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Formula to identify the Influence of steel fibres on the mechanical properties of HPC

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Abstract. This work performed to analyses the impact of hooked end steel fibres on the mechanical properties of high performance concrete. The mechanical properties considered incorporate compressive strength, split tensile strength and flexural strength. Taking in to thought parameters, such as, volume fraction of fibres, fibre aspect ratio and grade of concrete, a logical strategy called Taguchi technique was utilized to discover the ideal blend of factors. L9 Orthogonal Array (OA) of Taguchi network comprising of three variables and three dimensions is utilized in this work. The evaluations of concrete considered were M60, M80 and M100. M60 contained 15% of metakaolin as bond swap though for M80 it was 5% of metakaolin and for M100 it was 10% metakaolin and 10% of silica smolder. The volume portion of fiber was fluctuated by 0.5%; 1% and 1.5% and the viewpoints proportions considered were 50, 60 and 80. The test outcomes demonstrate that incorporation of steel fibres enhance significantly the the strength characteristics of concrete, predominantly the splitting tensile strength and flexural strength. In light of relapse investigation of the test information scientific models were produced for compressive strength, split tensile strength and flexural strength of the steel fibre-reinforced high performance concrete.

Keywords: steel fibres; fibre reinforced concrete; high strength concrete; mechanical properties; Taguchi analysis; Regression analysis

1. Introduction

Concrete is a highly versatile construction material: it is plastic and pliable when newly mixed, yet it is strong and lasting when hardened. The qualities explain why concrete is the most regularly used construction material on earth. High performance concrete (HPC) may be demarcated as concrete with a specified characteristic cube compressive strength greater than 60 N/mm^2. The fundamental applications for HPC in-situ solid development are in seaward structures, segments for tall structures, long-length spans and other roadway structures. Its primary advantages are the quantity of longitudinal reinforcement required is decreased.

Plain or unreinforced concrete is a brittle material, with a low elasticity and a low strain limit.. Fibres are added to concrete in order to overcome these limitations. Concrete containing short discrete fibrous materials that are uniformly dispersed and randomly oriented are called fibre reinforced concrete. The volume of fibres additional to a concrete mix is expressed as a percentage of the total volume of the composite, termed "volume fraction" (V_f). The aspect ratio (l/d) of fibre is calculated by dividing fibre length (l) by its diameter (d).

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The most essential property of steel fibre reinforced concrete (SFRC) is its more protection from splitting and break engendering. Because of this capacity to catch splits, fiber composites have expanded extensibility and elasticity, under flexural loading; and the strands can grasp the lattice together even after broad splitting. The net result of all these is to impart to the fibre composite noticeable post–cracking ductility which is unheard of in ordinary concrete (Afroughsabet and Ozbakkaloglu 2015, Ranjan *et al*. 2014, Chen and Qiao 2011).

Deng and Li (2007) investigated the tension and impact resistance of fibre reinforced concrete, five types of fibres were considered and the microfibre shows better resistivity than macro fibres. Ramadoss and Nagamani (2006) investigated tensile strength of concrete by incorporating flat crimped steel fibre of aspect ratio 80, obtained a increase of tensile flexural strength of 37.91% and spilt tensile strength of 55.94%. Thomas and Ramaswamy (2007) investigated the strength improvement of different grades of concrete (M35, M65 and M85) containing 0.5%, 1.0%, and 1.5% volume fractions of steel fibres, declaring that the maximum increase in tensile strength was about 40% but less than 10% for compressive strength and models were derived to predict the strength properties. Song and Hwang (2004) investigated the mechanical properties HSC containing 0.5%, 1.0%, 1.5% and 2% volume fractions of steel fibres, indicating that compressive strength improved up to 1.5% here as splitting tensile strength and modulus of rupture showed an improvement of 98.3% and 126.6% at 2%. Samer and Perumalsamy (1992) investigated on normal

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Table 1 Factors and their levels

Factors	Level 1	Level 2	Level 3
Fibre volume fraction (V_f)	0.5%	1.0%	1.5%
Fibre aspect ratio (*AR*)	50	60	80
Grade of concrete	M60	M80	M100

and high strength hooked end steel FRC subjected to compression, declaring considerable increase in toughness and a marginal increase in the compressive strength, strain corresponding to peak stress, and secant modulus of elasticity.

The present study reports the experimental results for the mechanical properties of SFRC namely compressive strength, split tensile strength and flexural strength for various grades of concrete like M60, M80 and M100 and for various dosages of fibre from 0.5% to 1.5% with 0.5% interval; three different aspect ratios of fibre (50, 60 and 80) were selected. The optimum combination of factors were identified for each property based on taguchi method of the experimental results and on regression analysis of the test data empirical relationship for the properties were derived. The proposed models can be used to forecast the mechanical properties of steel fibre reinforced concrete based on volume fraction of fibre, aspect ratio and the grade of concrete.

2. Experimental program

2.1 Materials

Ordinary Portland Cement (OPC) of 53 grade was used and its specific gravity was found to be 2.44. The other pozzolanic materials used were silica fume and metakaolin with specific gravity 0.23 and 4.55 respectively.

Manufactured sand (M-Sand) of specific gravity 2.55 and fineness modulus 2.55 was used as fine aggregate and it belonged to zone II as per IS 383:1970. The coarse aggregate of specific gravity 1.23 was used for this work. For M60, the maximum size of coarse aggregate used was 20 mm and for M80 and M100 grades of concrete the maximum size of coarse aggregate used was 12 mm. The physical properties were tested and found to fall within the codal limits. To improve the workability of the high strength concrete, superplasticizer (polycarboxylic ether) was added during the mixing of concrete. The slump of various grades of concrete was confirmed at 150 mm. Hooked end steel fibres of three different aspect ratios, 50 (50 mm length×1 mm diameter), 60 (30 mm length×0.5 mm diameter), and 80 (60 mm length×0.75 mm diameter), were used in this work.

2.2 Design of experiments

The experimental design proposed by Taguchi Analysis includes utilizing symmetrical exhibits to sort out the parameters influencing the procedure and the dimensions at which they changes. As a substitute of testing every single conceivable blend like the factorial plan, the Taguchi strategy tests sets of mixes were received. This considers the gathering of the fundamental information to figure out which all elements significantly affect the item quality with a base measure of experimentation, along these lines sparing time and assets.

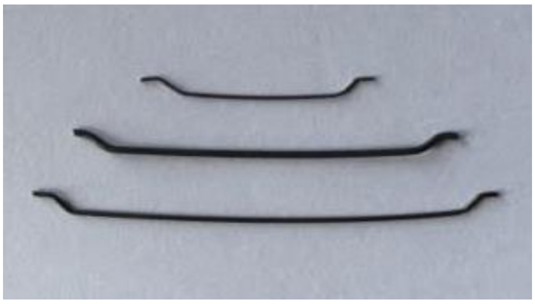

Fig. 1 Image of hooked end steel fibers

L_9 Orthogonal Array (OA) of Taguchi matrix consisting of three factors and three levels is used in this work. Strength parameters like compressive strength, split tensile strength and flexural strength were computed and the factors which influence the parameters were considered as the dependent variables. Table 1 shows the factors and their levels. Fig. 1 shows the image of Hooked End Steel Fibers.

2.3 Specimen preparation and test methods

Concrete mix proportions were prepared for various grades of concrete like M60, M80 and M100. M60 contained 15% of metakaolin as cement replacement whereas for M80 it was 5% of metakaolin and for M100 it was 10% of metakaolin and 10% of silica fume (Afroughsabet and Ozbakkaloglu 2015, Guneyisi *et al.* 2012, Nili and Afroughsabet 2010, Koksal *et al.* 2008). The mix proportions for various grades of concrete are provided in Table 2. The content of superplasticizer in the Table 2 is given as a percentage of the total weight of the cementitious material. The workability of the mix is ensured at time of preparation of concrete mixes by means of slump test. The specimens were cast in steel molds and compacted using steel rods. They were then left undisturbed to set and were demolded after 24 h. the demolded specimens were then immersed in water, for 28 days cured for 28 days.

For each of the tests, only the specimens corresponding to the combinations suggested by the L_9 orthogonal arrays were tested. Three trials were done for each combination inorder to ensure accuracy of the work. For compressive strength test the specimens cast were cubes of size 150 mm×150 mm×150 mm, and the test was carried out as per IS: 516–1959. The cube specimens were loaded in a compression testing machine at the rate of 8 kN/sec until failure. For split tensile strength test the specimens cast were cylinders of 150 mm diameter and 300 mm height and the test was carried out as per IS: 5816–1999. The cylinder specimens were loaded in the compression testing machine at the rate of 8 kN/sec. For flexural strength test the specimens were beams of size 150 mm×150 mm×700 mm when the maximum size of the aggregate used was 20 mm and beam of size 100 mm×100 mm×500 mm when the maximum size of the aggregate used was 12 mm. Two point

Table 2 Mix proportions of concrete mixes

Grade of Concrete	*w/c* ratio	Cement (kg/m^3)	Metakaolin (kg/m^3)	Silica Fume (kg/m^3)	Water (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Superplasticizer (%)
M60	0.35	389.61	68.75	-	160.43	568.38	1231.20	0.45
M80	0.30	526.80	27.73	-	166.36	526.71	1163.00	0.35
M100	0.26	518.27	63.98	57.59	166.36	455.33	1163.00	0.55

loading was used and the tests were carried out as per IS: 516–1959.

3. Results and discussions

The addition of steel fibres in various volume fractions was found to increase the mechanical properties of different grades of concrete. Maximum increase was noticed when 1.5% of fibres were added. The test results did not show much variation in compressive strength for different aspect ratios used. The increase in strength was more evident in the case of split tensile strength and flexural strength. The most extreme increment in the compressive strength because of the addition of steel fibres was observed to be huge about 16% in M60, M80, and M100 grades of concrete.

3.1 Statistical analysis

An analytical method called Taguchi method was used to analyse the test results. Analysis of variance on the experimental data from the Taguchi design of experiments can be used to find out the significance level of various factors and to select new parameter values to optimize the performance characteristics (Venkatesana *et al.* 2011). The data from the arrays can be analyzed by plotting the data and performing a visual analysis.

The favored parameter settings are resolved through analysis of the mean and "Signal-to-Noise" (SN) proportion, where factor levels that capitalize on the fitting SN proportion are ideal. There are three standard sorts of SN proportions relying upon the picked execution reaction.

- Larger the better (for making the system response as large as possible)
- Smaller the better (for making the system response as small as possible)
- Nominal the best (for reducing variability around a target)

For this work, the objective was to discover the blend of factor levels which would maximize the mechanical properties like compressive strength, split tensile strength and flexural strength. Therefore the condition that is chosen is "Larger is better". It takes into account the recognizable proof of key parameters that have the most impact on the execution qualities, with the goal that further experimentation on parameters can be performed and the parameters that have slight impact can be disregarded. In this investigation, Taguchi's graphical methodology is utilized to plot the minimal methods for each dimension of each factor and to choose the best setting for each control factor.

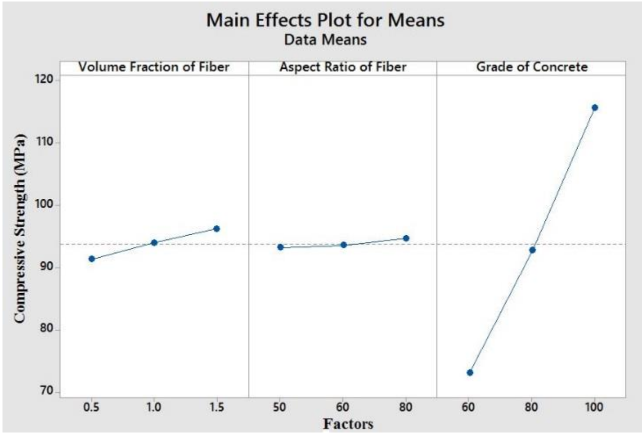

Fig. 2 Main effects plot of means for compressive strength

For this work, the objective was to discover the blend of factor levels which would maximize the mechanical properties like compressive strength, split tensile strength and flexural strength.Therefore the condition that is chosen is "Larger is better". Along lines, it takes into account the recognizable proof of key parameters that have the most impact on the execution qualities, with the goal that further experimentation on parameters can be performed and the parameters that have slight impact can be disregarded. In this investigation, Taguchi's graphical methodology is utilized to plot the minimal methods for each dimension of each factor and to choose the best setting for each control factor.

Inorder to find out an empirical relationship between the performance characteristics and the parameters, regression analysis is carried out. For this work the factors are significant at an α-level of 0.10. Based on that, the importance of various factors can be identified. The parameter R^2 describes the amount of variation observed in the result, is explained by the input factors. High R^2 value indicates that the model is able to predict the response with high accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model. If unnecessary terms are counted in the model, R^2 can be artificially high, but adjusted R^2 may get minor. The standard deviation of errors in the modelling is denoted by S and its value should be small enough.

3.1.1 Compressive strength

On analysis of the observed values of 28th day compression test corresponding to the combinations mentioned in Table 3, given by the OA, the main effects plots for means and SN ratios were obtained. Fig. 2 shows the main effects plot for mean values of compressive strength. A comparative pattern was observed for the SN proportions too.

Table 3 Compressive strength test results

Designation	Fiber Volume Fraction (V_f) %	Fiber Aspect Ratio (AR) (mm)	Grade of Concrete	Compressive Strength, (f^1_{ck}) (MPa)
$V_{0.5}A_{50}G_{60}$	0.5	50	M60	70.09
$V_{0.5}A_{60}G_{80}$	0.5	60	M80	89.83
$V_{0.5}A_{80}G_{100}$	0.5	80	M100	113.49
$V_{1.0}A_{50}G_{80}$	1.0	50	M80	91.87
$V_{1.0}A_{60}G_{100}$	1.0	60	M100	115.23
$V_{1.0}A_{80}G_{60}$	1.0	80	M60	72.98
$V_{1.5}A_{50}G_{100}$	1.5	50	M100	116.98
$V_{1.5}A_{60}G_{60}$	1.5	60	M60	74.56
$V_{1.5}A_{80}G_{80}$	1.5	80	M80	94.93

Table 4 Results of ANOVA* for compressive strength

Source	Seq SS	Contribution	Adj SS	*P*-Value
V_f	69012.10	84.26%	40.80	0.001
AR	8147.30	9.95%	7.50	0.040
f_{ck}	4736.60	5.78%	4736.60	0.000
Error	6.60	0.01%	6.60	-
R^2=99.99%		S=1.05174		

*Analysis of Variance

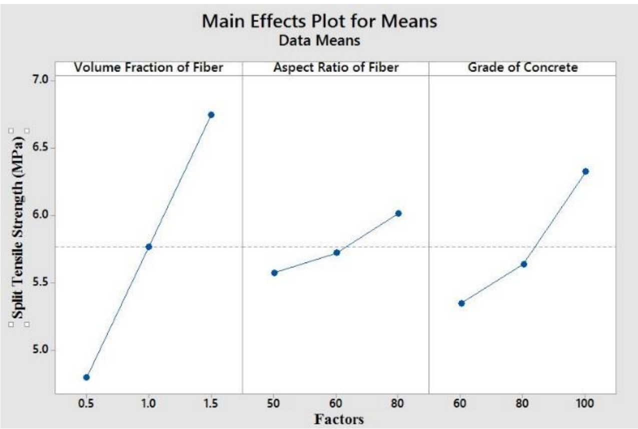

Fig. 3 Main effects plot of means for split tensile strength

Thus from the plot of means for all factors, it can be concluded that optimum value of compressive strength will be obtained for M100 grade of concrete when it is reinforced with fibres of aspect ratio 80 at a volume fraction of 1.5%.

Inorder to derive an empirical relationship between compressive strength and the concerned factors regression analysis was carried out and Table 4 shows the results of analysis of variance.

Volume fraction of fibre (V_f), grade of concrete (f_{ck}) and Aspect Ratio (AR) were found to be significant factors because their p-values were less than 0.10. Volume fraction follows grade of Concrete in its significance level whereas the Aspect Ratio (AR) of fibre was found to be comparatively a less significant factor. The regression equation for compressive strength is given by the following Eq. (1).

$$\text{Compressive Strength } (f^1_{ck}) = 4.932V_f + 0.0542AR + 1.0675f_{ck} \quad (1)$$

Table 5 Splitting tensile strength test results

Designation	Fiber volume fraction (V_f) %	Fiber aspect ratio (AR) (mm)	Grade of concrete	Splitting Tensile Strength, (f_{sp}) (MPa)
$V_{0.5}A_{50}G_{60}$	0.5	50	M60	4.00
$V_{0.5}A_{60}G_{80}$	0.5	60	M80	4.59
$V_{0.5}A_{80}G_{100}$	0.5	80	M100	5.80
$V_{1.0}A_{50}G_{80}$	1.0	50	M80	5.64
$V_{1.0}A_{60}G_{100}$	1.0	60	M100	6.09
$V_{1.0}A_{80}G_{60}$	1.0	80	M60	5.56
$V_{1.5}A_{50}G_{100}$	1.5	50	M100	7.08
$V_{1.5}A_{60}G_{60}$	1.5	60	M60	6.48
$V_{1.5}A_{80}G_{80}$	1.5	80	M80	6.68

Table 6 Results of ANOVA for split tensile strength

Source	Seq SS	Contribution	Adj SS	P-Value
V_f	286.42	93.24%	7.043	0.000
AR	16.76	5.45%	1.175	0.007
f_{ck}	3.58	1.16%	3.577	0.000
Error	0.44	0.14%	0.440	-
R^2=99.86%		S=0.271		

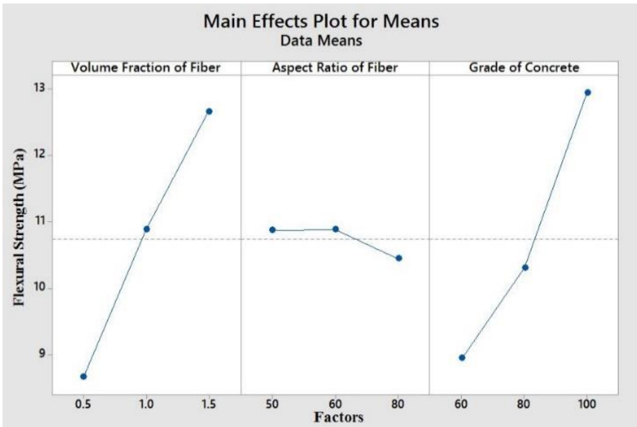

Fig. 4 Main effects plot of means for flexural strength

3.1.2 Split tensile strength

The observed values of 28th day split tensile strength test corresponding to the combinations given by the OA are given in Table 5. Fig. 3 shows the main effects plot for mean values of split tensile strength. A similar pattern was observed for the SN ratios as well.

Thus from the plot of means for all factors, it can be concluded that optimum value of split tensile strength will be obtained for M100 grade of concrete when it is reinforced with fibres of aspect ratio 80 at a volume fraction of 1.5%.

Regression analysis was carried out and Table 6 shows the results of analysis of variance for split tensile strength.

On evaluating the p-values, all the factors were found to be significant enough, though V_f and f_{ck} were found to be more significant compared to AR. The regression equation for split tensile strength is given by the following Eq. (2).

$$Split\ Tensile\ Strength\ (f_{sp}) = 2.049V_f + 0.02141AR + 0.02933f_{ck} \quad (2)$$

Table 7 Flexural strength test results

Designation	Fiber Volume Fraction (V_f) %	Fiber Aspect Ratio (AR) (mm)	Grade of Concrete	Flexural Strength, (f_{fl}) (MPa)
$V_{0.5}A_{50}G_{60}$	0.5	50	M60	6.78
$V_{0.5}A_{60}G_{80}$	0.5	60	M80	7.69
$V_{0.5}A_{80}G_{100}$	0.5	80	M100	10.85
$V_{1.0}A_{50}G_{80}$	1.0	50	M80	9.37
$V_{1.0}A_{60}G_{100}$	1.0	60	M100	13.22
$V_{1.0}A_{80}G_{60}$	1.0	80	M60	9.11
$V_{1.5}A_{50}G_{100}$	1.5	50	M100	15.40
$V_{1.5}A_{60}G_{60}$	1.5	60	M60	10.79
$V_{1.5}A_{80}G_{80}$	1.5	80	M80	10.69

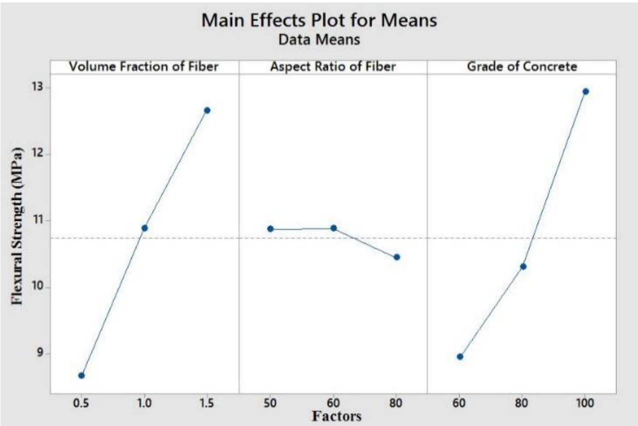

Fig. 4 Main effects plot of means for flexural strength

3.1.3 Flexural strength

The 28th day flexural strength test corresponding to the combinations given Table 7. Figs. 4 and 5 show the main effects plot for mean values and SN ratios of flexural strength.

From the plot of means for all factors, it can be concluded that optimum value of flexural strength will be obtained for M100 grade of concrete when it is reinforced with fibres of aspect ratio 60 at a volume fraction of 1.5%. Regression analysis was conducted and Table 5 shows the results of analysis of variance for flexural strength.

All factors like Volume Fraction (V_f) of fibre, Aspect Ratio of fibre (AR) and Grade of concrete (f_{ck}) are found to be significant factors because their p-values are less than 0.10. Volume fraction follows Grade of concrete in its significance level whereas the aspect ratio of fibre is the least significant factor. The regression equation for flexural strength is given by the following Eq. (3).

$$\text{Flexural Strength } f_{fl} = 3.942V_f - 0.01750AR + 0.09847f_{ck} \quad (3)$$

Table 8 Results of ANOVA for flexural strength.

Source	Seq SS	Contribution	Adj SS	P-Value
V_f	1003.10	92.30%	26.46	0.000
AR	42.30	3.89%	0.79	0.085
f_{ck}	40.31	3.71%	40.31	0.000
Error	1.11	0.01%	1.11	-
R^2=99.90%		S=0.430797		

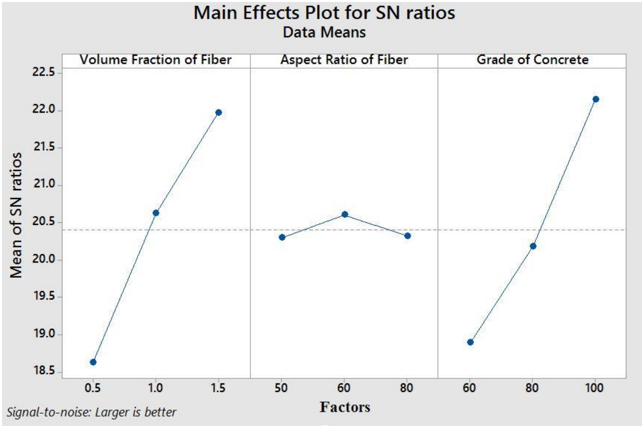

Fig. 5 Main effects plot of SN ratios for flexural strength

4. Conclusions

- Among the different factors considered, volume fraction and grade of concrete were found to be significant and aspect ratio of fibre was not found to have much influence for hooked end steel fibre.
- For compressive strength and split tensile strength the optimum strength was attained for M100 grade of concrete when reinforced with fibre of aspect ratio 80 at a volume fraction of 1.5%.
- In the case of flexural strength the optimum strength was attained when M100 grade of concrete was reinforced with fibre of aspect ratio 60 at a volume fraction of 1.5%.
- The test outcomes demonstrate that effect of steel fibre enhances extensively the strength performance of concrete, especially the splitting tensile strength and flexural strength.
- The maximum rise in the compressive strength due to the addition of steel fibres was 16% in various grades of concrete.
- The proposed empirical models derived based on the regression analysis of the test data predicted the strength properties of the steel fibre-reinforced concrete quite accurately. Thus, the proposed strength prediction models can be used for the assessment of the strength properties of SFRC based on the grade of concrete, fibre aspect ratio and fibre volume fraction.

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