THE PROPERTIES OF CONCRETE REINFORCED WITH MELT-EXTRACTED STEEL FIBERS

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ABSTRACT

The objective of this paper is to present the experimental investigation of the concretes with 1 and 2 percent of melt-extracted steel fibers by volume. Mixing methods for fiber were tried on trial mixes.

The compressive, tensile and flexural strength were measured. The results of tests on the fracture energy, bond and punching strength are also presented. The long-term effects are evaluated on the basis of creep and shrinkage tests for 60 days.

Moreover, bending tests on repaired concrete beams and impact tests on slabs are shown as part of the investigations towards possible applications of concrete modified with fibers.

The test results showed that melt-extracted steel fibers are effective in improving some concrete properties and made it possible to compare to other types of fiber.

Keywords: Melt-extracted steel fibers, fiber reinforced concrete, material properties.

1. INTRODUCTION

Steel fiber reinforced concrete is being used for new construction and for the repair of concrete structures. Historically, the major experience has been with the application of fiber reinforced concrete for road and airport pavements, floor slabs and concrete products. A new use has been in steel fibrous shotcrete. The methods of mixing, placing and finishing have been developed to a reasonable degree /1/.

Fiber reinforced concrete has received wide recognition for its crack and deformation control, ductility and energy absorption characteristics.

Fibers can be added to selected zones of precast and cast-inplace concrete. It may also be an improved means for the repair or strengthening of existing concrete structures.

Because this improvement depends on the type and percent of fiber, more data are needed on physical properties for various types of fiber reinforced concrete for studies directed toward modifications to existing design methods and specifications.

The investigations reported were carried out to study fiber reinforced concrete using stainless steel fibers produced by the melt-extraction process.

The paper presents some results of tests on material properties when 1 and 2 percent fiber by volume was used. Results are related to a no-fiber concrete of the same mix.

Application of fiber reinforced concrete containing 2 percent fiber by volume for the repair of concrete structures is demonstrated for two reinforced concrete beams.

Impact-resistance was also measured as the amount of energy used to fracture a plate element. The test program involved 9 slabs with each third casting mix having 0, 1 and 2 percent fiber by volume.

The findings related to the investigation of the individual strength characteristics are discussed in the paper.

2. MATERIALS AND MIX DESIGN

Mixing of fiber reinforced concrete can be accomplished by several methods. Conventional concrete mix proportions can be used for trial mixes and then modified by fiber and adjusted.

Uniform mixing and workability may be affected by the type and nature of fiber.

This paper presents some experimental investigations on concrete modified by melt-extracted stainless steel fibers.

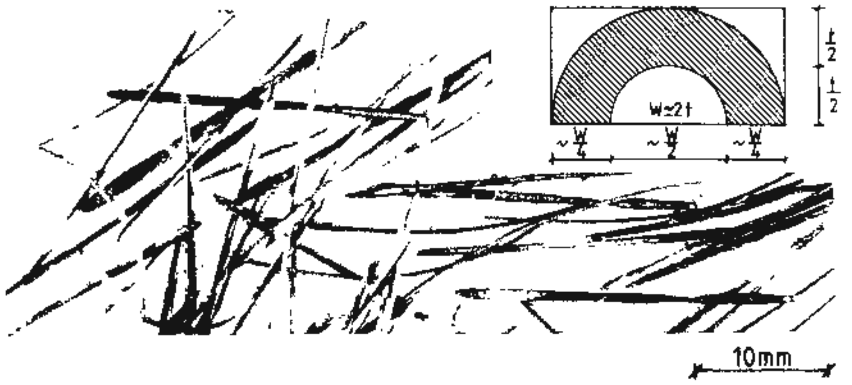


Fig.1. Melt-extracted stainless steel fibers (idealized cross-section and photograph)

The melt-extracted fibers are of an irregular crescent shaped cross-section and have a rough surface as shown in Figure 1. The fibers were manufactured by Fiber Technology Ltd. UK and are distributed by Norsk Jernverk A/S.

The length/width/thicknes of the fibers used in tests were 24/0.9/0.4 mm respectively as an average of 40 measurements at half the fiber length. In effect, the aspect ratio defined as length to equivalent diameter is in the range 30 to 50. The measured average fiber tensile strength was 600 MPa.

From the consideration of conventional concrete mix proportions, for concrete grade C45 corresponding to Norwegian Standards, an extensive trial mix program was carried out to determine the basic mix design.

The final concrete proportions used in all tests presented in this paper are listed in Table 1. A slump 100 to 150 mm was found useful to provide workability.

Table 1. Mix design (in kg/m3) and properties of fresh concrete

	Mix No.		
	1	2	3
Cement MP 30 - 10% PFA	453	457	451
Silica fume	30	30	30
Aggregate - 0 - 12 mm	1038	1045	1032
8 - 20 mm	554	558	551
Melt-extracted fiber	0	76	150
Rescon HP(S) - superplasticizer	1.5	4.9	10
Water	242	228	225
Slump (mm)	150	100	100
Entrained air content (%)	2.1	2.2	2.3
W/C ratio	0.53	0.5	0.5
Unit weight (kg/m3)	2320	2400	2450

Although slump of the trial concrete mix was significantly reduced by fibers, the use of excessive amounts of superplasticizer improved workability. No segregation or balling tendencies during mixing occured. However, the best results are obtained if fibers were added to aggregate and cement before water was added. Experience shows that mixing and placing (also for small jobs) as well as fiber dispersion throughout the mix were satisfactory.

3. TYPICAL PROPERTIES OF FIBER REINFORCED CONCRETE

Investigations are limited to basic concrete mixes specified in Table 1. All test results obtained on concrete modified with 1 or 2 percent fiber by volume are compared to those for no-fiber concrete. If not other stated concrete was tested after 28 days curing in water. The details on testing procedures are in /2/, however, a brief description is also given in this Chapter.

3.1. Strength and stress-strain behavior

Compressive strength tests on three 100 mm cubes were done in accordance with the Norwegian Standard. A stress-strain relation was registrated for each mix on two 100/280 mm cylinders at a deformation rate of 0.08 mm/min employing special equipment which allowed registration of the complete stress-strain curve under uni-axial loading. The tests gave results as shown in Figures 2 and 3.

The increase in compressive strength obtained for concrete modified with 1 to 2 percent fiber by volume is 11 to 15 percent. There was observed only marginal gains from 1 to 2 percent added fiber, which is probably a result of some decrease in workability with the increase of fiber content /3/.

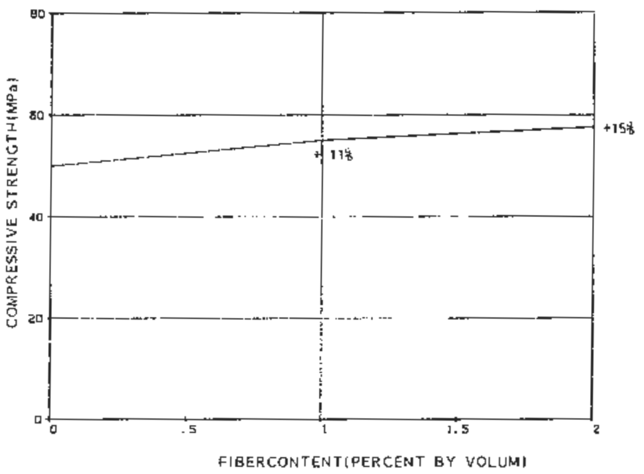


Fig.2. Compressive strength (100 mm cube)

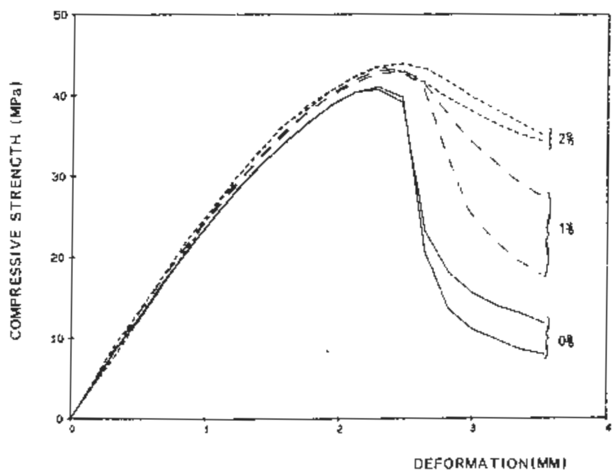


Fig.3. Stress-strain relationship

The experimental curves in Figure 3 show a significant increase in ductility (a much less steep descending part of the curve) for concrete with fiber. However, a concrete mix with a lower fiber content seems to be affected by a less uniform fiber distribution.

The curves in Figure 3 are esentially the same until 40 - 50 percent of ultimate load and indicate only slight increases in modulus of elasticity with the increase of fiber content.

Tensile strength of each concrete mix was measured on three 600/100/100 mm prisms at a deformation rate of 3.7 mm/min in a direct tensile testing apparatus. The mean values obtained are shown in Figure 4. The tensile strength increased almost linear as fiber content increased and for concrete with 2 percent fibers was about 30% higher than that of no-fiber concrete.

Typical registrated tensile stress-strain relations are shown in Figure 5. The addition of fibers improved not only direct tensile strength but also considerable additional energy was necessary to complete fracture. From the same relationship it can be observed that the modulus of elasticity in tension for concrete modified

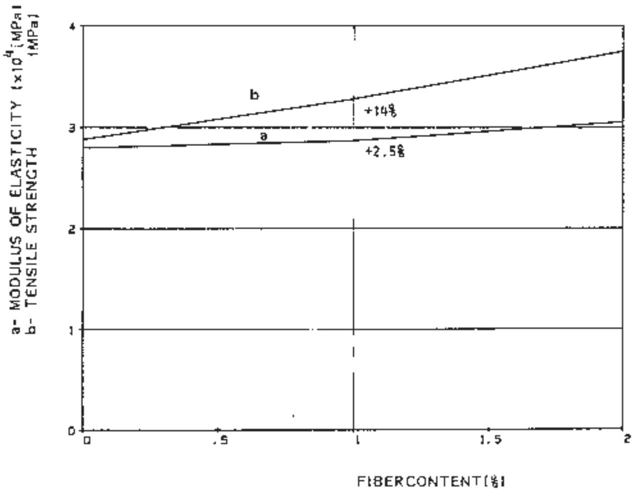


Fig.4. Tensile strength and E-modulus in tension

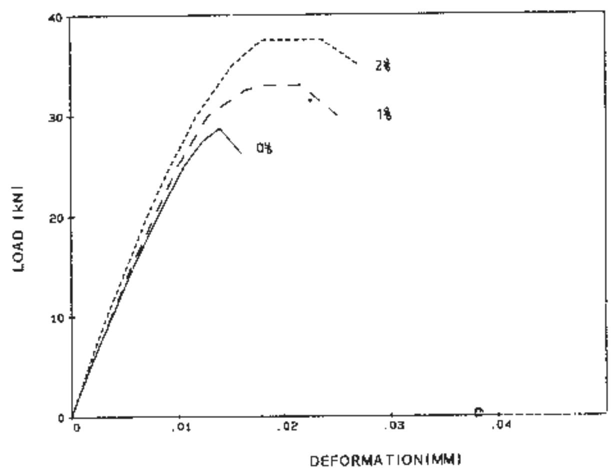


Fig.5. Typical Load-deformation curves

with fibers was improved in approximately the same ratio as that in compression.

Flexural strength was measured on 600/100/100 mm beams, tested in 3-point loading over a 550 mm span. The tests were carried out at a deflection rate of 0.1 mm/min. Figure 6 shows the flexural strength as the mean of three tests for each concrete mix. The increase in flexural strength was 20 or 25 percent due to the addition of 1 or 2 percent fiber, respectively.

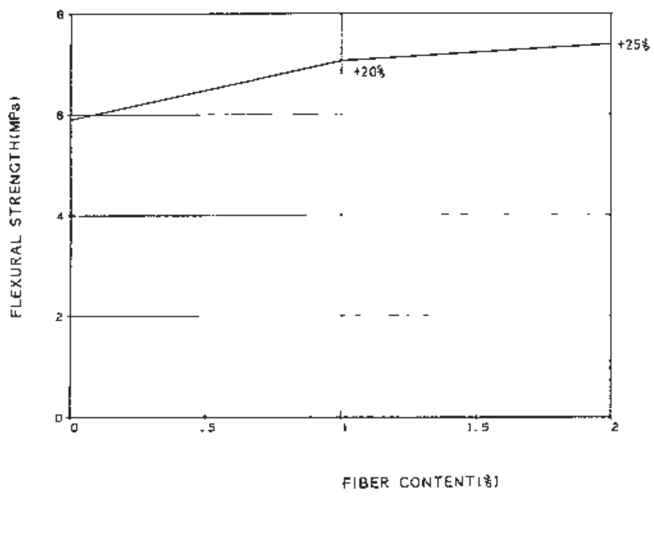


Fig. 6. Flexural strength

3.2 Fracture energy

The fracture energy defined as the total energy absorbed prior to failure was evaluated by taking the area under the load-deflection curve for notched 1200/100/100 mm beams in flexure.

The beams were subjected to 3-point loading over a 600 mm span. The depth of the notch was 40 mm. The beams were loaded at a deflection rate of 0.1 mm/min until 12 mm deflection i.e. 1/50 of the flexure span was obtained. The mean values of fracture energy from three tests for each concrete are shown in Figure 7. The values are calculated as the integral of (1/A)Pds where A is the area of the concrete section over the notch, P is the load and s is the actual deflection.

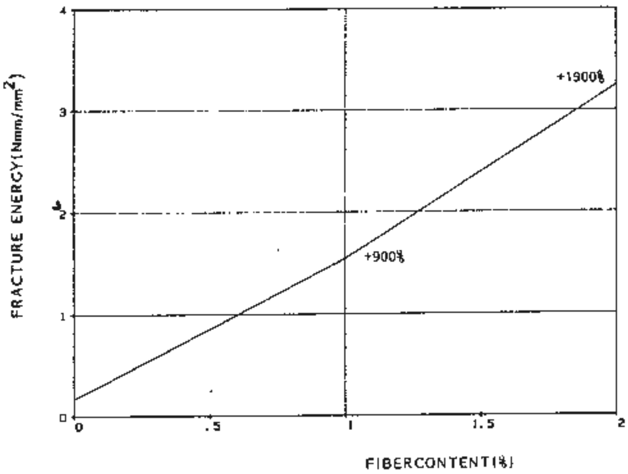


Fig.7. Fracture energy

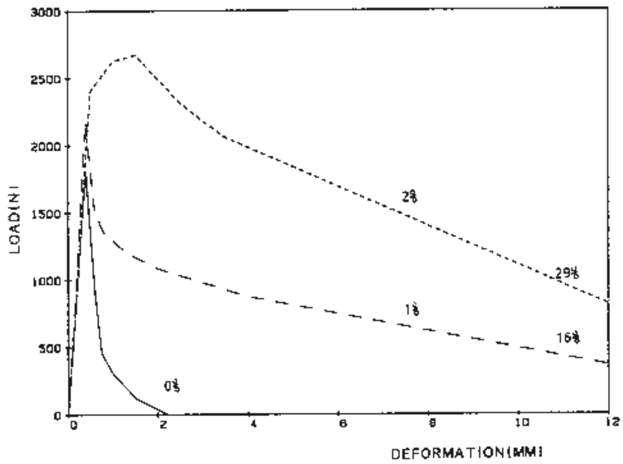


Fig.8. Typical load-deflection curves

The results shown in Figure 7 indicate a significant improvement as a result of the addition of fibers. The increase in fracture energy seem to be practically proportional to fiber content and is about 19 times that for no-fiber concrete. In Figure 8 typical registrated load-deflection curves are presented. Also shown are residual flexure capasities which increase linearly with fiber content.

3.3 Creep and shrinkage

The effects of long-term loading was investigated on 100/280 mm cylinders under a constant load of about 65 percent of ultimate load.

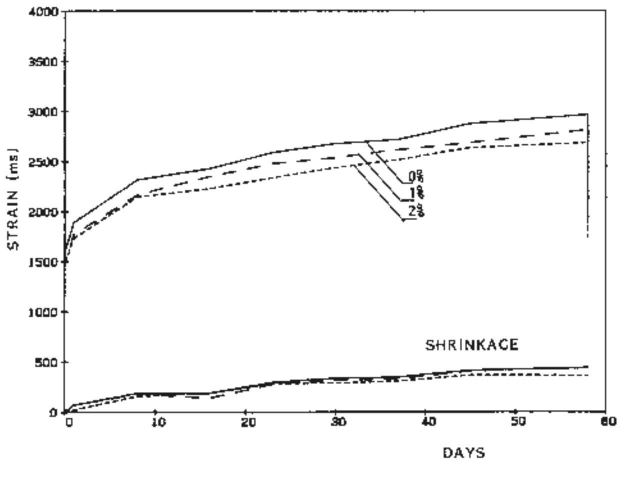


Fig. 9. Shrinkage and total strain in creep test

The creep test apparatus was employed in a room having a constant temperature of 20 C and a humidity of about 40% RH.

The specimens for the shrinkage tests were cured in water with a constant temperature of 20 C and the tests started after 21 days of curing.

The results of 60 days creep and shrinkage measurements are presented in Figure 9 and 10. The limited test data indicate that the addition of fiber had no significant effect on the creep coefficient, and that the creep coefficient tended to decrease.

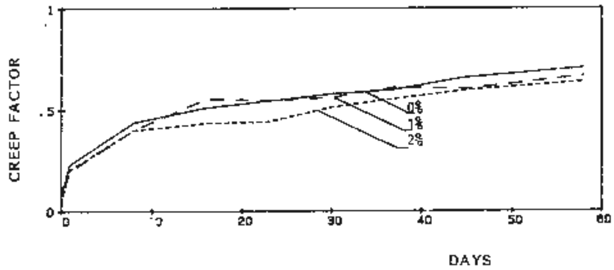


Fig. 10. Creep coefficient (defined as the creep strain to initial strain)

3.4 Bond and punching shear strength

Two different tests on bond strength were undertaken towards the possible application of fiber reinforced concrete not only in realization of composite structures but also in repair or strengthing of existing concrete structures.

Bond-tension strength at interface (vertically to interface) between 50 mm fiber modified concrete overlay and no-fiber base concrete was tested on specimens of 60 mm diameter using a bond testing apparatus. Ten measurements were done for each concrete mix.

Table 2. Bond-tension strength

Fiber content (in percent by volume)	Bond (MPa)		Fracture in base or overlay concrete (in percent)
	Mean	Standard dev.	
o	2.30	0.51	10
1	2.21	0.44	33
2	2.55	0.61	60

Although the test results presented in Table 2 showed no evident improvement when fibers were added to the concrete mix, the higher percent of fractures in the base or overlay concrete occured with the increase in fiber content.

Shear-bond strength at interface was investigated on specimens where concrete of each mix were cast into a gap 100/100/100 mm formed between two previously hardened no-fiber concrete cubes of the same dimensions. The tests were carried out in a testing machine where the specimens were loaded on a steel plate 100/100 mm centraly located and supported on the same steel plates at a distance of 100 mm. The mean values from three measurements for each concrete mix are shown in Table 3.

Table 3. Shear-bond strength

Fiber content (percent by volume)	Shear bond (MPa)
0	0.55
1	1.50
2	1.34

There was a large scatter in the experimental values, howeve, the increase in the bond strength was significant, although no evident indication on the influence of increased fiber content was observed.

Punching shear strength was tested on specimens of 250/250/50 mm. Three measurements for each concrete mix were done after 60 days. A 50 mm diameter steel cylinder was centrally located on the specimen over a 60 mm diameter hole in the bottom steel plate and then loaded to penetrate or diagonally split the specimens.

Table 4. Punching shear strength

Fiber content (percent by volume)	Punching shear strength (MPa)	Punching/ compress- ive str.	Increase (percent)
0	18.1	0.26	0
1	27.2	0.38	49
2	32.3	0.42	64

The results presented in Table 4 show a 49 to 64 percent increase in the static punching shear for concrete with 1 to 2 percent by volume of fibers.

4. TEST ON REPAIRED BEAMS

4.1. Outline of test

Two arbitrarily chosen, simply supported beams have been tested by bending. The test beams were of the same rectangular cross section and only a different percentage of longitudinal tensile reinforcement was provided. The details of the beams are shown in Figure 11.a.

The concrete was proportioned for a target 80 MPa cube strength at 28 days. The cube strength was 125 MPa when the beams were tested after approximately 560 days.

Deformed bars with measured yield stress of 510 MPa were used as tensile reinforcement.

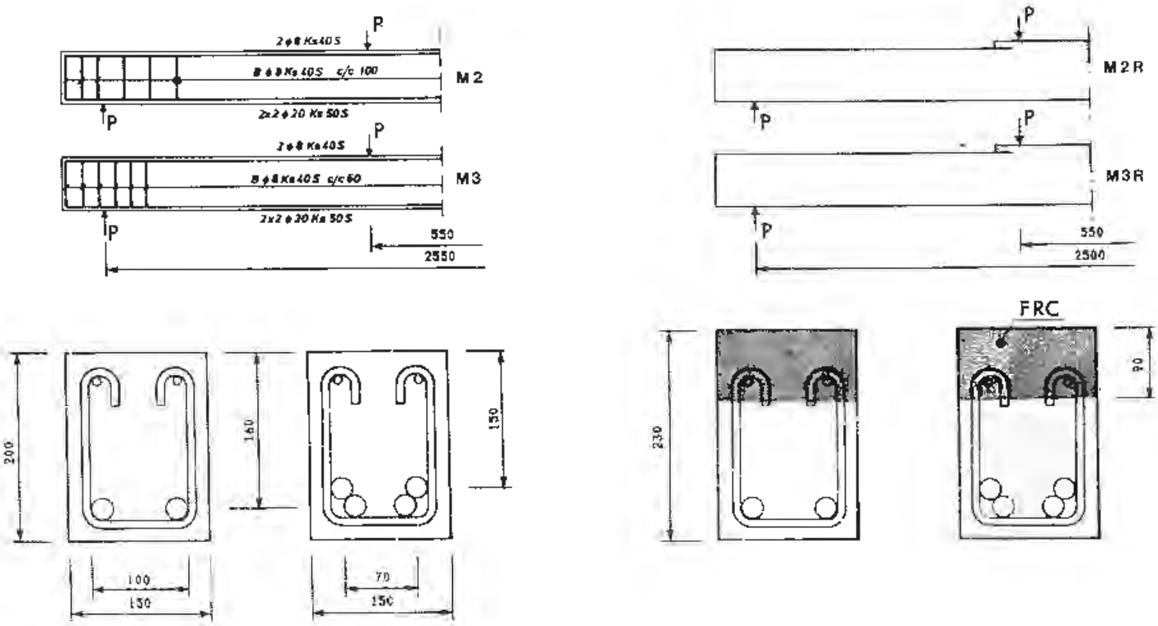


Fig. 11. Test beams: a – original beams M2 and M3, b – the same beams repaired marked M2R and M3R.

The beams were initially tested under 2-point symmetric loading applied to the top surface. Then, after failure, the beams were straightened and all cracked concrete was removed to approximately 1/3 of the beam depth. The interface was prepared by cleaning and moistening before casting a new topping.

For the new-cast topping a concrete mix containing 2 percent fiber by volume was selected.

However, to obtain the same bending capasity after repairing the beams, the need for an increase of the compressive zone was deduced on the basis of a slightly modified analysis of the composite section /4/. The overall cross-sectional dimensions of the repaired beams are given in Figure 11.b.

The casting mix was the same as mix No. 3 shown in Table 1. The cube strength of the fiber reinforced topping at testing after 30 days was 61 MPa.

4.2. Test arrangement

Since the moment-curvature relationship represents an important property and is useful to illustrate behavior for any structural member in flexure, only the details of determining moment versus curvature at midspan are presented.

The distribution of strain throughout the depth of the beam were obtained from measurements of deformation using a 200 mm mechanical strain gauge.

The gauge lines for beams before and after repair are shown in Figure 12.

The beams were loaded in a loading frame. After each increment of loading, all strain measurements were taken and cracks were marked.

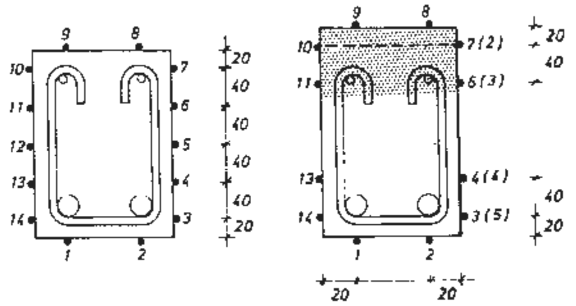


Fig. 12. Gauge lines for beam M2/M3 and M2R/M3R

Loading was continued until the beams ruptured completely or developed very large deflections.

4.3. Flexural behavior of repaired beams

Using testing procedures as described, strain progress versus bending moment and ultimate bending strength of beams were obtained directly.

The strain distributions over the depth of beams obtained from averaging the readings measured on individual gauge lines on opposite sides of the beam are shown in Figure 13.

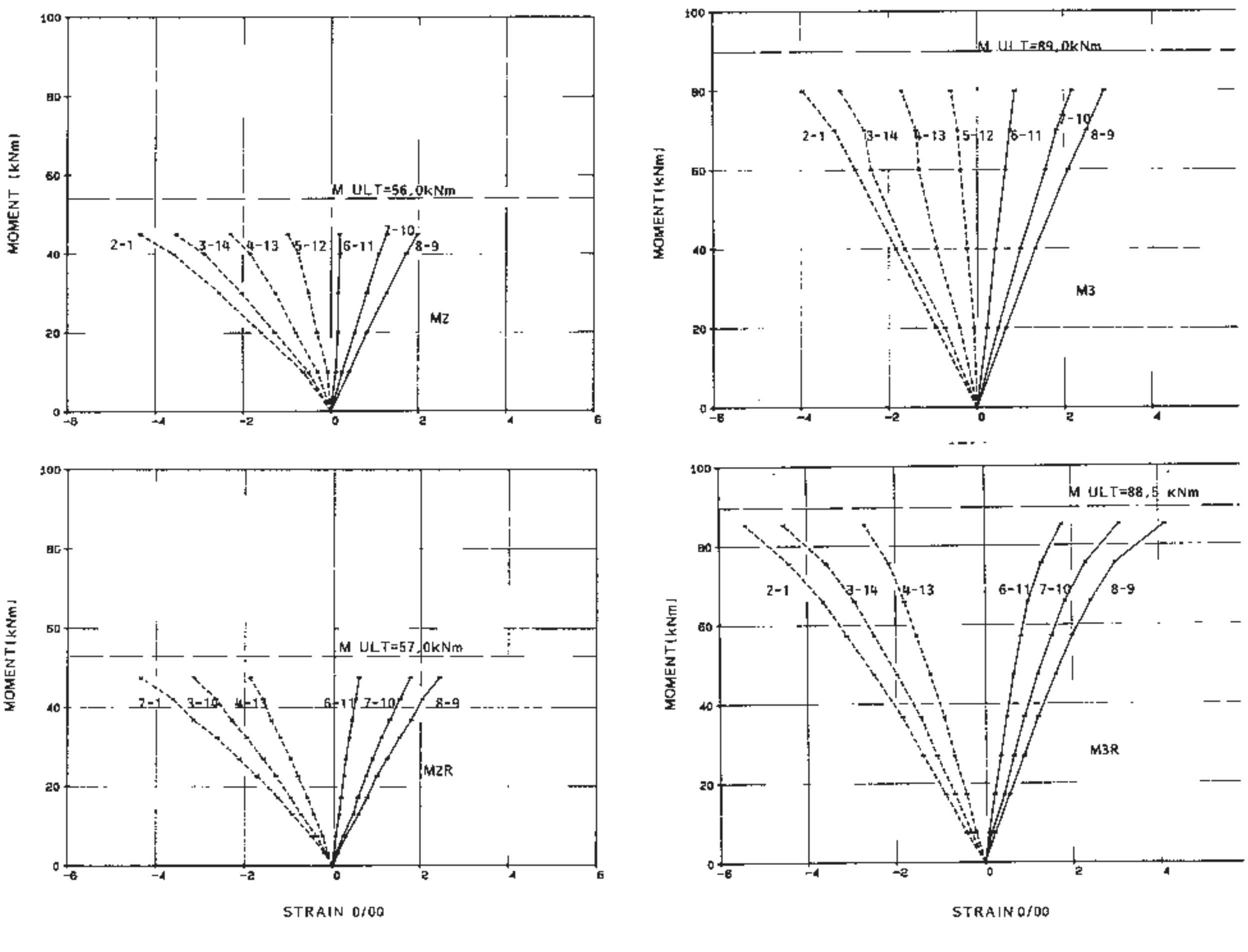


Fig. 13. Moment - strain relationship for tested beams

The variation of strain with depth at each level of load wa overall linear or nearly linear for any given beam. The averag strains varied in tension zone only for the beam M2R, because o distortion resulting from cracking. For this beam th distribution of cracks was less uniform.

Crack distributions are shown in Figure 14. Although these ar for repaired beams, they are similar to the crack pattern observed in the flexure span at initial loading.

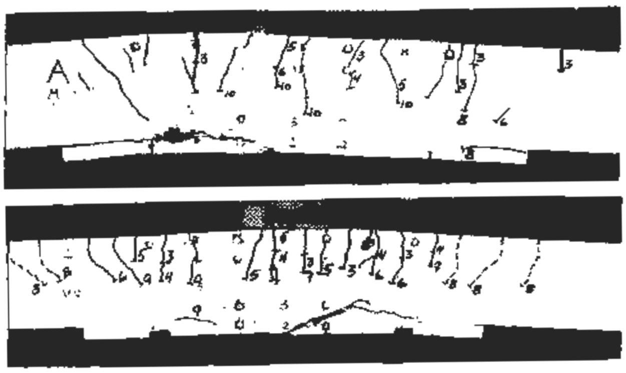


Fig. 14. Test beams after failure

Curvature (Ø) and flexural stiffness (B = M/Ø) were derive indirectly from measured strains by linear correlation for each load increment where M is the actual bending moment in cross section.

The relationship between actual applied moments and curvature are presented in Figure 15. However, conditions at the early stages of initial loading before first flexural cracking were ignored.

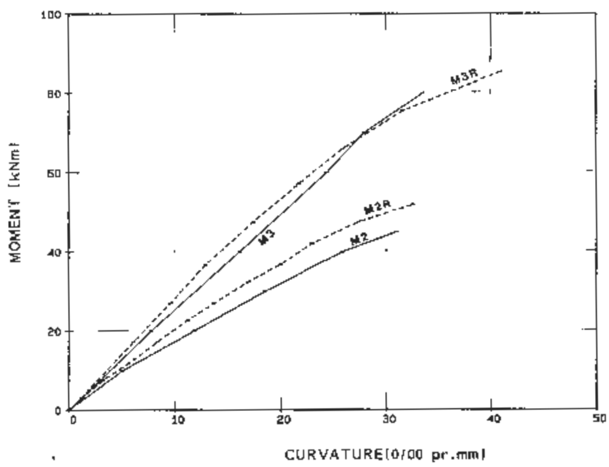


Fig. 15. Moment - curvature relationship

It is interesting to note that the curves shown in Figure 15 confirm the increase of flexural stiffness for the repaired beams. However, at a load increment near ultimate load the slope of the curve for beam M3R decreases, at an increasing rate, until failure occurs at strains larger than 0,004.

As may be observed in Figure 13, there is a tendency towards a redistribution of stresses and the resulting compressive forces tended to move down.

As shown in Chapter 2 this is consistent with the ductile characteristic of the concrete which was used in the compressive zone.

Because the overall objective is only to present the information on strength and deformation characteristics of fiber reinforced concrete, comparisons of different calculating methods will not be discussed in this paper.

5. IMPACT RESISTANCE TEST

5.1. Experimental investigation

The impact-resistance were evaluated by a falling weight test. Although such tests only provide an indication of the relative strengths rather than the absolute quantities, they have a certain illustrative importance /5/.

The test program involved nine slabs, each 900/900/50 mm, simply supported around the perimeter to leave a span of 715 mm. The specimens were cast in series of three from the same mix as shown in Chapter 2 i.e. containing no fiber (F0), 1 (F1) and 2 (F2) percent fiber by volume. All specimens were cured in the same manner and tested at 60 days. The compressive strengths of concrete at testing for series F0/F1/F2 were 67/68/72 MPa, respectively.

The tests were carried out using a 20 kg weight being dropped from various heights. The impacting tup had a 50 mm diameter and was instrumented in order to record the load, which can be interpreted to get the impact energy used to fracture the specimen. Figure 16 shows a typical recording of load versus time.

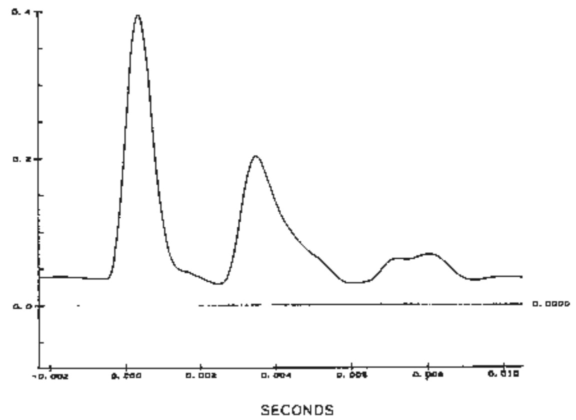


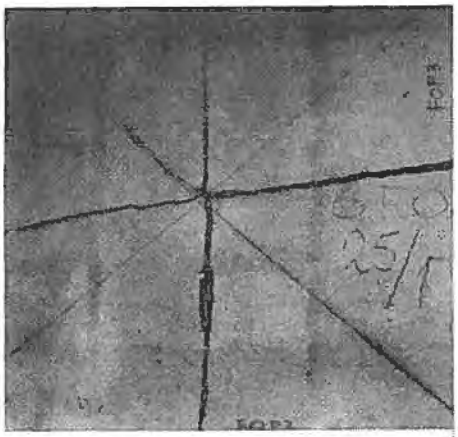
Fig. 16. Typical record of impact

For each series an initial drop height was chosen and if no evident failure occured, the drop height was increased and the test was repeated on the same specimen. After each impact the slabs were examined and their condition noted. Such a procedure

Table 5. Results from the impact test

Energy (J)	F0			F1			F2		
	No.1	No.2	No.3	No.1	No.2	No.3	No.1	No.2	No.3
20		1							
39		1		1					
59		1							
69			1						
78		S	S	1					
118				1					
157				1					
177	S								
196				1					
235				CP	C				
294					C				
353					C				
392					CP	CP	C		
491							C		
589							CP	C	
687								CP	CP
Max.			78			392			687
%			100			500			875

S-shattered, C-cracked, P-penetrated



F0 No. 3 (top)

F1 No. 1 (underside)

F2 No. 2 (underside)

Fig. 17. Typical pattern of failure

was repeated until the slab was in fragments or failure occured by penetration. For each new slab tested, initial drop heights were approximately equal to that for the slab previously tested.

5.2. Impact behavior

The results from testing are summarized in Table 5 where the pattern of failure is also marked. In the table, an energy level sufficient to crack or to penetrate the concrete is given in joules (J). A typical pattern of failure for each concrete type is shown in Figure 17.

The impact tests indicated not only that increasing fiber content increased impact resistance, but also the pattern of failure changed from fragmentation for no-fiber concrete, through crackes and penetration at 1 percent of fibers, to pure penetration (with insignificant cracks at underside) for concrete with 2 percent fiber by volume. None of the fiber reinforced concrete specimens were fragmented and these still had residual bearing capacity after failure.

6. DISCUSSION AND CONCLUSIONS

The tests on concrete with 1 and 2 percent fiber, i.e. for the volume of fibers normally employed, showed that melt-extracted steel fibers were effective in improving some concrete properties.

The fibers did not have a very significant influence on ultimate compressive strength. However, after reaching the ultimate load, the decrease in measured load with increasing deformation was much less for concrete with fibers than that for no-fiber concrete. There was a considerable increase in ductility.

Almost a linear increase to 30 percent in tensile strength for 2 percent by volume of fiber was observed in the direct tensile tests. Improvements in tensile strength measured in the flexural tensile tests were a 20 to 25 percent increase for concrete with a fiber content from 1 to 2 percent.

Measurements of fracture energy indicated that the toughness increased linearly and was in the order of 19 times higher for concrete with 2 percent of fibers than that of no-fibers concrete.

It has been confirmed by tests that the addition of fibers also improves other short-term strength characteristics as bond, shear strength and impact resistance. However, behavior in long-term loading and shrinkage does not seem to be affected.

In the falling weight tests fibrous concrete has provided significant impact resistance. An impact equivalent to 78 joules was sufficient to fragmentate specimens of no-fiber concrete. Using the same testing procedure a 5 to 9.75 times higher energy was needed to penetrate the specimens for concrete with 1 to 2 percent fiber content. Specimens with fibers were cracked on the underside but only minor cracks were reflected on the top surface and penetrations were only of local character.

Investigations on repaired beams confirmed that fiber reinforced concrete exhibits the physical properties which would make it an excellent material. However, such a conclusion is not only limited to fiber types discussed in this paper.

Additional research including durability is needed to establish rational design procedures for concrete modified with various types of fiber including melt-extracted steel fibers.

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