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HANDLING OF UNCERTAINTIES IN ATTRIBUTING THERMOSHOCK IN FIBROUS CONCRETE STRENGTH: A PROBABILISTIC APPROACH

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Hallmark professionalism in probabilistic analysis is to quantify the uncertainties involved in construction materials subject to intrinsic randomness in its physical and mechanical properties and is now gaining popularity in civil engineering arena. As well, knowledge of behaviour of materials is continuously evolving and its statistical descriptors are also changing when more and more data collected or even data updated and hence reliability analysis has to be carried out with the updated data as a continuous process. As per the committee report ACI 544.2R, it is found that there is no attempt made for probabilistic relation between cube compressive strength and cylinder compressive strength for fiber reinforced concrete. In consequence of this report, a robust relation between cube and cylinder of experimentally conducted compressive strength was established by Monte-Carlo simulation technique for different types of fibrous concrete like steel, alkali resistant glass and polyester fibrous concrete before and after thermoshock considering various uncertainties. Nevertheless simulated probabilistic modals, characteristic modals, optimized factor of safety and allowable designed cylinder compressive strength have been developed from the drawn probability of failure graph, which exhibits robust performance in realistic Civil Engineering materials and structures.

Keywords: Fibrous concrete, Normal distribution, Probability, Quality control, Reliability, Thermoshock.

1. INTRODUCTION

Most of the Countries follow cube specimen and some countries use cylinder specimen for finding compressive strength of concrete. Generally cylinder compressive strength is crookedly taken as

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0.8 times the strength of cube compressive strength but experiments have shown that there is no unique relationship between cube and cylinder compressive strength. Similar situation is existing for fibrous concrete also. Nowadays strength of structural materials is required after fire extinguished with water leads to themroshock. Strength from cube or cylinder specimen is currently required for fibrous concrete with its different types to predict one from the other before and after thermoshock. A number of researchers have reported that experimental tests are carried out for the compressive strength of fibrous concrete either by using cube or cylinder specimen. Most of the researches depict that on increasing the volume of fibres, compressive strength is also increased up to the volume of 1 percent and beyond this volume of fibres improvement was not effective. Some studies report that effect of size and shape of concrete specimen affects the relation between cube and cylinder compressive strength. Also it was suggested by various researchers that there is loss in strength and also in other properties of concrete and steel at elevated temperature Elevated temperature has significant effect on compressive strength in the hot and cold states and there is 15% definite loss of compressive strength from its original strength at 150 degree Celsius[1-5]. It was also found that thermal cycles have adverse effect on the compressive strength of ordinary concrete.

The compressive strength of ordinary concrete for M20 and M30 decreased by about 13% at 50°C after 28 thermal cycles. The resistance to adverse effect of thermo cycles is more for fly ash concrete when compared to ordinary concrete. While referring earlier experimental studies and committee report ACI 544.2R, it is found that experiments were carried out for compressive strength of fibrous concrete either in cube or cylinder specimen and there is no attempt made to relate cube compressive strength to cylinder compressive strength for fibre reinforced concrete. Moreover finding the robust relation between them is very difficult due to uncertainties involved in concrete as well as fibres properties or may be due to insufficient data [6-11]. In consequence of the report ACI and for handling uncertainties, Monte-Carlo simulation technique is applied for assessing the strength of fibrous concrete. By using this technique, a novelty endeavour by probabilistic analysis has been attempted for relation between cube and cylinder compressive strength by considering strength as random variable which depends on complex material properties of different types of fibrous concrete like steel, alkali resistant glass and polyester fibrous concrete before and after thermoshock. Nevertheless simulated probabilistic modals, characteristic modals, reliability based optimized safety factor and allowable designed cylinder compressive strength, have been developed and such models exhibit robust performances in realistic civil engineering structures.

2. EXPERIMENTAL WORKS

The properties of ingredients are shown in table 1.The details of fibres used in this study are presented in table 2. Chemical admixture like organic based and naphthalene based Super plasticisers were used for taking care of workability of concrete while adding fibres and uniform dispersion of fibres. Details of basic ingredients required for reference mix and reproportioned mix by super plasticiser are presented in table 3. In this attempt all the experiments have been conducted keeping concrete cube size as 150mm and cylinder size as 150mm X 300 mm (slenderness ratio height/Diameter ratio as 2). After 28 days normal curing, compressive strength of fibrous concrete in cube and cylinder specimen was found. To conduct thermo shock test, all the specimens after 28 days curing were placed inside the hot air oven and were heated to a temperature of 200 degree Celsius sustained for two hours. Then the specimens were taken out from oven with some precaution. All the heated specimen were immediately quenched in water and the cooling was

Table 1. Properties of Ingredients

ITEMS	PROPERTIES
Specific gravity of cement	3.10
Specific gravity of coarse aggregates	2.65
Specific gravity of fine aggregates	2.60
Grade of sand	zone II
Water absorption of coarse aggregates	1.1%
Water absorption of fine aggregates	2.51%

Table 2. Details of fibres used

PROPERTIES	CORRUGATED STEEL FIBRE	AR GLASS FIBRE	POLYESTER FIBRE
Specific gravity	7.86	2.6	1.334
Number of Fibres/kg	22,820 Nos	212 Million	Millions
cut length ‘mm’	36	12	12
Diameter ‘mm’	0.45	0.015	0.045
Aspect ratio	80:1	857:1	267 : 1

Table 3. Mix Details

MIX	PROPORTIONS	MIX	PROPORTIONS
R	1: 1.60: 2.90: 0.49	R	1: 1.60: 2.90: 0.49
OSP	1: 1.80: 3.50: 0.49 +0.8% SP (Organic Based)	NSP	1: 1.80: 3.50: 0.49 +0.8% SP (Naphthalene Based)
OS1…OS5	ASP+(0.2%,0.4%,0.6%,0.8%,1%)SF	NS1…NS5	BSP+(0.2%,0.4%,0.6%,0.8%,1%)SF
OG1…OG5	ASP+(0.2%,0.4%,0.6%,0.8%,1%)ARGF	NG1...NG5	BSP++(0.2%,0.4%,0.6%,0.8%,1%)ARGF
OP1…OP5	ASP+(0.2%,0.4%,0.6%,0.8%,1%)PF	NP1…NP5	BSP+(0.2%,0.4%,0.6%,0.8%,1%)PF

done for about half an hour. The specimens were then tested under compression testing machine. All the experimental test results in a shortened form are presented in table 4.

Table 4. Ratio between Cube and Cylinder Compressive strength of fibrous concrete

NO of MIXES	MIX	CYLINDER COMP STRENGTH by EXP CY MPa	CUBE COMP STRENGTH by EXP C_X MPa	RATIO= CY/ C_X	PREDICTED CYLINDER COMP STRENGTH by MODEL-3.7
1	R	19.62	27.11	0.723	18.43
2	OSP	24.32	38.16	0.637	25.95
3	OS1	24.89	38.26	0.651	26.02
4	OS2	24.95	38.34	0.651	26.07
5	OS3	25.65	39.55	0.649	26.89
9	OG2	18.71	28.74	0.651	19.54
10	OG3	18.73	28.77	0.651	19.56
11	OG4	21.20	32.30	0.656	21.96
16	OP4	21.41	32.88	0.651	22.36
17	OP5	22.45	34.51	0.651	23.47
94	T-NG5	31.24	46.43	0.673	31.63
95	T-NP1	25.65	38.16	0.672	26.00
96	T-NP2	25.75	38.48	0.669	26.22
97	T-NP3	28.05	38.04	0.737	25.92
98	T-NP4	28.52	38.21	0.746	26.04
99	T-NP5	27.33	38.55	0.709	26.27

3. PROBABILITY ANALYSIS BY MONTE CARLO SIMULATION

In this experimental work, compressive strength of fibrous concrete is treated as a random variable in which there are several uncertainties which contributes total variation in strength due to variations in the quality of concrete ingredients, fibres properties, weighing, mixing, curing and testing procedures. As well, knowledge of behaviour of materials is continuously evolving and its statistical descriptors are also changing when more and more data collected or data updated. Nevertheless getting all the field data for different ingredients of fibrous concrete is quite impossible and expensive equally. To resort such situation, simulation techniques are the only powerful tool for analyzing response of randomly driven system which is typically governed by different equation. This is driven by ensemble of inputs which are compatible with prescribed probabilistic model and characterizing the model by suitable distribution like normal or lognormal distribution. Later simulating ensemble of random numbers which are compatible with given power density function of the system, response quantities of interest is processed statistically to estimate parameters or descriptors like mean, variance, skewness and kurtosis by the method of moment. Consequently probabilistic analysis was made in the following two phases for finding relation R* between cube and cylinder compressive strength of different fibrous concrete.

In phase-I, by referring table 4, reliability analysis was carried out for analysing experimentally conducted cube and cylinder compressive strength (Cx and CY) of different fibrous concrete by considering various material properties involved in it for establishing the respective probabilistic strength along with its coefficient of variation and probability density function for its type of distribution. Statistical parameters are presented in table 5 & 6. While looking at the value of the coefficient of variation COV, all the values of COV are found within the allowable value 15% and it conforms that all the test results are in good quality control.

Table. 5. Statistical Properties of Random variables of fibrous concrete cube

METHOD of TEST	TYPE of FIBRE	Log (mean) ~	Cov %	TYPE of DISTRIBUTION
Before Thermo shock	Steel Fibre	3.770	8.480	LN
	AR Glass Fibre	3.770	9.200	LN
	Polyester Fibre	3.730	5.150	LN
After Thermo shock	Steel Fibre	3.688	9.150	LN
	AR glass Fibre	3.695	10.500	LN
	Polyester Fibre	3.611	3.640	LN

Table. 6. Statistical Properties of Random variables of fibrous concrete cylinder

METHOD of TEST	TYPE of FIBRE	Log (mean)~	COV %	TYPE of DISTRIBUTION
Before Thermo shock	Steel Fibre	3.432	10.800	LN
	AR Glass Fibre	3.470	12.300	LN
	Polyester Fibre	3.397	8.200	LN
After Thermo shock	Steel Fibre	3.237	12.200	LN
	AR Glass Fibre	3.275	13.300	LN
	Polyester Fibre	3.205	9.300	LN

In phase-II, using the data from phase–I Monte-Carlo simulation technique was used to simulate the complete random behaviour of relation between cube and cylinder compressive strength of different types of individual fibrous concrete before and after thermoshock $R^*_{i=1to3}, R^*_{i=4to6}$ espectively as shown in table 7 and probabilistic models are obtained for different fibrous concrete.

This technique offers solutions which are compatible with experimental data but simulation processes requires a very large number of random numbers for analyzing uncertainty propagation. From simulation, probability distribution, cumulative distribution of R^* for various types of fibrous concrete and lognormal probability paper plot were obtained. A computer programme was developed to handle sampling and distribution of random variables, and its simulation is explained briefly here.

1. Generating ten thousand random cube compressive strength with defined coefficient of variation individually for steel, AR glass and polyester fibrous concrete before and after thermoshock from the table 5.
2. Generating ten thousand random cylinder compressive strength with defined coefficient of variation individually for each fibrous concrete as step 1 from the table 6.
3. Normalization between 0 to 1 was made for relation R^* between cube and cylinder compressing strength of fibrous concrete. Normalized ratio R^* was used for computation of probabilistic models for each fibrous concrete before and after thermoshock.
4. Determination of statistical properties like mean, COV, skewness and kurtosis for different types of fibrous concrete before and after thermoshock of the relation R^* generated.
5. In the present study, Relation R^* is considered satisfactory if mean, COV and other statistical parameters are converged after N number of cycles by repeating the steps 1 to 4 to get uniform reliability index and probability of failures.

Reliability Index $\beta = \frac{\mu}{\sigma}$ where μ, σ are mean and standard deviation.

Probability of failure $P_f = \Phi(-\beta) = 1.0 - \Phi(\beta)$

where Φ is Cumulative distributed function (CDF).

It means while β is large, the probability of failure will be very small.

Factor of safety is calculated by ratio between relation obtained from simulation and allowable ratio, $\delta = \frac{R^*}{R_a^x}$, and allowable ratio $R_a^* = R^*(1+u\,\delta x)$ where u is standard normal variate and δx is coefficient of variation COV.

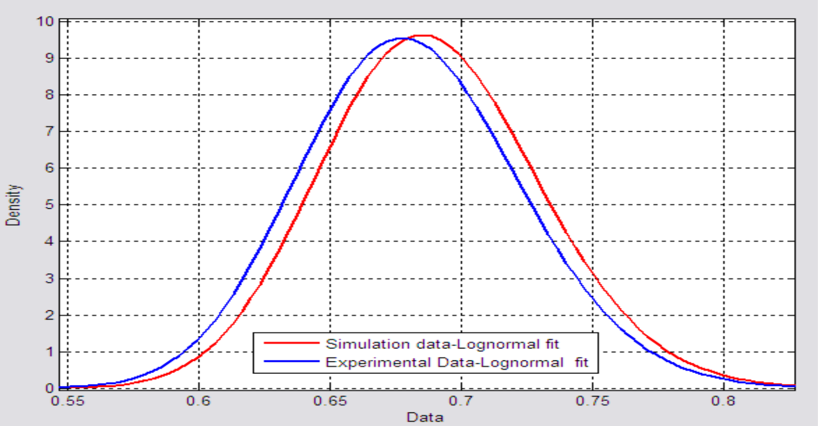

Fig. 1. Frequency distribution of R_7^* of Experimental and Simulated data

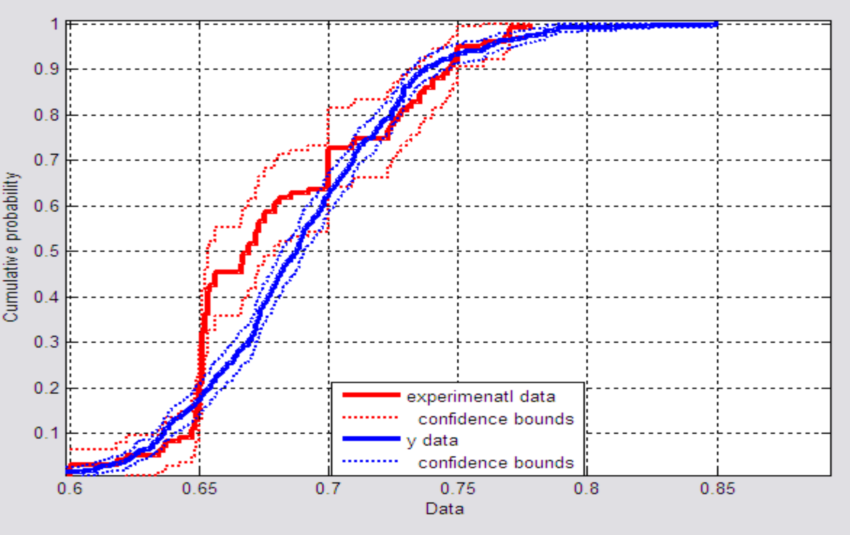

Fig. 2. Cumulative distribution of R_7^* for experimental and Simulated data

Fig. 3. Log Normal Probability Paper Plot for R_7^*

All the probabilistic results are presented in table 7. Mean value obtained from experimental values are found to be very close to the results obtained from simulation technique. The coefficient of variation of different fibrous concrete are found as higher values than the values obtained before thermoshock. It was expected that coefficient of variation would fall out of the allowable value 15% after thermoshock. But invariably all the coefficients of variations of different types of fibres are found to be within the allowable value of 15%.

Heretofore probabilistic analysis was made individually for different types of fibrous concrete which consists of different densities. When sufficient data is not available for particular type of fiber in such situation a generalized probabilistic modal is to be arrived irrespective of type of fibers used. In this analysis, 99 ratios were considered from the mixes R to T-NP5 as in table 4. From the simulation, generalised relation for fibrous concrete R_7^* was obtained. In general all the fibrous concrete have reliability more than 3.9 and a very low probability of failure which indicates all ratios $R^*_{i=3.1to3.6}$ as well $R^*_{3.8}$ can be considered to be more reliable from safety point of view.

Novel Simulated Probabilistic Models before thermoshock:

(3.1) For Steel fibre CY = 0.7207 X Cube compressive Strength (Cx)

(3.2) For AR glass fibre CY = 0.7213 X Cube compressive Strength (Cx)

(3.3) For Polyester fibre CY = 0.7199 X Cube compressive Strength (Cx)

Novel Simulated Probabilistic Models after thermoshock:

(3.4) For Steel fibre CY = 0.6456 X Cube compressive Strength (Cx)

(3.5) For AR glass fibre CY = 0.6687 X Cube compressive Strength (Cx)

(3.6) For Polyester fibre CY = 0.6704 X Cube compressive Strength (Cx)

Novel Simulated Probabilistic generalized Model for any type of fiber:

(3.7) CY = 0.69 X Cube compressive Strength (Cx)

Novel Simulated Probabilistic generalized characteristic Model for any type of fiber:

(3.8) CY = 0.63 X Cube compressive Strength (Cx)

4. INFERRENCES FROM THE PROBABILITY FAILURE GRAPH

‘Probability failure graph’ is drawn between factor of safety and probability failure. Failure graphs are shown in figures 4, 5 and 6 in both linear and logarithmic scales. It is seen that highly non-linear variation of failure probabilities were obtained. While decreasing the failure probability, factor of safety increases vice-versa. In the figure 4, variations for steel and AR glass fibrous concrete coincide while polyester fibrous concrete deviated from the above two. From the figure 4, reducing safety factor from 2 to 1.85 does not affect failure probability critically. But reducing the safety factor from 1.85 to 1.45 causes serious effect on probability of failure and this range is considered as dangerous zone. It is also seen that on further increasing the safety factor from 2 to 3 will decrease the allowable ratio $\mathbf{R_A}^*$ which in turn decrease the design cylinder strength leads larger section and increase the cost of the section with no important increase in reliability. Similarly in polyester fibrous concrete, there is no change in failure probability on reducing factor of safety 2 to 1.4. It is disastrous while further reducing safety factor. Hence from the figure 4, optimized factor of safety is to be evaluated for the best designing of structures. It is inferred that optimized safety factor for steel, AR glass and polyester fibrous concrete is found to be 1.74, 1.72 and 1.56 before thermoshock respectively. Figure 5 shows the non-linear variation between safety factor and failure of probabilities after thermoshock and optimized safety factor for steel, AR glass and polyester fibrous concrete is 1.9, 2.12 and 1.45 after thermoshock respectively. Similarly figure 6 shows the non-linear variation between safety factor and failure of probability for any type of fibrous concrete. Safety factor for fibrous concrete is 1.66. It shows how probability analysis guides for selection of factor of safety.

Table 7. Probabilistic Values of Ratio between cube and cylinder fibrous concretes

Method of Test	Type of Fibre	Experimental Value of Ratio between cube and cylinder fibrous concretes	Probabilistic Values of Ratio between cube and cylinder fibrous concretes										
			Simulated Probabilistic Ratio R^*	COV %	Skew ness	Kurtosis	Kolmogorov Smirnov Test (KS)		Chi Squared Test		Type of Distribution	Reliability Index	Probability of Failure
							K~S Test Value - Data	K~S Test allowable Value*	Chi-squared Value - Data	Chi-squared allowable Value*			
Befor Ther mo shock $R^*_{3.i=1to3}$	Steel Fibre	0.710	0.720	13.80	0.44	3.57	0.009	0.019	15.8	21.026	LN	5.76	4.56E-09
	AR Glass Fibre	0.737	0.721	13.6	0.37	3.19	0.005		8.28		LN	4.88	5.34E-07
	Poly ester Fibre	0.717	0.719	9.70	0.33	3.10	0.010		8.34		LN	7.44	4.75E-14
After Ther mo shock $R^*_{3i=4to6}$	Steel Fibre	0.637	0.645	15.2	0.44	3.33	0.01		20.3		LN	4.22	1.17E-05
	AR Glass Fibre	0.658	0.668	17.1	0.46	3.23	0.009		16.3		LN	3.93	4.22E-05
	Poly ester Fibre	0.668	0.670	10.0	0.29	3.16	0.007		5.87		LN	6.69	1.1E-11
$R^*_{3.7}$	Any Fibre (General case)	0.690	0.690	12.9	0.39	3.39	0.008		7.56		LN	5.32	1.67E-08

5. DISCUSSION OF THE TEST RESULTS

Average strength of specimens of all the test results are shown table 4. The individual variation of fibrous concrete strength was found as within the range of ± 15 percent of the average. The mixes OSP and NSP were carried out to find out improvement in strength of fibrous concrete over OSP, NSP and reference mix. From the results of extensive experimental works conducted before and after thermoshock, it was observed that cube or cylinder compressive strength of concrete with steel and alkali resistant glass fibres have higher strength than polyester fibres. This may be due to the fact specific gravity of these two fibres are higher than concrete. Based on the general observation

Table 8. Probabilistic, Characteristic and Allowable ratio for evaluating allowable designed Cylinder Compressive Strength

Method of Test	Type of Fibre	Simulated probabilistic Ratio R^*_i= CY/ C_X	Characteristic Ratio = CY/ C_X	Factor of Safety FOS	Allowable designed Cylinder comp Strength N/mm^2 $R_A^*=R^*_{3.i}$/ Fos
Before Thermo shock $R^*_{3.i=1to3}$	Steel Fibre	0.7200	0.6708	1.74	0.4071
	AR Glass Fibre	0.7213	0.6873	1.72	0.4275
	Polyester Fibre	0.7190	0.6647	1.56	0.4585
After Thermo shock $R^*_{3i=4to6}$	Steel Fibre	0.6456	0.5985	1.90	0.3381
	AR Glass Fibre	0.6687	0.6052	2.12	0.3102
	Polyester Fibre	0.6704	0.5834	1.45	0.4615
$R^*_{3.7}$	Any Fibre (General case)	0.690	0.6333	1.66	0.4149

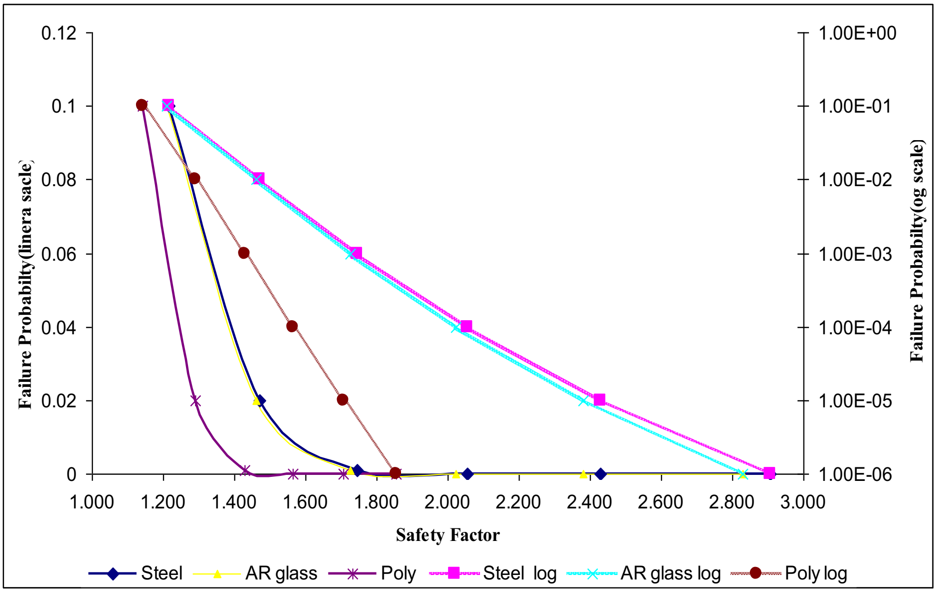

Fig. 4. Safety Factor vs Failure probability of fibrous concrete before thermoshock

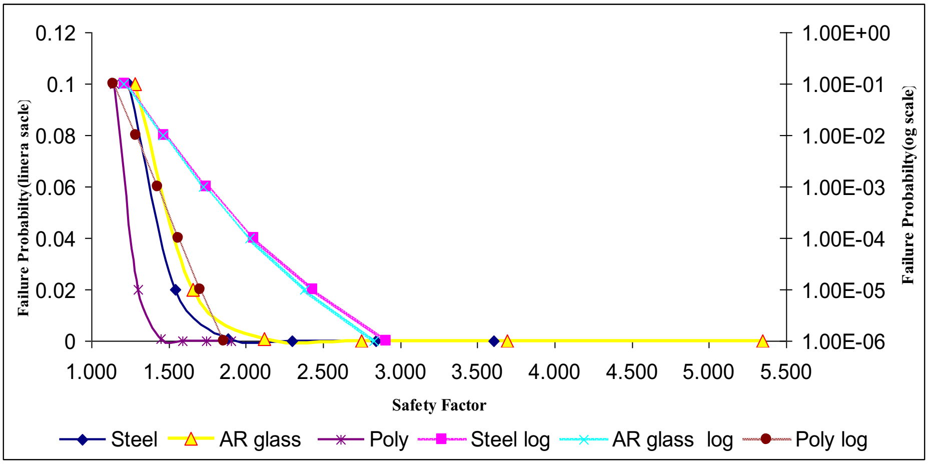

Fig. 5. Safety Factor vs Failure Probability of fibrous concrete after thermo shock

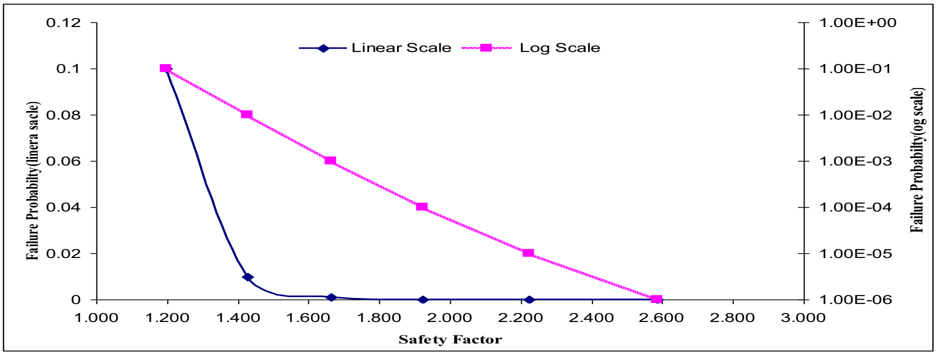

Fig. 6. Safety Factor vs Failure Probability of fibrous concrete before and after thermoshock

cube and cylinder compressive strength of fibrous concrete increased with the increase of fiber content from 0.2% to 1.0 %. It was also found that experimental results for cylinder compressive strength was lower than cube compressive strength as in table 4. It was expected that the specimens would lose its mass due to dehydration during thermoshock and consequently the unit weight would therefore decrease. But the unit weight of the different fibrous concretes were not affected by the thermal shock. There are some difference of opinion as regards the increase of compressive strength of concrete at the temperature ranges between 200 to 400 degree Celsius and added that no such improvement in strength of concrete on heating. While observing the experimental results as in table 4, it was found that almost compressive strength of concrete with cube and cylinder specimen decreased to nearly 10 percent to 15 percent of unheated specimen at each mixes under thermoshock test at 200 degree Celsius. It was found that mixes with AR Glass fibre under naphthalene based superplasticiser found strength after thermoshock is 0.97 times unheated specimen which concludes concrete mix AR Glass fibre is not much affected by thermoshock.

6. VALIDATION

It is quite indispensable to validate all types of modals developed here. From table 9, it has been found that simulated probabilistic Strength almost closely matches with earlier reported results.

Table.9. Comparative Analysis of probabilistic strength, characteristic strength and designed strength with reported Experimental strength

Sl. No	Reported Experimental Strength N/mm^2			Simulated Probabilistic Strength N/mm^2		Characteristic Strength N/mm^2	Allowable designed Cylinder comp Strength N/mm^2 R_a=R* / Fos	Allowable designed Cylinder comp Strength N/mm^2 =0.67* characteristic strength
	Cube comp strength	Cylinder comp strength CY	Ratio = CY/ Cx	Cylinder compressive strength by model-3.1	Cylinder compressive strength by model-3.7	Cylinder compressive strength by model-3.8		
Yaghoub Mohammadi et al [2008]	69.8	51.17	0.732	50.32	48.19	44.20	28.97	29.61
Ganesan et al [2006]	66.4	47.92	0.720	47.90	45.86	42.10	27.57	28.20
	76.3	51.35	0.672	55.05	52.71	48.35	31.69	32.39
NP5 7days curing	39.4	25.64	0.65	28.40	27.25	26.22	18.08	17.60
NP5 28days curing	45.0	32.82	0.728	32.46	31.15	28.55	20.67	19.12

7.CONCLUSIONS

In consequence of this report, a novelty endeavour by probabilistic analysis has been made by Monte-Carlo reliability analysis as an attempt for analyzing robust relation between cube and cylinder compressive strength of different types of fibrous concrete and some major conclusions were drawn from this research.

I. Incredibly before and after thermoshock, cube and cylinder compressive strength of fibrous concrete was not getting affected and found to be increased invariably with the increase of volume of fibres.
II. Developed probabilistic models for relation between cube and cylinder compressive strength of different types of fibrous concrete like steel, alkali resistant glass and polyester fibrous concrete before and after thermoshock will be useful for obtaining the cylinder compressive strength of fibrous concrete.
III. Nevertheless characteristic models for relation are also developed for predicting the characteristic cylinder compressive strength from cube compressive strength of fibrous concrete. It will be ideally useful for design of reinforced concrete structures also optimized factor of safety and allowable designed cylinder compressive strength was also developed and such models exhibit robust performance in realistic civil engineering structures.

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POSTĘPOWANIE W PRZYPADKU NIEPEWNOŚCI W PRZYPISYWANIU SZOKU TERMICZNEGO W WYTRZYMAŁOŚCI BETONU WŁÓKNISTEGO: PODEJŚCIE PROBABILISTYCZNE

Słowa kluczowe: Beton włóknisty, Rozkład normalny, Prawdopodobieństwo, Kontrola jakości, Niezawodność, Szok termiczny.

STRESZCZENIE:

Większość krajów korzysta z sześciennych próbek, a kilka innych używa próbek cylindrycznych w celu ustalenia wytrzymałości na ściskanie betonu. Na ogół wytrzymałość na ściskanie cylindra jest nieuczciwie ustalana jako 0,8 wytrzymałości sześcianu na ściskanie, ale doświadczenia wykazały, że nie ma unikalnego związku między wytrzymałością sześcianu a wytrzymałością cylindra. Podobna sytuacja występuje również w przypadku betonu włóknistego. Zgodnie z raportem komisji Amerykańskiego Instytutu Betonu ACI 544.2R okazuje się, że nie podjęto próby wykazania probabilistycznego związku między wytrzymałością sześcianu na ściskanie a wytrzymałością cylindra w przypadku żelbetu. Obecnie wytrzymałość materiałów konstrukcyjnych jest wymagana, ponieważ gaszenie pożaru wodą prowadzi do szoku termicznego. Przewidywanie wytrzymałości próbki sześciennej lub cylindrycznej przed i po szoku termicznym jest wymagane w przypadku betonu włóknistego różnych typów.

W niniejszej pracy eksperymentalnej wytrzymałość na ściskanie betonu włóknistego jest traktowana jako zmienna losowa, w której istnieje kilka niepewności, co ma wpływ na łączną zmianę wytrzymałości w wyniku zmian jakości składników betonu, właściwości włókien, ważenia, mieszania, utwardzania i procedur badawczych. Również wiedza na temat zachowań materiałów stale się rozwija, a ich statystyczne deskryptory również się zmieniają wraz z zbieraniem coraz większej ilości danych oraz ich aktualizacją. Niemiej jednak uzbieranie wszystkich danych pola dla różnych składników betonu włóknistego jest zarówno niemożliwe, jak i drogie. Taki stan rzeczy powoduje trudną sytuację w przypadku ustalania zdecydowanego związku między nimi z powodu niepewności związanych z betonem, a także właściwości włókien lub mogą być spowodowane niewystarczającą ilością danych. Techniki symulacyjne są jedynym skutecznym narzędziem do analizowania odpowiedzi losowo napędzanego układu w celu rozwiązania takiej sytuacji, co jest zazwyczaj obliczane przez różne równania. Jest to powodowane zbiorem danych wejściowych, które są kompatybilne z wcześniej opisanym modelem probabilistycznym oraz charakteryzujących ten model przez odpowiedni rozkład, taki jak rozkład normalny lub logarytmiczno-normalny. Później, symulując zestaw losowych liczb, które są kompatybilne z podaną funkcją gęstości mocy układu, udział ilościowy odpowiedzi jest przetwarzany statystycznie w celu oszacowania parametrów lub deskryptorów, takich jak średnia, odchylenia, skośność i kurtoza. W konsekwencji, przeprowadzono analizę probabilistyczną w następujących dwóch fazach ustalania związku R* między wytrzymałością na ściskanie sześcianu i cylindra różnych betonów włóknistych.

W fazie-I, przeprowadzono analizę niezawodności w celu przeanalizowania doświadczalnego wytrzymałości na ściskanie sześcianu i cylindra różnych betonów włóknistych poprzez wzięcie pod uwagę różnych właściwości materiałowych związanych z nim w celu ustalenia odpowiedniej wytrzymałości probabilistycznej wraz z współczynnikiem funkcji zmienności i gęstości prawdopodobieństwa dla swojego typu rozkładu. Obserwując wartość

współczynnika zmienności (COV), wszystkie wartości COV mieszczą się w dopuszczalnej wartości 15% i można stwierdzić, że wszystkie wyniki badań spełniają wymagania kontroli jakości.

W fazie II, wykorzystano dane z techniki symulacji Monte-Carlo z fazy I w celu symulacji losowego zachowania związku między wytrzymałością na ściskanie sześcianu a wytrzymałością cylindra biorąc pod uwagę wytrzymałość jako losową zmienną zależną od złożonych właściwości materiałowych różnych typów betonu włóknistego, takich jak beton włóknisty z włóknami ze stali, szkła odpornego na działanie alkaliów i poliestru przed i po szoku termicznym $R^{*}_{i=1to\,3}\,.\,R^{*}_{i=4to6}$ Niemniej jednak symulowane modele probabilistyczne, charakterystyczne, zoptymalizowany czynnik bezpieczeństwa oparty na niezawodności i dopuszczalna wytrzymałość na ściskanie cylindra również zostały opracowane.

W tym znaczeniu, niektóre główne wnioski zostały wyciągnięte z tych badań.

I. Co niezwykłe, przed i po szoku termicznym, wytrzymałość na ściskanie sześcianu i cylindra nie zmieniała się i okazało się, że rosła niezmiennie wraz ze wzrostem wielkości włókien.

II. Opracowane modele probabilistyczne dla związku między wytrzymałością na ściskanie sześcianu i cylindra różnych rodzajów betonu włóknistego, takich jak beton włóknisty z włóknami ze stali, szkła odpornego na alkalia i poliestru, przed i po szoku termicznym, będą przydatne do uzyskania wytrzymałości na ściskanie cylindra z betonu włóknistego.

III. Niemniej jednak charakterystyczne modele związku są również opracowane do odróżniania charakterystycznej wytrzymałości na ściskanie cylindra od wytrzymałości sześcianu z betonu włóknistego. Będą one idealne do projektowania konstrukcji żelbetowych. Opracowano również zoptymalizowany czynnik bezpieczeństwa i dopuszczalną zaprojektowaną wytrzymałość na ściskanie cylindra, i takie modele wykazują solidną wydajność w przypadku realistycznych obiektów inżynieryjnych.