and Manu Santhanam, 2007 [4]). It has also been demonstrated that the fibre distribution and orientation are important factors affecting properties of the fresh and hardened concrete, as proposed by Bensaid Boulekbache et al. [5].

The glass fibre reinforced concrete has increasingly been used in architectural and structural concrete members thanks to its anticorrosive properties, combined with high strength exceeding that of steel fibres. Junji Takagi [6] investigated the effect of randomly oriented glass fibres on the flexural strength, compressive strength, splitting tensile strength, and Young's modulus of concrete, and concluded that there was an increase in strength with an increase in fibre content. However, studies have shown that the use of uncoated E-glass fibres in concrete affects its durability due to high alkaline environment in concrete, and weakens the fibres, which in turn affects the overall strength of concrete. This setback due to durability was overcome by using the alkaline resistant (AR) glass fibres [7], which was found to reduce the propagation of shrinkage cracks [8] and improve the tensile and flexural strengths of concrete [9].

Although several research studies on the alkaline resistant glass-fibre reinforced concrete have so far been conducted, it appears that short coated E-glass fibres in concrete have not been investigated. It should be noted that the glass-fibre coating not only protects the fibres from alkaline environment but also improves its tensile strength significantly [10]. Although the durability of coated fibres is very essential, it is beyond the scope of this study. The durability of coated rigid fibres, considered both separately and with concrete, needs to be investigated, which could be the scope of some future research. Also, the cost-related study of coated fibres, and their comparison with other fibre types, are left to future investigators. This paper focuses on the investigation of properties of the Coated E-Glass Fibre Reinforced Concrete (CGFRC). The volume of fibres and grade of concrete were varied to evaluate the influence of these fibres in concrete under compression and tension. Since the addition of fibres influences the flow properties of concrete, flow table tests were carried out to determine its workability. The coatings of these fibres induce stiffness thereby preventing the balling of fibres, as observed in uncoated fibres. A fibre aspect ratio of 30 was maintained throughout this study. This aspect ratio was found to be lower than the optimum aspect ratio of steel fibres used in concrete by other researchers [11]. The low aspect ratio was considered necessary due to increase in its stiffness and low lateral strength. The objective of this paper is to establish the resistance of coated E-glass fibres in concrete to compressive and tensile loads. Using the test results, mathematical models were developed to express the strength of fibre reinforced concrete.

2. Materials

The ordinary Portland cement conforming to IS: 8112 [12] (equivalent to ASTM – Type-I cement standards), with a specific gravity of 3.15 g/cm^3, was used to prepare concrete. Fine and coarse aggregates with the specific gravity of 2.6 g/cm^3 and 2.7 g/cm^3, respectively, were used. The fine and coarse aggregates were well graded as per IS 383 [13]. E-glass fibre roving of 1200 Tex with an average filament diameter of 17 μm, with the density of 2.65 g/cm^3, was used to prepare coated fibres. The fibres were used without any pre-treatment. The epoxy resin containing a suitable hardener was used as a coating material to fabricate the fibres.

The coated E-glass fibres shown in Figure 1 were made at the laboratory. The E-glass fibre roving was coated with epoxy resin and the excess resin was removed through a narrow slit. The wet coated fibres were allowed to dry at room temperature for about 24 hours by holding them in tension, to avoid fibre wrinkles in coated fibres. Later on, the fibres were post-cured in oven for two hours. The dried fibres were then cut to the required lengths to attain the desired aspect ratio of 30. The coated glass fibre properties are presented in Table 1.

Figure 1. Coated E-Glass Fibres

Table 1. Properties of Coated Glass Fibres

Fibre shape	Straight
Fibre length [mm]	30
Fibre diameter [mm]	1
Aspect ratio	30
Elongation [mm]	4.273
Modulus [GPa]	55.737
Tensile strength [MPa]	1587.779

Three concrete grades were prepared to cast the test specimens. Their mix proportions are presented in Table 2. The cement, sand and coarse aggregate were initially mixed with water to prepare the fresh concrete. The coated fibres pre-mixed with cementitious paste were added in small quantities to the fresh concrete and mixed thoroughly. The pre-mixing was conducted to improve bonding properties of the coated fibres and concrete. The fibre mixed concrete was then cast in steel moulds and vibrated using a mechanical vibrator to reduce the air voids content and attain good compaction. The cast specimens were demoulded after 24 hours and cured in water for 28 days before testing. The specimens were completely dried before conducting the tests.

3. Experimental study

3.1. Testing of fibres

The tensile strength of coated glass fibres was determined as per testing standards ASTM D2343-03 [14] using the material testing machine as shown in Figure 2. Five tensile test specimens, each 250 mm in length, and 150 mm in gauge length, were prepared with their ends embedded in the fibre mat laminate. This special attachment was needed to prevent the crushing of fibres and to provide the necessary grip during tensile testing. The specimen was loaded under displacement control with the loading rate of 5 mm/min. The tensile strength and modulus of coated glass fibres were calculated as per expression given in the standard. The calculated values are presented in Table 1. The load and extension plot was obtained, as shown in Figure 3.

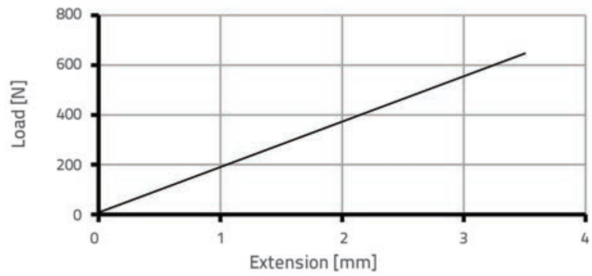

Figure 3. Graph depicting relation between load and extension

3.2. Testing methodology for concrete

Tests were conducted to examine workability of the coated E-glass fibre concrete by the flow table test method. The flow table test was conducted as per IS:1199:1959 [15]. Concrete cubes measuring 150 x150 x 150 mm were used as test specimens for compression tests. The compression tests were carried out as per IS 516 [16]. Three sets of cubes, each made of different concrete grade, in combination with varying percentages of fibres (0 %, 0.5 %, 1 %, 1.5 % and 2 %), totalling to 45 cubes, were cast and subjected to compressive strength testing. The compression testing machine 2000 kN in capacity was used to test the cube specimens. The loading rate was set to 14 MPa/min. Similarly, 45 cylindrical specimens measuring 150 x 300mm were cast and tested to obtain the splitting tensile strength. The split tensile test is a simple and reliable test for determining the tensile strength of concrete [17]. The splitting tensile strength tests were carried out as per IS 5816 [18].

The tested specimens presented in Figure 4 show that the core was intact in all fibre reinforced concrete cubes, while the peripheral concrete had split and fallen apart. This may be attributed to the greater anchorage of fibres in the core region, which are therefore more effective

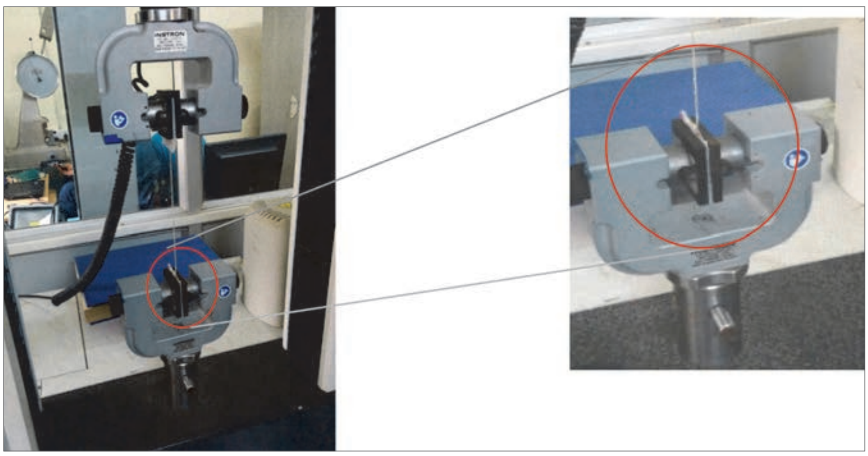

Figure 2. Tensile test setup and end griper

Table 2. Control Mix Proportions

Series no.	Cement content [kg/m³]	Water-cement ratio	Fine aggregate [kg/m³]	Coarse aggregate [kg/m³]	Water content [l/m³]
CGFRC-1	372	0.5	580	1177	186
CGFRC-2	413	0.45	552	1154	185
CGFRC-3	450	0.4	444	1265	180

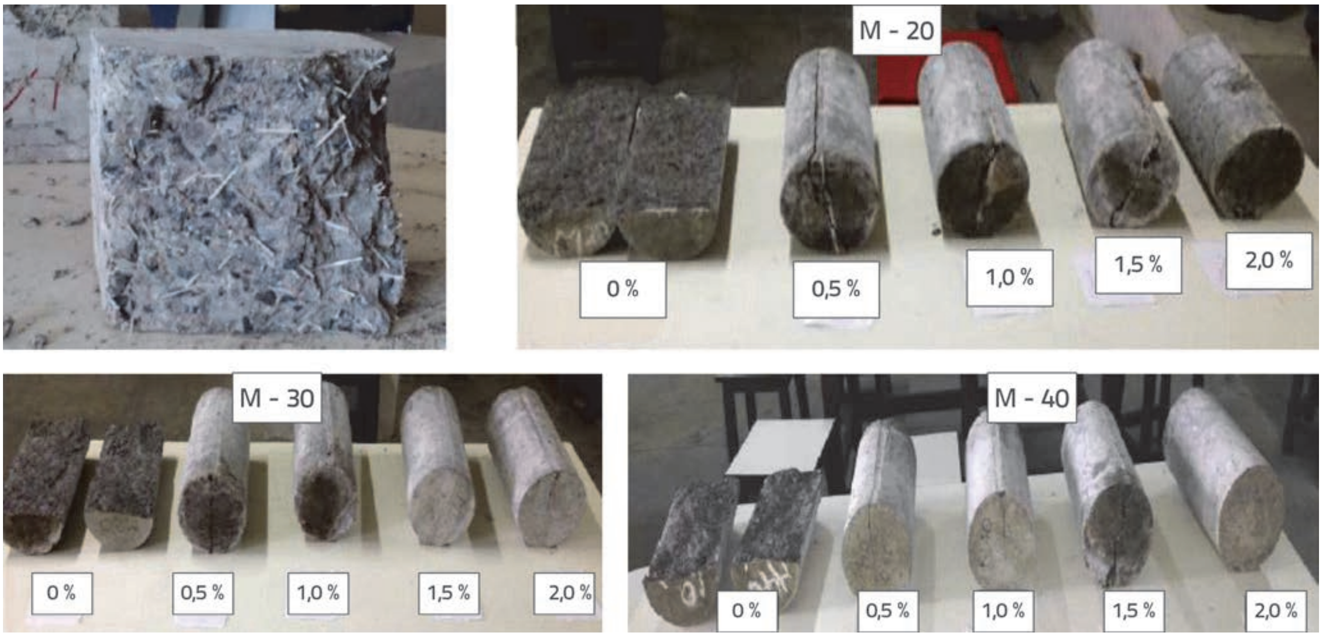

Figure 4. Fractured concrete cube and cylindrical specimens

in resisting crack formation compared to fibres present along the periphery. In case of cylindrical specimens, only the cylinder without fibres split into two halves, while the remaining cylinders - although cracked - did not split and fall apart, which shows that fibres are highly resistant to tension.

4. Test results and discussion

4.1. Fresh concrete test results

The influence of fibres on the workability of concrete is evaluated by means of flow test since the presence of fibres hinders flow properties of fresh concrete. The relative flow behaviour for various grades of concrete and different fibre volume fractions is depicted in Figure 5. It can be seen that flow decreases with an increase in the percentage of fibre volume fraction. The flow was reduced by less than 25 percent when the fibre volume fraction increased from 0 % to 2 %. The reason can be attributed to the straight shape of coated fibres and their short length, which can be advantageous as they cause minimum hindrance to the flow of concrete.

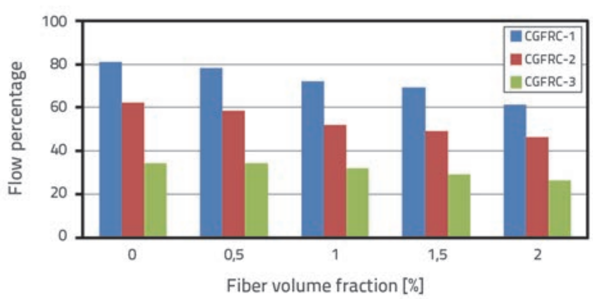

Figure 5. Flow properties of CGFRC

4.2. Hardened concrete test results

4.2.1. Compressive strength results

An average compressive strength of concrete was analysed for three different grades with varying percentages of fibre volume fraction. The corresponding results are presented in Table 3. When the tested specimens were cut open along the crack for investigation, the distribution of fibres was observed to be reasonably good, without any balling of fibres. This may be attributed to the short length of fibres and their straight and rigid shape. Also there was no indication of de-bonding of fibres from concrete. It was observed that the peak load was achieved for a fibre volume of 1.5 %. On further increase in fibre volume beyond 1.5 %, a sharp decline in compressive strength of concrete was registered for the addition of fibres of up to 2 %. This decrease in strength may be attributed to poor compaction of concrete due to the presence of a greater amount of fibres, as stated by earlier researchers in works related to steel fibre reinforced concrete [19]. The fibre coating increased the stiffness of fibres thereby preventing proper compaction of concrete.

4.2.2. Splitting tensile strength results

The peak load was registered for each test specimen to calculate the splitting tensile strength. The average splitting tensile strength of concrete is presented in Table 3. It was observed that the splitting tensile strength increased with an increase in the fibre volume fraction. Both the plain and fibre reinforced concrete specimens failed due to cracking at their respective ultimate loads. However, the splitting of cylinder into two separate halves was observed in the plain concrete

Table 3. Test results for compressive and tensile strength

Series	Fibre volume fraction [%]	Compressive strength		Splitting tensile strength	
		f_c [MPa] (average values)	Relative f_c [%]	f_{st} [MPa] (average values)	Relative f_{st} [%]
CGFRC-1	0	28	100	2.65	100
	0.5	31.11	111.11	3.15	118.67
	1.0	31.56	112.70	3.33	125.33
	1.5	33.78	120.63	3.43	129.07
	2.0	28.44	101.59	3.63	136.8
CGFRC-2	0	37.33	100	3.40	100
	0.5	41.33	110.71	3.57	105
	1.0	44.44	119.05	3.82	112.5
	1.5	45.78	122.62	4.08	120.21
	2.0	39.11	104.76	4.50	132.5
CGFRC-3	0	46.67	100	3.75	100
	0.5	46.22	99.05	3.85	102.64
	1.0	48.89	104.76	4.13	110.19
	1.5	50.67	108.57	4.27	113.96
	2.0	47.11	100.95	5.08	135.47

specimens only. This proves that coated E-glass fibres can effectively resist tension in concrete. It was established that the crack depth and width values were smaller in fibre reinforced specimens, which points to the effectiveness of coated fibres and their distribution. The increase in splitting tensile strength with an increasing volume of fibres was expected since the presence of fibres across the failure plane resists propagation of cracks more effectively.

Figure 6. Fibres in concrete across crack section

One tested specimen in each percentage variation of fibres was selected and was then cut open along the cracked failure surface for observation. It was registered that there was a uniform distribution of fibres in concrete. The number of fibres present across the crack was physically counted to determine the effective fibres resisting the splitting tensile force. Figure 6 shows fibres in concrete across the crack. As stated by earlier researchers, the orientation of rigid fibres also contributes to the capacity of fibres to resist propagation of cracks [20]. It was found that approximately 10 % to 20 % of the total fibres across the crack section were perpendicular to the loading plane, while all other fibres were oriented at different angles to the failure crack. On observation of the fibres, it was found that the fibres were not ruptured due to application of load, and that there was a good bond between the fibres and concrete.

5. Analysis of test results

The analysis of test results was carried out using the multiple regression analysis method to relate the test variables *i.e.* the grade of concrete and percentage of fibre volume to strength properties. A relationship was established to relate the influence of fibres on compressive strength (f_c) and splitting tensile strength (f_{st}) of concrete. The proposed general prediction model s given as follows:

$$f_{CGFRC} = A\left(f_c^{'}\right)^{\alpha} + B\,V_f + C\,V_f^2 \tag{1}$$

where:

- f_c' - 28-day compressive strength of concrete
- V_f - volume fraction of fibres
- A, B, C - regression coefficients
- α - amounts to 0.5 and 1.0 for the splitting tensile strength and compressive strength, respectively.

The first term represents the effect of characteristic strength of concrete, while subsequent terms are dependent on the volume fraction of fibres present in concrete. The model proposed in this paper is similar to the one proposed by Song et al. [21] except for the changes in the coefficients, representing coated E-glass fibres instead of steel fibres.

$$f_c = 0.98 \cdot f_c^{'} + 10.325 \cdot V_f - 4.526 \cdot V_f^2 \quad (2)$$

$$f_{st} = 0.546 \cdot \sqrt{f_c^{'}} + 0.276 \cdot V_f + 0.123 \cdot V_f^2 \quad (3)$$

The coefficient of determination (COD) was found to be 0.91 for both proposed equations (Eqns. (2) and (3)). It was observed that the compressive strength of concrete decreased with the addition of 2% of fibres. In Eqn. (2), it was found that the coefficient of V_f^2 was significant due to non-linear behaviour of the compressive strength of concrete with the addition of fibres. The splitting tensile strength of concrete was found to vary linearly with the addition of fibres. The coefficient of V_f^2 was very low due to linearity of test results.
It is known that the strength of CGFRC is also dependent on various factors such as the fibre shape, fibre length and aspect ratio, orientation of fibres, embedded length, and concrete properties. Since no literature is available on research about the coated E-glass fibres in concrete, further research is needed to validate the proposed equations with additional experimental data. The relationship between predicted values and experimental values is presented in Table 4. This table shows that predicted values are convincingly close to experimental values. The correlation between the experimental values and strength model values (from Eqns. (2) and (3)) can be seen in Figures 7 & 8. The closeness of experimental values and predicted values is described by the linear trend presented in Figures 7 and 8.

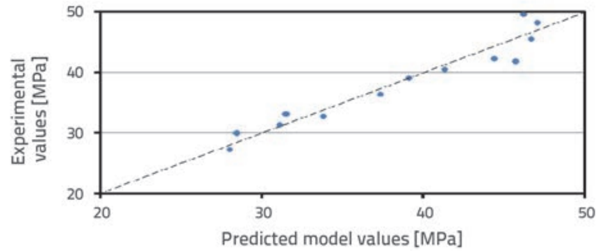

Figure 7. Relation between experimental and model values for compressive strength

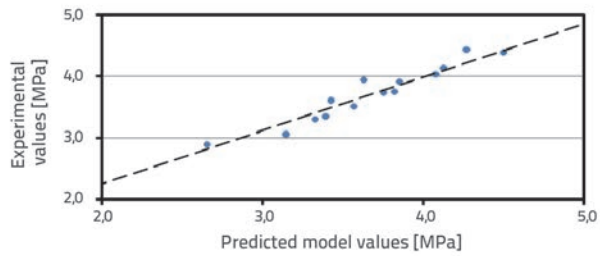

Figure 8. Relation between experimental and model values for splitting tensile strength

Table 4. Comparison of predicted values and experimental values

Series	Fibre volume fraction [%]	Compressive strength			Splitting tensile strength		
		Experimental $(f_c)_{exp}$	Predicted $(f_c)_{pre}$	$(f_c)_{pre}/(f_c)_{exp}$	Experimental $(f_{st})_{exp}$	Predicted $(f_{st})_{pre}$	$(f_{st})_{pre}/(f_{st})_{exp}$
CGFRC-1	0	28	27.44	0.98	2.65	2.89	1.08
	0.5	31.11	31.47	1.01	3.15	3.06	0.97
	1.0	31.56	33.24	1.05	3.33	3.29	0.99
	1.5	33.78	32.74	0.97	3.43	3.58	1.05
	2.0	28.44	29.98	1.05	3.63	3.94	1.08
CGFRC-2	0	37.33	36.59	0.98	3.40	3.34	0.98
	0.5	41.33	40.62	0.98	3.57	3.51	0.98
	1.0	44.44	42.39	0.95	3.82	3.74	0.98
	1.5	45.78	41.89	0.92	4.08	4.03	0.99
	2.0	39.11	39.13	1.00	4.50	4.39	0.97
CGFRC-3	0	46.67	45.73	0.98	3.75	3.73	1.00
	0.5	46.22	49.76	1.08	3.85	3.90	1.01
	1.0	48.89	51.53	1.05	4.13	4.13	1.00
	1.5	50.67	51.04	1.01	4.27	4.43	1.04
	2.0	47.11	48.28	1.02	5.08	4.78	0.94

6. Conclusion

The objective of this study was to evaluate strength properties of concrete reinforced with coated E-glass fibres. The following conclusions were drawn after the testing and analysis of results:

- As expected, the flow of concrete was found to be affected by the addition of fibres. Yet, it did not prove to be a great obstruction to the flow of concrete due to straight shape of fibres. The measured concrete flow properties indicate that the flow gradually decreased by only 25 percent for an increase in fibre content ranging from 0 % to 2 %.
- It was found that the compressive strength of concrete increased with an increase in fibre content. However, the addition of fibres beyond 1.5 % had a retarding effect on compressive strength. The increase in strength for the fibre volume fraction of up to 1.5 % was found to be in the range of 10 % to 20 % of the control-mix concrete strength.
- The splitting tensile strength showed a linear variation with respect to an increase in the volume fraction of fibres. The strength improved significantly with an increase of about 35% compared to the control mix concrete, for the 2 % fibre volume fraction. These fibres were found to be effective in resisting propagation of tensile cracks.
- The proposed empirical models, formulated by multiple regression analysis of experimental test data to predict strength properties of fibre reinforced concrete, were found to be close to test results. However, further research is needed to validate the proposed equations.

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