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Evaluation of Properties of Shotcrete Material for Underground Cavern for Hydro Power Project

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Abstract. In this paper is aimed to determine properties of shotcrete with steel fibers reinforcement, strictly as per ASTM standard method C 1018-89$^{\varepsilon\text{-}1}$ (May 1990). The testing was done using closed- loop servo controlled electro-hydraulic +/- 10t MTS system acquired under UNDP. This shotcrete was adopted by the Hindustan Construction Company, for use in underground caverns for Koyna Project stage-IV. Using special MTS bend test fixture, the sawn beams with Dramix steel fibers were tested under third-point loading, applying constant rate of deflection of 0.05mm per minute. The X-Y Recorder gave autographical record. From this record, the point, deflection, strength and toughness at First-Crack are evaluated. Toughness Indices $I_{5,}$ $I_{10,}$ I_{20} and Residual Strength Factors $R_{5,\ 10}$ and $R_{10,\ 20}$ are determined. The performance of this SFR shotcrete versus elastic, elastic-plastic, brittle material is indicated. The value of I_5 for this SFR shotcrete is 1.92 to 4.37 as against 1 for plain concrete and 1 to 6 for fibrous concrete. Similar behavior is observed for I_{10} and I_{20}.

Keywords: *underground cavern, shotcrete, ASTM C-1018, first crack, deflection,strength, toughness indices, Residual strength factors*.

1 Introduction

This paper describes the determination of properties of steel fiber reinforced shotcrete material as per standard method. ASTM C 1018-89$^{\varepsilon 1}$. This material was adopted to be used for underground caverns of stage-IV of Koyna hydroelectric project in Maharashtra state, India. Work on this project producing 1980 MW power at Sahyadri hills range, Western Ghats with fall of 500 m was commenced in 1954. Specific advantage was a very large hydraulic head available over a short distance. Stage- (I and II) producing 620 MW power was completed in 1966. Water discharged in tail race tunnel still had hydraulic head of 120m. It was utilized in stage III completed in 1977 and producing 320 MW power.

The work on stage-IV was commenced in 1989 to produce 1000 MW power using water resource, Shivsagar reservoir, same source as for stage-(I and II). Novel technique, double lake tapping was used for the first time in Asia(1). Hindustan Construction Company executing construction of underground caverns for stage-IV adopted steel fiber reinforced shotcrete instead of conventional shotcrete over weld mesh.

Replacement of meshes by fibers results in savings in time normally required for fixing and pinning of meshes. It results in significant savings in the amount of concrete. There is distribution of resistances by the fibers against the tensile forces throughout the section of Steel Fiber Reinforced Shotcrete. Fibers restrict early shrinkage cracking, increase bond to rock surface and add the ductility to shotcrete. For this purpose, minimum recommended quantity of steel fiber is 30kgf(300N) per cubic meter(2).

At this point of time that HCC approached the department to get ascertained the properties of SFR Shotcrete as per ASTM C 1018-89. The purpose of the testing is to assess the performance of the shotcrete as regard to the flexural strength and the capacity to retain strength when subject to large deflections.

An elaborate testing program to evaluate the properties of steel fiber-reinforced shotcrete was carried out strictly as per the Standard Test Method ASTM C1018-89$^{\varepsilon\text{-}1}$ (May 1990) at the Applied Mechanics Department, Faculty of Technology and Engineering, The M S University of Baroda, Vadodara, Gujarat. The simply supported sawn beams of steel fiber reinforced concrete were tested under third-point loading while applying constant and controlled rate of deflection of 0.05mm per minute on the beam. The load-deflection curve was obtained using an X-Y plotter.

The areas up to the specified points on a load-deflection curve so obtained during a test are used to evaluate the flexural toughness of concrete. ASTM recommends the choice of sufficiently large scale for the load and beam deflection to be continuously monitored through X-Y Plotter. The data presented in this paper is acquired by using sophisticated instrumentation and methodology suggested by ASTM method. This was possible as the entire testing program was carried out using closed-loop servo controlled +/- 10t dynamic MTS series 810 Material Testing System acquired by the department under United Nations Development Program Project

The properties determined as per ASTM Method C-1018-89 (May 1990) are:

1 Evaluation of first-crack strength
2 Determination of toughness indices (which show actual performance as regard to the pattern of material behavior).
3 Determination of residual strength factors (which represent the average value of strength retained after first-crack as a percentage of first-crack strength for corresponding deflection interval.

Sawn beams of steel fiber-reinforced shotcrete material to be tested were transported to the department by the Hindustan Construction Company which was executing the work of construction of underground caverns for Koyna Hydroelectric Project stage-IV. Instead of conventional shotcrete over weld mesh, the steel fiber reinforcement shotcrete was adopted.

2 Specimen Details

2.1 Steel fiber reinforced shotcrete beam specimens

The shotcrete beam specimens with the proportion of steel fiber reinforcement of (30kgf, 40kgf, 50kgf) 294.3N, 392.4N, and 490.5N per cubic meter as per authors were prepared at HCC Company project site. The beam specimens were of sawn type and of ASTM recommended size of 350mm x 100mm x 100mm. Three specimens of each of the three samples designated S-50, S-40, S-30 were tested under third point loading over a span of 300mm. Specimens were subjected to careful grinding to minimize errors in deflection measurements on samples.

Symbols S-40/A, S-40/B, S-40/C represent specimens no 1, 2, and 3 for the sample S-40 which had steel fibers of 40kgf (392.4N) per cubic meter of sample.

2.2 Steel Fibers

DRAMIX steel fibers used for reinforcement were imported from Belgium. The various properties given below are from publication: Marc Vander Walle N.Y. Bakaertstraat 2, 8500 Zwevegem, Belgium, 2nd edition,1992.

- d - diameter 0.5mm
- f_u - ultimate tensile strength > 345 Mpa
- l =-length 30mm
- aspect ratio l/d = 60

ASTM A-820-85 specifies that the average tensile strength shall not be less than 345 MPa.

3 Material Test System

The whole testing program is done in the department using dynamic +/- 10-ton servo controlled closed-loop Electro Hydraulic Material Test System Machine setup of MTS System Corporation, USA. It consisted of three main components

1) Load Frame
2) Hydraulic Power Supply
3) Electronic console.

The electronic console consisted of various modules like Digital Function Generator, Phase Shifter, Digital Data Display Oscilloscope, 5-channel strip chart recorder, X-Y plotter. The X-Y plotter measures the load and deflection of the beam under 3rd point loading. ASTM C 1018-89 describes and discusses at length the various aspects as regards to the deflection measurement. In the tests described in this paper, the output of load cell and LVDT transducer were coupled with X-Y plotter to obtain automatically the continuous graphical curve (record) of load vs. deflection of the beam during the test. The plot for specimen 40A is shown herewith in Fig 3 and Fig 4. The explanatory and illustrative curves by ASTM C 1018 are shown in Fig 2. In order to accurately determine areas under load deflection curve ASTM method recommends that scales initially chosen for load and deflection are reasonably large.

For the beam size in this testing program, a load scale on which 25mm (1 inch) corresponds to a flexural stress of 0.5855 Mpa (88psi) is chosen, as against the recommended value of 1 Mpa. Also, a deflection scale on which 25mm (1 inch) corresponds to a deflection of 0.1mm is chosen (same as recommended value of up to 0.1mm I_{10} criterion). The LVDT was located at mid-span. Digital Data Display displayed the load and deflection values with precision of 1N and 0.01mm respectively and digital printout of these readings vs. time was availed at every 15 seconds interval.

Fig 1. MTS Bend Test Fixture for third point loading

It comprised of load applying and support blocks extending over full width of the shotcrete beam and maintained in vertical position and in contact with cylindrical rods by means of spring-loaded screws as shown in the photo above

Actual load deflection curve (record on X-Y plotter) for each of 9 specimen is very long. The curve on X-Y plotter for specimen 40/A are digitally recreated using matplotlib and shown in Fig 3 and Fig 4

All numerical values of parameters obtained using curves on X-Y recorder for remaining 8 specimens are presented in tabular form in Table 3.

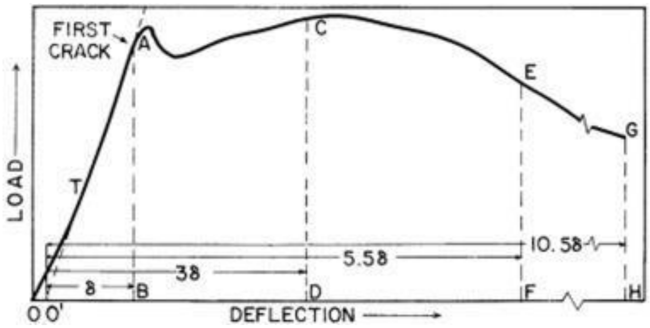

Fig 2. Illustrated 1018 curve as per ASTM

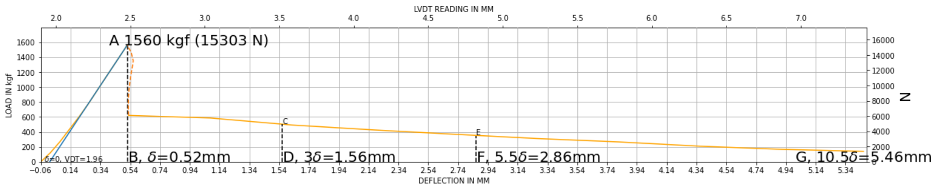

Fig 3. Sample 40/A

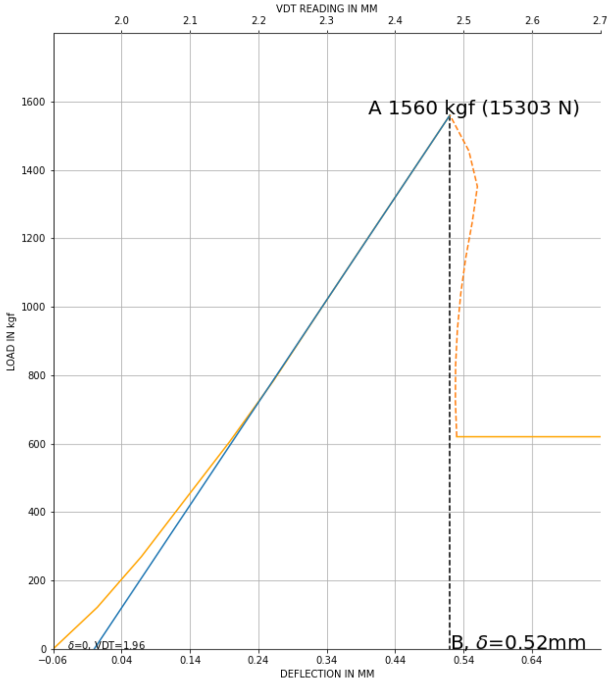

Fig 4. Close-up of Fig 3, left hand side

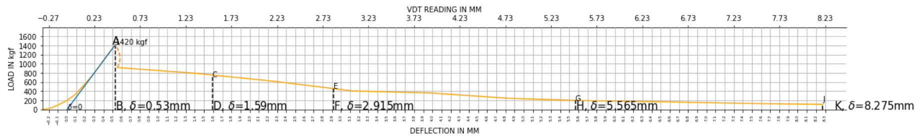

Fig 5. Sample 50/B

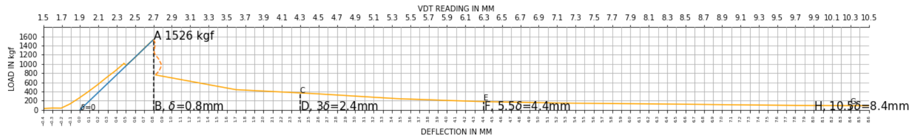

Fig 6. Sample 30/C

3.1 Analysis of Load-Deflection Curve for various properties

The upward concavity seen in the initial portion of the curve is indicative of extraneous effects due to seating or twisting of the specimen on its supports or deformation of the supporting system. From each curve, the following are determined:

i) First crack – the point on load-deflection curve at which the curve first becomes nonlinear (approximately the onset of cracking in the concrete matrix)

ii) First crack deflection – the deflection value δ on the load-deflection curve at the first crack. This is a very useful parameter and it serves as basis to evaluate other parameters in this ASTM Method C-1018

iii) First crack strength – modulus of rupture at the first crack

iv) First crack toughness – the energy equivalent to the area under load deflection curve up to first crack deflection δ

v) Toughness indices – the number obtained by dividing area up to specified deflection by area up to first crack

vi) Toughness index I_5, I_{10}, I_{20} – the number obtained by dividing the area up to corresponding deflection value of 3 times, 5.5 times, and 10 times of δ, value of deflection at first crack, by the area up to first crack

vii) Residual strength factor, $R_{5,10}$ and $R_{10,20}$ which represent strength retained after first crack and as a percentage of first crack strength for a corresponding deflection interval

3.2 Evaluation of Properties

The load deflection curves obtained in this testing program are concave upwards.

1) The point A on the curve is identified as a point the curvature first increases sharply. Then straight-line AT, the linear portion of load deflection curve is extended and new origin O' is obtained. If the curve happens to be convex upward the line AO' is drawn as per fig 1(b) of ASTM C1018-89$^{\varepsilon\text{-}1}$
2) For illustration purpose, the curve obtained for specimen 40/A as given by Figure 3 is analyzed

Table 1

First crack deflection	0.52mm
First crack load P	1560kgf (15303.6N)
Maximum load	1560kgf (15303.6N)
Length of beam l'	350 mm
Span length of beam l	300 mm
Depth of beam	100 mm
Width of beam	100 mm
1st crack strength	4.59 MPa
Toughness index I_5	2.38
Toughness index I_{10}	3.68
Toughness index I_{20}	5.189
Residual strength factor $R_{5,10}$	26
Residual strength factor $R_{10,20}$	15.09
Position of fracture, distance from mid span	Middle third of the span

For the case in which the fracture initiates in the middle third of span length

$$M = \frac{P}{2} \times \frac{l}{3} = \frac{Pl}{6}$$

For b=d section modulus

$$z = \frac{bd^2}{6} = \frac{d^3}{6}$$

Above two criteria are satisfied in all the specimens tested in this program. Hence:

$$f = \frac{M}{z} = \frac{3P}{d^2}$$

$$= \frac{3\ x\ 15303\ N}{(100mm)^2}$$

$$\therefore f = 4.59\ MPa = 1st\ crack\ strength$$

As P_{max} is also equal to 15303N, Flexural strength = 4.59 Mpa

3.3 Evaluation of I_5, I_{10}, I_{20} for specimen 40/A

Table 2

Deflection δ	δ = 0.52mm	3δ = 1.56mm	5.5δ = 2.86mm	10.5δ= 5.46mm
	0.52-0	1.56-0.52	2.86-1.56	5.46-2.86
	0.52mm	= 1.04mm	= 1.3mm	= 2.6mm
Area O'ABC	1560 kgf			
	15303N	5297.4N	3973.05N	2305.35N
	$\frac{15303N}{2} \times 0.52mm$	x 1.24 mm	x 1.3 mm	x 2.6mm
	=3978N-mm	=5509.3N-mm	=5164.9N-mm	= 5993.1N-mm
Area A'BDC	$\frac{600+480}{2} kgf$			
	540 kgf			
	5297.4N			
Area CDFE	$\frac{480+330}{2} kgf$			
	= 405 kgf			
	= 3973N			
Area EFHG	$\frac{330+140}{2} kgf$			
	= 235 kgf			
	= 2305.3 N			
$\sum Area$	3979	9488	14653	20646
Toughness Index		$\frac{9488}{3979} = 2.38 = I_5$	$\frac{14653}{3979} = 3.66 = I_{10}$	$\frac{20646}{3979} = 5.189 = I_{20}$

Residual Strength Factor $R_{5,10} = 20 (I_{10}-I_5) = 25.6$

Residual Strength Factor $R_{10,20} = 10 (I_{20} – I_{10}) = 15.29$

Table 3

Average Values of Properties			
Property	Sample S-50	Sample S-40	Sample S-30
First-crack deflection (mm)	0.45, 0.53, 0.46	0.52, 0.52, 0.42	0.52, 0.46, 0.80
Average (mm)	**0.48**	**0.487**	**0.593**
First-crack Strength (MPa)	4.28, 4.19, 4.11	4.59, 5.05, 4.33	4.09, 4.82, 4.47
Average (MPa)	**4.193**	**4.967**	**4.46**
Flexural Strength (MPa)	4.32, 4.18, 4.1	4.59, 5.05, 4.32	4.15, 4.82, 4.49
Average (MPa)	**4.203**	**4.986**	**4.82**
First-crack toughness (N-m)	3.2, 3.7, 2.95	3.98, 4.38, 8.32	3.54, 3.70, 5.96
Average (N-m)	**3.28**	**3.77**	**4.4**
Toughness Index I_5	3.31, 3.43, 4.37	2.29, 1.92, 1.86	2.9, 1.75, 1.99
Average	**3.7**	**2.02**	**2.21**
Toughness Index I_{10}	5.14, 5.57, 7.54	3.65, 2.96, 2.07	4.97, 2.58, 2.9
Average	**6.08**	**2.893**	**3.48**
Toughness Index I_{20}	7.24, 7.96, 11.10	5.13, 4.35, 3.85	6.57, 3.71, 3.81
Average	**8.76**	**4.44**	**4.69**
Toughness Index I_{30}	8.24, 9.10, 12.19	---, 4.76, 4.63	7.43, 4.38, --
Average	**10.09**	**4.69**	**5.905**
Residual Strength Factor $R_{5,10}$	36.66, 40.28, 63.52	27.22, 20.74, 16.86	41.44, 16.76, 18.1
Average	**46.82**	**21.6**	**25.4**
Residual Strength Factor $R_{10,20}$	21.24,24.05,35.37	14.84,13.92,11.47	16, 11, 9.13
Average	**26.5**	**13.41**	**12.43**

4 Conclusions

1) Replacement of shotcrete over weld mesh by steel fiber reinforced shotcrete results in many advantages. There is savings in time which is required for difficult process of fixing and pinning the weld meshes to tunnel surface having asperities and irregularities. SFR shotcrete adopts easily to rock surface.
2) In weld mesh case, there may remain pockets of voids behind weld mesh. These pockets are subject environment forces and results in damage to lining. These possibilities are reduced in SFR shotcrete. Also, it results in quite a uniform thickness of lining as compared to weld mesh shotcrete lining. Rebound ratio in shotcrete is less. This results in cost savings in shotcrete material.
3) The presence of steel fiber throughout the section of shotcrete material reduces initial shrinkage cracks and hence results in better bond between the shotcrete lining and the rock surface.

4) The distributed steel fiber in the shotcrete increased resistance to cracking and tends to arrest propagating crack surface resulting in adding of ductility. This results in increased capacity of SFR shotcrete material to be able to retain significant flexural strength over a wide range of increasing deflection after first cracking.
5) It is seen that the value of first-crack deflection for 8 specimens of fiber reinforced shotcrete tested varies in a narrow band, from 0.42mm to 0.53mm. For the remaining 9th specimen, it is 0.8mm.
6) For the 9 specimens tested the first-crack strength between 4.18MPa and 5.05Mpa
7) For the 9 specimens tested, flexural strength varies between 4.19 MPa and 5.05Mpa. The point of 1st-crack and the point of maximum load are not much distinctly placed.
8) The theoretical value of 3δ criterion Toughness Index, I_5, is 5 for linearly elastic behavior up to first-crack and for perfectly plastic behavior thereafter. For plain concrete it is 1. For steel fiber reinforced SFR shotcrete tested in this program, it varies from 1.92 to 4.37. For fibrous concrete, the range is 1 to 5 as per ASDM.
9) Theoretical values of I_{10} and I_{20} for elastic perfectly plastic material is 10 and 20 respectively. For plain concrete material it is 1 and 1 respectively. For the fiber reinforced shotcrete material tested in this program, the corresponding value is between 2.07 to 7.54 and between 3.71 to 11.10 respectively. As per ASTM, the observed range for fibrous concrete is 1 to 12 and 1 to 25.
10) The pattern of behavior of fiber reinforced shotcrete tested in this program indicates that it is positioned between that of elastic plastic material and brittle plain concrete material.
11) Residual strength factors for fiber reinforced shotcrete material tested in this program, viz. $R_{5,10}$ and $R_{10,20}$ are in between 46.8 to 25.4 and 26.5 to 12.43 respectively. The value of 100 corresponds to perfectly plastic behavior. Lower values indicate less performance. Residual strength factors for brittle plain concrete are zero.
12) For all 9 samples tested. the fracture initiated at a section in the middle third of the span and propagated in it up to the termination of the test.

5 Notations and symbols

Term	Notation	Description
First crack	The point, A	The point on low deflection curve at which the form of the curve becomes non linear
First crack deflection	The deflection, δ	The deflection value on the load-deflection curve at first crack
First crack strength	Modulus of rupture, R	$R = Pl/bd^2$
First crack toughness	-	Energy equivalent to the area OAB under the load deflection curve upto the first crack deflection δ
Toughness	-	The energy equivalent to the area under the load deflection curve to the specified deflection
Toughness indices	I_5, I_{10}, I_{20} corresponding to the specified deflection of value equal to 3δ, 5.5δ, and 10.5δ	The number obtained by dividing the area upto the specified deflection by the area upto the first crack deflection
Residual strength factors	$R_{5,10}$ and $R_{10,20}$	Retention strength over a range of deflection

6 Acknowledgements

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