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THE STRAIN RATE EFFECT ON THE FLEXURAL STRENGTH AND COST OF STEEL FIBER REINFORCED CONCRETE BEAMS

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Abstract:-
The beneficial effect of strain rate upon the ductility and loading capacity of steel fiber reinforced concrete (SFRC) beams subject to quasi-static and dynamic three point bending tests with various amounts of steel fibers and the economical influence on the construction was investigated in this paper. Experimental results revealed that the loading capacity of SFRC beams attained higher values at dynamic strain rates applied in beams with low dosage of steel fibers. In addition, the cost construction of these SFRC beams was mainly affected by concrete class and not fibers dosage to attain SFRC beams the optimum loading capacity.

Keywords:- *Steel; Fibres; Experiment; Flexure; Concrete beam; Strain rate; Loading capacity; Cost*

1. INTRODUCTION

Steel fiber reinforced Concrete (SFRC) by enclosing admixtures, cement and aggregates of fine and various gradations can improve its workability and can take full advantage of the fibers encapsulated. Some of a plenty of applications, where steel fibers are used, are encountered in concrete slabs without reinforcement bars to carry flexural loadings as in Civil Engineering structures (1). It has been shown that steel fibers are effective in supplementing rather or in some cases replacing the stirrups in beams (2-4). In addition, tests have shown that steel fibers supplementary with reinforcing bars can increase the moment capacity of RC beams (5,6). Various studies have also shown that steel fibers provide an adequate internal mechanism, such that with shrinkage-compensating cements, complement each other and help in concrete cohesion (7). In particular, when fibers are added to a concrete mix, fiber characteristics such as their type, shape, aspect ratio defined by the length/diameter, play an important role in modifying the behavior of the SFRRC material (8). Dwarakanath and Nagaraj (9) gave an economical and efficient use of steel fibers. Several methods have been applied to predict the static flexural strength of small beams reinforced only with steel fibers using empirical data from laboratory tests or the law of mixtures (10,11).

The aim of the present paper is to investigate the strain rate effect on the flexural strength as well as on the cost construction of SFRC beams with various amounts of steel fibers dosage and concrete class. The experimental data deduced and processed statistically reveal that increase of loading capacity of SFRC beams is more pronounced in beams with relatively low (25 kg/m^3) dosage of steel fibers. The failure behavior of beams shows that fracture pattern is sharp in SFRC beams subject to dynamic than to static loadings leading to higher loading capacity of beams. The advantages of SFRC concern enhanced ductility, high impact and brittle resistance, which result to a cost saving in structures, which is due to elimination of conventional reinforcing or even a reduction in section thickness and shock vibration damage resistance.

2. Experiment

2.1 Specimens

The material used for the fabrication of SFRC beams were C16/20 - and C20/25 - concrete class including steel fibers in amounts of 25 and 50 Kg per m^3 in relation to concrete volume. No shear as well as flexural reinforcement existed in the beams, which are subject to three point bending (Fig. 1). The strain rate applied on the beams is quasi-static of 0.2 and dynamic of 4 kN/sec, respectively. For test requirements, three groups of SFRC beams having dimensions 1500 mm (length) X 200mm (height) X 100mm (width) were constructed. The geometry of steel fibers and the concrete mixer are illustrated in Figure 2(a) and 2(b).

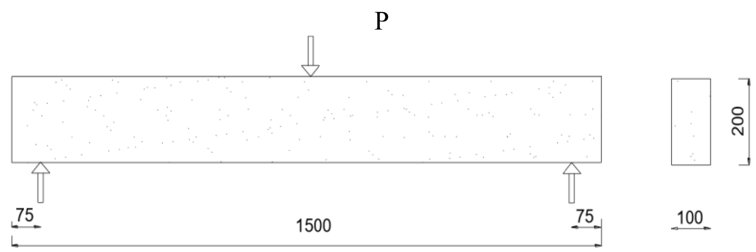
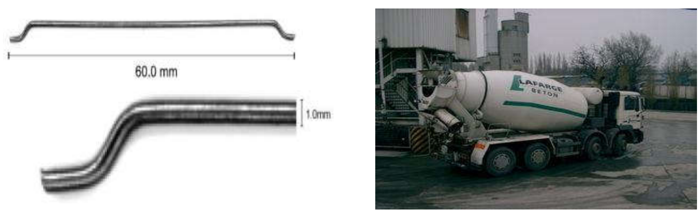


Fig. 1: Geometry and loading of SFRC beams.

The fibres consist of a cold drawn steel wire with low carbon percentages and a minimum tensile strength capacity equal to 1100 MPa. The fibers are uniformly dispersed by 100-150 revolutions of concrete mixture, after its casting, and their aspect ratio is equal to 60. The minimum fiber dosage encapsulated in the beams is then given by

$$\text{Minimum Fibre Dosage} = 67658 / (l/d)\ 2 \qquad [1]$$

Where l and dare the length and diameter of fibre. The maximum allowed fibre dosage is 50 Kg/m^3 according to the technical specifications of industry constructing the fibres.



(a) (b)

Fig. 2: Hooked end steel fiber provided by E.T.A.L. *S.A.* (a) and concrete by Lafarge *Co* (b).

Besides the beams constructed three cubes and three cylinders were obtained from each mixture and tested to compression and splitting tension, respectively, to evaluate compressive and tensile strength of concrete.

2.2. Experiment setup

All tests were executed in Reinforced Concrete Laboratory of Civil Engineering Department at Piraeus University of Applied Sciences (P.U.A.S.). The beams were simply supported over an effective span of 1350 mm and subject to a monotonic three-point bending loading. The loading was applied stepwise through a 200 KN

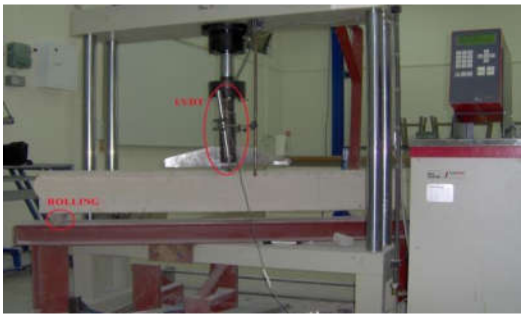


Fig. 3: Test setup.

capacity, servo-hydraulic machine in force-controlled mode at the center of a stiffened spreader trapezoidal beam, which in turn applied at mid-span of beam (Fig. 3). The deflections of beam were measured at mid-span using a linear variable differential transducer (LVDT) and in the same time a load-cell recorded the loadings automatically. An automatic data-acquisition system was used to store the values of loadings and deflections.

3. Results and discussion

3.1 Compressive strength of concrete.

After curing the beams and specimens at 28 days, drying of specimens was occurred for 2 days. After drying compressive tests were performed to cubes of 150 mm side in order to determine the concrete class. The results concerning the compressive strength of concrete, which constitutes SFRC beams, are given as follows:

cubes	1st group (C20/25) [MPa]	2nd group (C16/20) [MPa]
1	35,0	27,5
2	36,9	29,3
3	36,0	29,0
avX_3	35,97	28,60

Table1: Compressive strength of concrete used in beams.

These average values are introduced in the following formulae of criterion E of EKOS 200 regulation to derive the concrete class (12):

$avX_3 \geq f_{ck} + 3.7$ (MPa)

$$X_i \geq f_{ck} \quad [2]$$

Where avX_3 is the average value of the compressive strengths obtained for three sampling cubes, Xi is the compressive strength of each cube separately and f_{ck} is the cube characteristic strength of concrete in compression.

3.2 Tensile strength of concrete.

To evaluate tensile strength of concrete, splitting tests in concrete cylinders were executed in the Laboratory. The main advantage of splitting test is that external compressive loadings are just applied. The maximum value of tensile stress, $f_{max,sz}$, computed at failure, from the theory of elasticity, is the splitting tensile strength and provided by:

$$f_{max,sz} = 2*P / (\pi*d* h) \quad [3]$$

where P is the splitting fracture loading, illustrated in Table 2, and d, h are the 150 mm diameter and the 300 mm height of cylinder, respectively.

	1st group (C 20/25) P [kN]			2nd group (C 16/20) P [kN]		
CYLINDERS	**VIRGIN**	**SFRC** (25 kg/m^3)	**SFRC** (50 kg/m^3)	**VIRGIN**	**SFRC** (25 kg/m^3)	**SFRC** (50 kg/m^3)
1	192.4	207.8	227	151.5	169.5	179
2	187.6	209	232	147.2	169.1	182.6
3	191	208	230	150	168.5	180
av P	190	208.3	229.67	149.5	169	180.5
fmax,sz (kN/m^2)	2694	2947.9	3249.2	2115	2390.9	2554

Table 2: Splitting fracture loading, P, of concrete used in beams.

3.3 Test program and results

The following tree diagram (Fig. 4) indicates the experimental program, according to which 36 beams virgin and SFRC made of C20/25- or C16/20-concrete class, which

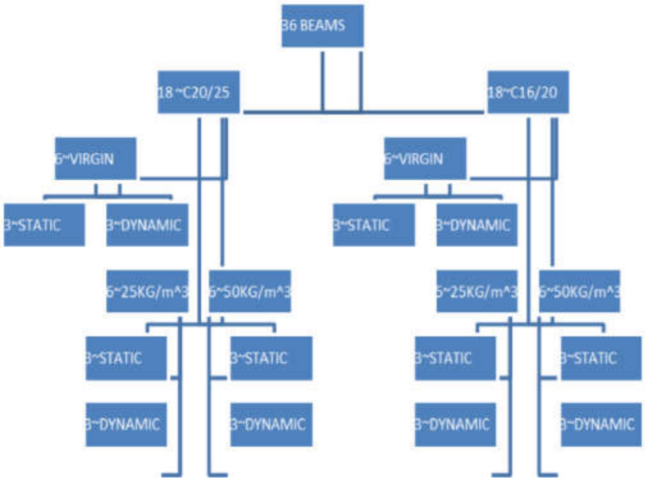


Fig. 4: Test schedule of SFRC beams subject to quasi-static or dynamic loading.

Include steel fibers at amounts of 25 or 50 kg/m^3, were subject to a quasi-static loading rate of 0.2 and a dynamic one of 4 kN/sec, respectively.

3.3.1 First group of beams (C20/25).

This group of eighteen beams made of C20/25 concrete class consisted of six control beams, six beams made of SFRC with 25 kg steel fibers per m^3 of concrete and another six beams made of SFRC with 50 kg steel fibers per m^3 of concrete. The beams were subject to three - point bending and was measured their maximum loading capacity and deflections. Some of the beams were loaded at quasi-static strain rate of 0.2 kN/sec and the rest of them at dynamic strain rate of 4 kN/sec.

Indicative Beams	Concrete class	Fibers amount (kg/m^3)	Strain rate (kN/s)	max Loading (kN)	Deflection (mm)	Average max loading (kN)	Average deflection (mm)
B.1.V.s.1	C20/25	-	0.2	5.41	0.51	-	-
B.1.V.d.1		-	4	6.32	0.47		
B.1.1.s.1		25	0.2	7.94	0.55	6.85	0.935
B.1.1.s.2		25	0.2	5.76	1.32		
B.1.1.d.1		25	4	8.45	0.76	8.02	1.055
B.1.1.d.2		25	4	7.36	1.64		
B.1.1.d.3		25	4	7.95	1.07		
B.1.1.d.4		25	4	8.33	0.75		
B.1.2.s.1		50	0.2	4.11	0.21	5.18	0.44
B.1.2.s.2		50	0.2	5.63	0.97		
B.1.2.s.3		50	0.2	5.37	0.22		
B.1.2.s.4		50	0.2	5.61	0.36		
B.1.2.d.1		50	4	6.53	1.16	6.275	0.925
B.1.2.d.2		50	4	6.02	0.69		

Table 3: Failure characteristics for 1st group (C20/25) of SFRC beams.

The experimental results have shown that the failure mode of these beams was clearly flexural and no shear cracks appeared in the beams, as Fig. 4(a-b) illustrates independently of the applied strain rate. The cracks emanated from beam bottom, near the mid-span of each beam, were propagated upwards. The results have shown that

(a) (b)

Fig. 4: Crack patterns of SFRC beams made of C20/25 concrete and 25 kg/m^3 steel fibers at loading rates of (a) 0.2 and (b) 4 kN/sec.

SFRC beams with steel fibers absorb higher loadings and in this way their deflection values are increased compared to those encountered in control beams. In addition, beams made of SFRC with 25 kg of steel fibers per m^3 of concrete performed better in loading capacity with strain rate than SFRC beams with 50 kg/m^3 fibers.

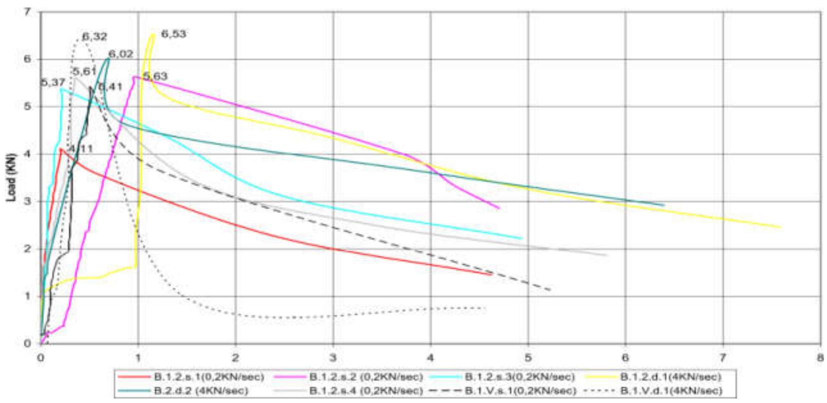


Fig. 5: Indicative loading vs. deflection variation curves of SFRC (50kg/m3) beams with C20/25 concrete class at static and dynamic strain rates.

Specifically speaking, the average maximum loading capacity of beams subject to dynamic strain rate was 8.02 KN attained at an average deflection of 1.055 mm, which is 17.08 % higher than that appeared in beams subject to a quasi-static strain rate (Table 3). Table 3 also indicates that beams made of SFRC with 50 Kg/m^3 steel fibers behaved similarly, as beams made of SFRC with 25 Kg/m^3 steel fibers, with strain rate applied. Then, the failure characteristics (max loading and deflection) of SFRC beams were increased in similar trends and attained smaller values from static to dynamic strain rates.

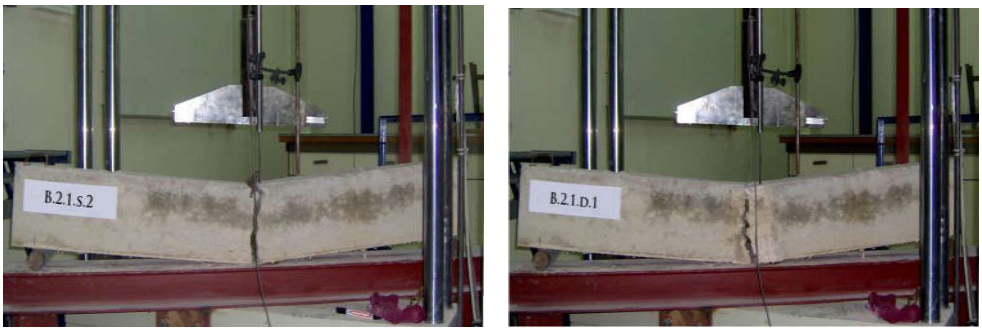
3.3.2 Second group of beams (C16/20)

The second group consisted of eighteen beams from C16/20 concrete class. Six were control beams, six of beams were made of SFRC with a weight percentage of fibers equal to 25 kg per m^3 of concrete, and the remaining six were constructed from SFRC with increased, 50 kg/m^3, amount of steel fibers. Few changes appeared in relation to the fracture of first beams (C20/25) group. Firstly, it was noticed that relatively smaller values of maximum load carrying capacity occurred in these beams, but this was reasonable since the concrete's quality was in this group weaker than that in first group of beams. Another observation was the relatively better adhesion and workability of fibres within C16/20 rather than within C20/25 concrete. The crack patterns were almost same for both groups of specimens, except for the faster propagation of cracks at the second group of SFRC beams due to less stiffer concrete. Table 4 followed illustrates the failure characteristics of the second group of SFRC beams.

Indicative Beams	Concrete class	Fibers amount (kg/m^3)	Loading rate (kN/s)	max loading (kN)	Deflection (mm)	Average max loading (kN)	Average deflection (mm)
B.2.V.s.1	C16/20	-	0.2	4.9	0.41	4.9	0.41
B.2.1.s.1		25	0.2	5.96	1.15	6.27	0.92
B.2.1.s.2		25	0.2	6.7	0.76		
B.2.1.s.3		25	0.2	6.14	0.85		
B.2.1.d.1		25	4	7.14	0.22	7.295	0.425
B.2.1.d.2		25	4	7.45	0.63		
B.2.2.s.1		50	0.2	4.98	0.63	4.9	0.63
B.2.2.s.2		50	0.2	4.82	0.63		
B.2.2.d.1		50	4	6.31	0.18	5.67	0.725
B.2.2.d.2		50	4	5.03	1.27		

Table 4: Failure characteristics of 2nd group (C16/20) of SFRC beams.

The failure characteristics for beams of this group was, as expected, flexural and the crack pattern was rather sharp in dynamically (Fig. 6(b)) than in statically fractured beams (Fig. 6(a)). In addition, as concerns with the loading carrying capacity, it was lower at both loading rates compared to those attained in first (C20/25) group of SFRC beams, due to weaker (C16/20) concrete quality.



(a) (b)

Fig. 6: Crack patterns of SFRC beams made of C16/20 concrete and (a) 25 kg/m^3 steel fibers at loading rate of 0.2 and (b) 50 kg/m^3 steel fibers at loading rate of 4 kN/sec.

The strain rate effect is less pronounced at this group of SFRC beams (Fig. 7), where higher ultimate loading capacities prevail in dynamically than in statically tested beams. Specifically speaking, the average maximum loading capacity of beams subject to dynamic loading was 7.295 KN attained at a relatively low average deflection of 0.425 mm, which is 16.35 % higher than that obtained for beams subject to a quasi-static loading (Table 3).

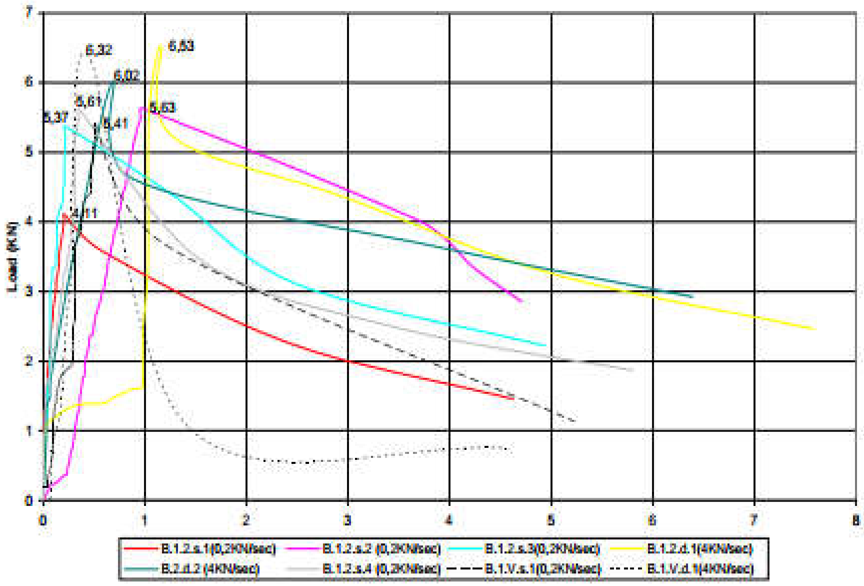
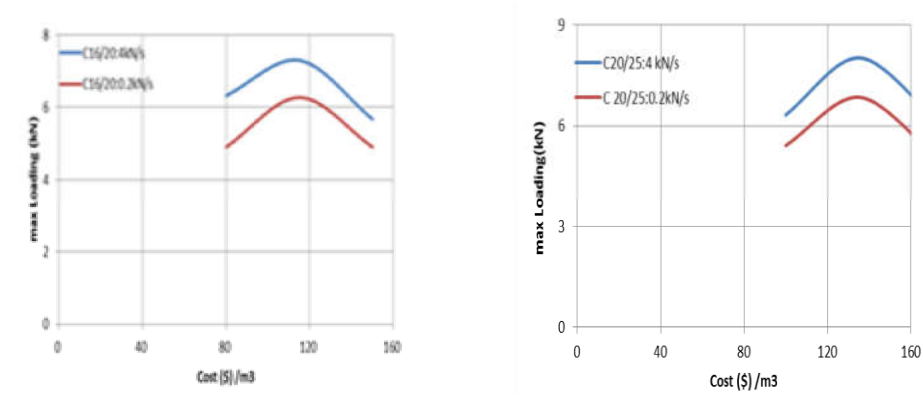


Fig. 7: Indicative loading vs. deflection variation for SFRC (25kg/m3) beams with C16/20 concrete at static and dynamic loading rates.

Inspection and comparison of values illustrated in Tables 3 and 4, for dynamic loading, shows that an increase in load carrying capacity followed by an improvement in the post-peak behavior occurs in SFRC beams with decreased fiber dosage.

4. Cost estimation and correlation with sfrc beam strength

Fig. 8 illustrates the variation of SFRC beams loading capacity made of C16/20 (a) and C20/25 (b) concrete class at a static of 0.2 kN/s and a quasi-dynamic strain rate of
4kN/sec.



(a) (b)

Fig. 8: Max loading variation vs. cost of SFRC for (a) C16/20 and (b) C20/25 concrete class at various strain rates.

Inspection of these figures indicates that at an optimum cost of about 115 \$ and 135\$ per m^3 for C16/20 and C20/25 concrete class, it can be achieved a maximum flexural loading of 7.30 and 8.02 kN, respectively, at dynamic strain rate. The same is also valid for static strain rate of 0.2 kN/sec. This optimum cost of SFRC beams represents the sum of cost for pure concrete, equal to 80 (C16/20) or 100 (C20/25) \$ per m^3 , and the cost for steel fibers at dosage 25 kg/m^3, equal to 35 \$.

5. Conclusions

The following concluding remarks can be drawn:

a) Strong concrete-class (C20/25) results in increase of ultimate loading capacity and simultaneously lower deflections in relation to those appeared for SFRC beams with C16/20 concrete-class. These variations are more intense at higher strain rates.
b) SFRC beams made of C20/25 concrete performed rather better at dynamic strain rates and attain higher loading capacities at smaller deflections than similar beams of C16/20 concrete did.
c) SFRC beams performed well enough, when subject to dynamic loadings, presenting higher stiffness and less ductile behavior, since they present a steepest increase of loading after first cracking.This is apparent independently of concrete-class used.
d) The flexural strength of SFRC beams became less sensitive to the applied strain-rate, as the strength of concrete was decreased.
e) Inexpensive cost of construction of SFRC beams attaining an optimum flexural strength was achieved using strong concrete and low fibers dosage at dynamic strain rate.

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