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Strength and Permeability Characteristics of Steel Fibre Reinforced Concrete

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Abstract**—**The results reported in this paper are the part of an extensive laboratory investigation undertaken to study the effects of fibre parameters on the permeability and strength characteristics of steel fibre reinforced concrete (SFRC). The effect of varying fibre content and curing age on the water permeability, compressive and split tensile strengths of SFRC was investigated using straight steel fibres having an aspect ratio of 65. Samples containing three different weight fractions of 1.0%, 2.0% and 4.0% were cast and tested for permeability and strength after 7, 14, 28 and 60 days of curing. Plain concrete samples were also cast and tested for reference purposes.

Permeability was observed to decrease significantly with the addition of steel fibres and continued to decrease with increasing fibre content and increasing curing age. An exponential relationship was observed between permeability and compressive and split tensile strengths for SFRC as well as PCC. To evaluate the effect of fibre content on the permeability and strength characteristics, the Analysis of Variance (ANOVA) statistical method was used. An α level (probability of error) of 0.05 was used for ANOVA test. Regression analysis was carried out to develop relationship between permeability, compressive strength and curing age.

Keywords**—**Permeability, grade of concrete, fibre shape, fibre content, curing age, steady state, Darcy's law, method of penetration.

I. Introduction

ADDITION of steel in form of short and discrete fibres to plain concrete has been found to enhance its engineering properties like compressive, tensile, flexural and shear strengths and also its toughness and ductility [1]-[5]. The durability of concrete has always got the attention of researchers as it is very important that the structures should be able to perform the functions, for which these have been designed, throughout their life span. Even though durability is important, this aspect of SFRC has not been thoroughly investigated and only a few references are available on its behavior to aggressive environment [6]-[8]. Of the many factors affecting the durability of plain as well as steel fibre reinforced concrete permeability is the key factor. A lot of research has been carried out on the effect of various factors on the permeability of plain concrete [9]-[13] but the permeability aspect of fibrous concrete in general and steel fibre reinforced concrete in particular have not been investigated and very limited literature is available on this key property of SFRC [14]-[18].

The results of an investigation carried out to study the effects of fibre content on the compressive and split tensile strengths and water permeability of SFRC are presented in this chapter. Cube samples of concrete were cast incorporating 1.0%, 2.0% and 4.0% weight fractions of straight fibres and tested after 7, 14, 28 and 60 days of curing to achieve these objectives. The concrete grade was kept the same. Companion samples were also cast for plain concretes of the three grades for comparison. An attempt was made to develop relationship between strength and permeability characteristics.

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II. Materials Used

The materials used in this study were ordinary Portland cement of 43 grade having initial and final setting times of 87 and 373 minutes, respectively and the 3-days and 7-days compressive strengths of 23 Mpa and 34 Mpa respectively. The fine and coarse aggregates had fineness moduli of 3.08 and 6.65, respectively. The cement and aggregates were tested to fulfill the requirements of IS: 8112 [19] and IS: 383 [20], respectively. The maximum size of the aggregate was limited to 10mm, thereby facilitating the use of 100 mm size cubes and better distribution of fibres. Straight and crimped steel fibres having an aspect ratio of 65 and a length of 36.4mm, cut in the laboratory were used in this study.

III. Experimental Programme

A concrete mix having mix proportions as shown in Table I was used throughout this study. The mix designed as per the design procedure outlined in SP: 23 [21]. While designing the mix the sand content was kept as 50% of the total aggregates by weight. This was further done to achieve uniform distribution of fibres. The concrete constituents were mixed in the dry state. The fibres were also added in the dry state through sieving. Water was added in the end. Cubes of 100 mm size were cast for all mixes. The casting of samples was done in well oiled steel moulds. The samples were compacted on a vibrating table, demoulded after one day and water cured till the date of testing. The cube specimens were subjected to water permeability test after 7, 14, 28 and 60 days of water curing.

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TABLE I
CONCRETE MIX PROPORTIONS

Mix No	Cement Content: kg/m^3	Fine Aggregate: kg/m^3	Coarse Aggregate: kg/m^3	Fibre Content %	Water: kg/m^3	Compressive Strength Mpa
M1	364.45	853.64	862.4	0	196.8	31.50

IV. Testing of Samples for Measurement of Co-efficient of Permeability

The determination of water permeability of samples was done as per the procedure laid out in IS: 3065- 1965 [22]. The permeability tester used was a 3-cell tester comprising of three test cells, a pressure chamber and an air compressor supplying water to the test samples under required pressure. The test cell made from a metal cylinder can safely with stand a pressure of 2.0 MPa. The inner dimension of the cell was 115mm where as the size of the specimen was kept as 100mm. The sealing compound used to fill the annular space between the specimen and the cell comprised of two parts of resin and one part of wax by volume. The resin was applied smoking hot. All surfaces of the sample except the top one through which water was to be supplied were painted with the hot sealing compound. The specimen was placed centrally in the cell. Short pieces of jute soaked in molten sealing compound were tightly packed in the sides of lower portion of the annular space. The remaining portion of the space was then filled with the compound which was constantly stirred and compacted so as to release any entrapped air.

The testing of seal for any leakage was done after allowing the sealing compound to harden for 24 hours. The top surface of the sealed specimen was covered with a layer of water. The hose pipe from the air compressor was connected to the stem of the sheet metal funnel and air was admitted at a pressure of about 0.4 – 0.5 MPa into the specimen. A faulty seal would be indicated by the presence of air bubbles coming out of top surface. The sealing would ensure a Uni.-directional flow from top to bottom through the specimen. The water was allowed to flow through the specimens at a pressure of 0.8 MPa – 1.0 MPa. The test was carried out at the room temperature i.e. 25+/- 10°C. The co-efficient of permeability was calculated by using Darcy's formula, which is applicable at steady state flow conditions. The steady state flow condition was deemed to be achieved when the discharge through the sample became constant for 24 hours. The discharge readings through the samples were taken at regular intervals of 4-6 hours. The observation of outflow from the specimen was likely to be affected by evaporation. Precautions were taken to eliminate the evaporation losses. After the achievement of steady state flow, a graduated glass tube was connected to the stem of the funnel. The connection was made in such a way so as to eliminate any evaporation losses. The discharge measurements were taken at every 4 –6 hour interval for about 48 hours. An average of all the discharge readings was taken to determine the co-efficient of permeability. The steady state conditions were obtained in most of the cases in 7-10 days. The co-efficient of permeability of a test specimen was calculated from the rate of inflow by using the following equation which is based on Darcy's Law,

$$K = Q /(A * H/L * T)$$

where

K = Co- efficient of permeability in m/sec;

Q = Quantity of water in cubic metres percolating over the entire period of test;

A = Area of the surface of the specimen exposed to water flow;

H = Water head causing flow, measured in metres;

L = Dimension of the specimen in the direction of flow, in metres.

T = Time in seconds over which discharge is measured

The Darcy's Law can be applied only for steady state flows. It has been observed by many investigators that steady state flow conditions could not be achieved in concrete mixes having low permeability even after subjecting the test samples to pressures as high as 3.5 Mpa for a test period extending up to several weeks. In such cases, some investigators have used the Depth of Penetration to determine the water permeability of concrete [9]-[13]. In the present study also steady state conditions could not be achieved in some cases even after a testing period of 15 days. The sample, after removal from the test cell, was split open and the water penetration depth was measured at different places and an average of all the values was taken . The co-efficient of permeability was calculated by using the following formula :

$$K = D^2 \upsilon \ /(2 * T*H)$$

where,

K= co-efficient of permeability, m/sec;

D = Depth of penetration, metres;

T = Time taken to penetrate the depth D, sec;

H = Pressure head, metres;

υ = Porosity of concrete in fraction.

Procedure outlined in ASTM C 642- 1990 [23] was used to determine the porosity of concrete.

V. Results, Analysis and Discussions

The mean co-efficient of permeability, the compressive and split tensile strength of concrete mixes incorporating 0.0%, 1.0%, 2.0% and 4.0% weight fractions of straight fibres after 7, 14 , 28 and 60 days of curing have been listed in Table II. The values tabulated are the mean values for three samples in most of the cases. Some of the observations were observed to be much different from the others and thus were considered for rejection as outliers. The basis for rejection as given by *Kennedy and Neville* [24] are that, "the samples containing the extreme observation did not come from the population. Chauvenet's Criterion was applied to all data points and the points meeting the criterion were identified and excluded from further analysis. In such cases, the co-efficient of permeability values given in Table II are average of two samples. These results have also been graphically presented in Figs. 1-3.

VI. Effect of Age

The results presented in Table II and Figs. 1-3 clearly indicate the effect of age on permeability, compressive and split tensile strengths of concrete. The curves clearly show that the coefficient of permeability decreases and strength parameters increase with curing age. The decrease in permeability and increase in strength with age is due to the progress of hydration, the pores in concrete get filled up by products of hydration resulting in less capillary voids.

VII. Effect of Fibre Content

The variation of permeability with age for different fibre contents is shown in Fig. 1. The figure shows a set of four curves, each curve for each weight fraction of the fibre considered in this study. From this figure it is evident that the addition of steel fibres causes significant reduction in the permeability of concrete and permeability continues to decrease with increasing fibre contents. The decrease in 28 days coefficient of permeability of mix with 1.0%, 2.0% and 4.0% weight fraction of straight fibres as compared to plain concrete samples was 73.96%, 81.82% and 65.99 % respectively. Similar decreases were observed for mixes tested after curing periods of 7, 14 and 60 days. The decrease in permeability with the addition of steel fibres is mainly attributed to the reduction in shrinkage and creep cracks by about 50% with the addition of steel fibres [25]. The other possible reason may be due to breaking of the continuity of pores and inter-connectivity of porous channels by the impermeable steel fibres.

The relationship between compressive strength and coefficient of permeability of SFRC is shown in Fig. 2. The relationship is exponential in nature. It is clear from the figure that the coefficient of permeability decreases with increasing fibre content whereas the compressive strength indicates a significant increase with increase in fibre content. The increase in compressive strength at lower weight fraction of fibres is not very significant but is appreciable at 4.0% weight fraction of fibres.

Fig. 3 shows the relationship between coefficient of permeability and split tensile strength of SFRC. The relationship is exponential in nature. It is clear from the figure that the coefficient of permeability decreases with increasing fibre content whereas the split tensile strength indicates a significant increase with increase in fibre content. The increase in split tensile strength at lower weight fraction of fibres is not very significant but is appreciable at 2.0 % and 4.0% weight fraction of fibres.

VIII. Treatment of Results

The effect of the fibre content on the co-efficient of permeability of fibre reinforced concrete was aided by using the analysis of variance (ANOVA) statistical method. The ANOVA method was used to determine whether the effect of fibre content on permeability and compressive and split tensile strengths was statistically significant. The ANOVA is a numerical technique which is based on the fact that if a system of testing involves a number of independent factors each of which contributes to the scatter of results and hence to variance, then the variance for the whole system is equal to the sum of the component variances of the individual factors. If a testing program involves 'p' different types of samples, each sample having 'n' items, the ANOVA technique enables us to split the variance of all 'pn' items into variance between samples (due to variation of content or method of manufacture) and variance within samples (representing the inherent variation or the experimental error). Each variance in terms of mean square is calculated as the sum of squares of deviations divided by the appropriate number of degrees of freedom. The number of degrees of freedom for between sample variances is one less than the types of samples, ν_1 = (p-1) and the degrees of freedom for within sample variances is given by

ν_2 = p (n-1). The ratio of between sample mean square to within sample mean square is calculated and is known as F_{actual}. From statistical tables for known values of degrees of freedom and significance level, $F_{critical}$ is seen and compared with $F_{actual.}$ Null hypothesis of no difference between two samples is accepted if F_{actual} is less than $F_{critical}$ and rejected if F_{actual} is greater than $F_{critical}$ An α level (probability of error) of 0.05 was used for ANOVA test. ANOVA test indicated that the effect of fibre content. Tables III-V present the values of variance ratio for permeability, compressive and tensile strengths, respectively, of concrete mixes with varying fibre contents. As the F_{actual} values are greater than the $F_{critical}$ values for all the cases, it can be concluded that the effect of fibre content on the permeability, compressive and tensile strengths of concrete is significant.

IX. Conclusions

Based on the reported results of this study, the following conclusions can be drawn.

1. The permeability of concrete decreases significantly with the inclusion of steel fibres in concrete and continues to decrease with increasing weight fractions of fibres. This was observed for mixes tested after curing ages of 7, 14, 28 and 60 days.
2. The permeability of plain as well as fibrous concrete decreases significantly with curing age.
3. The compressive and split tensile strengths exhibit exponential relationship with coefficient of permeability for PCC as well as SFRC mixes.

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TABLE II
AVERAGE VALUES OF COEFFICIENT OF PERMEABILITY

Fibre Content (%)	Age (Days)	Fibre Factor		Compressive Strength (MPa)		Split Tensile Strength (MPa)		Coefficient of Permeability (x 10^{-12} m/sec)	
		SFC	CFC	SFC	CFC	SFC	CFC	SFC	CFC
0	7	0	0	23.00	23.00	1.63	1.63	97.68	97.68
0	14	0	0	28.00	28.00	1.90	1.90	66.66	66.66
0	28	0	0	31.50	31.50	2.30	2.30	49.08	49.08
0	60	0	0	33.00	33.00	2.44	2.44	38.00	38.00
1	7	0.65	0.715	24.00	24.20	1.72	1.94	26.23	21.61
1	14	0.65	0.715	29.00	31.30	1.99	2.09	19.25	16.36
1	28	0.65	0.715	33.70	34.50	2.39	2.71	12.53	10.89
1	60	0.65	0.715	34.50	35.30	2.57	2.76	9.44	9.08
2	7	1.30	1.43	25.80	26.70	1.85	2.08	17.43	15.98
2	14	1.30	1.43	32.80	31.00	2.21	2.39	10.16	10.91
2	28	1.30	1.43	35.20	35.70	2.66	2.89	6.54	6.90
2	60	1.30	1.43	36.70	39.00	2.98	2.89	6.17	5.09
4	7	2.60	2.86	28.20	29.80	2.57	2.31	12.73	10.63
4	14	2.60	2.86	35.20	34.70	2.80	2.62	6.90	7.26
4	28	2.60	2.86	40.50	41.00	2.98	3.31	6.00	5.13
4	60	2.60	2.86	41.20	42.70	3.25	3.49	4.50	3.91

TABLE III
VARIANCE RATIO VALUES FOR PERMEABILITY OF CONCRETE MIXES WITH VARYING FIBRE CONTENTS (ALL AGES, $N_1 = 3$, $N_2 = 8$)

Fibre Shape	Fibre Content	Actual Variance Ratio, F_{actual}				Critical Variance Ratio, $F_{critical}$
		7 Days	14 Days	28 Days	60 Days	
Straight	0%,1.0%,2.0% & 4.0%	52.74	204.63	107.55	101.15	4.07
Crimped	0%,1.0%,2.0% & 4.0%	58.73	265.27	107.51	13.34	4.07

TABLE IV
VARIANCE RATIO VALUES FOR COMPRESSIVE STRENGTH OF CONCRETE MIXES WITH VARYING FIBRE CONTENTS (ALL AGES, $N_1 = 3$, $N_2 = 16$)

Fibre Shape	Fibre Content	Actual Variance Ratio, F_{actual}				Critical Variance Ratio, $F_{critical}$
		7 Days	14 Days	28 Days	60 Days	
Straight	0%,1.0%,2.0% & 4.0%	4.2	10.1	33.0	8.5	3.24
Crimped	0%,1.0%,2.0% & 4.0%	8.3	8.1	14.6	12.8	3.24

TABLE V
VARIANCE RATIO VALUES FOR SPLIT TENSILE STRENGTH OF CONCRETE MIXES WITH VARYING FIBRE CONTENTS (ALL AGES, $N_1 = 3$, $N_2 = 16$)

Fibre Shape	Fibre Content	Actual Variance Ratio, F_{actual}				Critical Variance Ratio, $F_{critical}$
		7 Days	14 Days	28 Days	60 Days	
Straight	0%,1.0%,2.0% & 4.0%	17.2	13.0	5.0	18.8	3.24
Crimped	0%,1.0%,2.0% & 4.0%	7.9	6.8	7.6	9.5	3.24

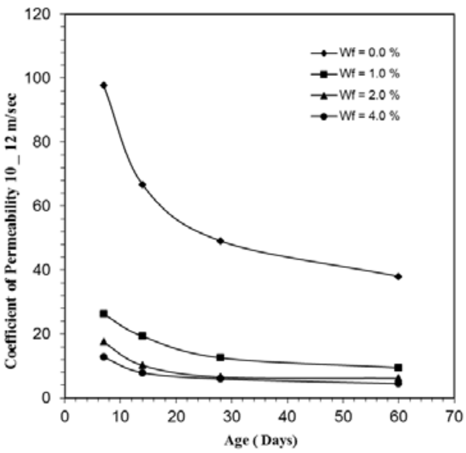

Fig. 1 Coefficient of permeability vs. concrete age (Crimped Fibres)

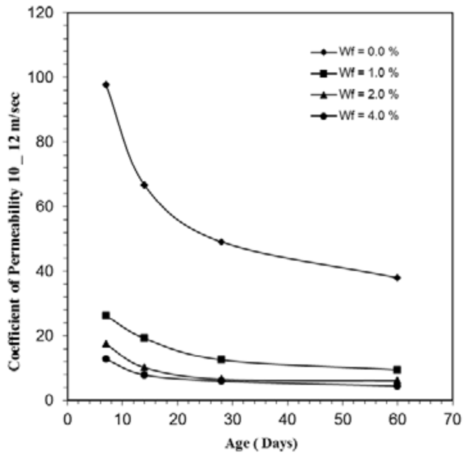

Fig. 2 Coefficient of permeability vs. concrete age (Straight Fibres)

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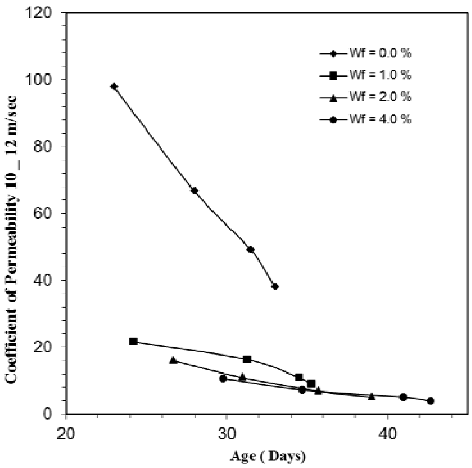

Fig. 3 Coefficient of permeability vs. compressive strength (Crimped Fibres)

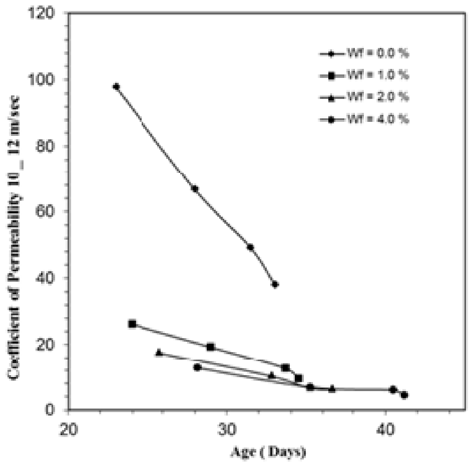

Fig. 4 Coefficient of permeability vs. compressive strength (Straight Fibres)

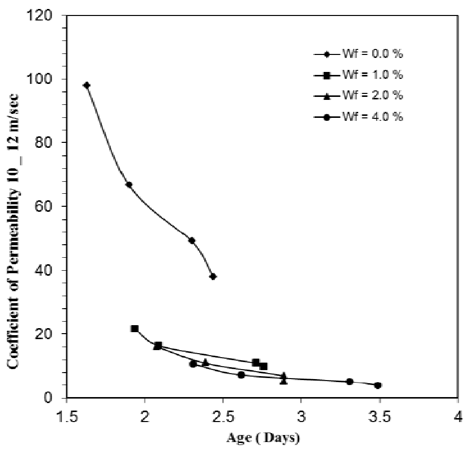

Fig. 5 coefficient of permeability vs. compressive strength (crimped fibres)

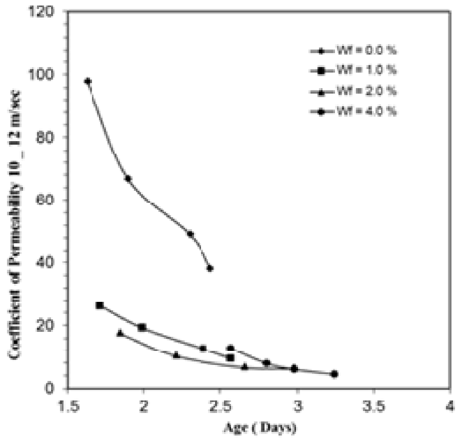

Fig. 6 Coefficient of permeability vs. split tensile strength (straight fibres)

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