- Technical Paper -

INFLUECE OF STEEL FIBERS ON MECHANICAL PROPERTIES OF REINFORCED CONCRETE BEAMS WITH RANDOM CRACKS

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ABSTRACT

In this study, expansion agent was used to create random cracks. Two fiber percentages were considered in order to assess the influence of fiber volume on the mechanical properties of RC beams with random cracks. From the strain history it was possible to observe that some form of chemical prestress was caused by the expansion agent. Flexure and shear tests on RC beams were carried out. Steel fibers proved to be effective in arresting the cracks and reducing the compressive strain in the rebars due to chemical prestressing.

Keywords: expansion agent, steel fibers, chemical prestress, concrete strength

1. INTRODUCTION

Random cracking, also known as map cracking, as well as the decrease in Young's modulus of concrete are two of the effects of the Alkali Silica Reaction (ASR). These are caused by the expansion of the silica gel that is formed due to the reaction between the alkali in the cement and the silica contained by the aggregates. The gel thus formed, swells, when water is present, exerting pressure on the surrounding mortar matrix and aggregates. When this pressure exceeds the tensile strength of the mortar matrix, cracking occurs. Many studies have been conducted to better understand this phenomenon, [1] and methods have been proposed and developed to either slow down or completely avoid ASR. However, some of the methods were proven to have an unexpected effect on the long run, as reported in [2].

Nevertheless, there are cases when finding non reactive aggregate is either impossible or very expensive and the use of reactive or less reactive aggregates is the only option at hand. In order to counteract the possible damages due to excessive expansion, civil engineers have different methods they can use.

This study is aimed at investigating the possibility of using short steel fibers in order to reduce the deleterious ASR effect on structures. The idea of using short fibers came from the well known fact that they behave very good as crack arresters. The benefit of using fibers in concrete and the properties of short fiber reinforced concrete (SFRC) have been investigated by many researchers [3] and constitutive models have been developed to describe the behavior of SFRC [3].

Because ASR takes a lot of time and special conditions to develop, the use of expansion agent, also known as shrinkage reducing admixture, came as a solution to solving this inconvenience. Expansion agents are special products developed to increase the volume of concrete through specific chemical reactions. According to Collepardi et al. [4] there are two main types of expansion agents: those based on ettringite formation and those based on the formation on calcium hydroxide. For the purpose of this study, an expansion agent of the second type was used. Based on the observations made by Collepardi et al. [4] the process related to lime hydration occurs within 1-2 days. Thus, after 7 days of curing the agent has already reached its maximum potential expansion and the concrete its designed strength.

2. MATERIALS

2.1. Concrete

For this study a concrete with a design compressive strength of 30 N/mm^2, obtained from uniaxial compression tests on cylinders, at 7 days, was considered. Four different mix proportions

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Table 1 Mix proportions for each of the concrete batches

Concrete Type	W*1 [kg/m^3]	C*2 [kg/m^3]	W/C [%]	S*3 [kg/m^3]	G*4 [kg/m^3]	EA*5 [kg/m^3]	F*6 [kg/m^3]	AE*7 [kg/m^3]	SP*8 [kg/m^3]
C	175	350	50	788	963	-	-	2.8	1.4
0F80EA	175	350	50	721	963	80	-	2.8	1.4
05F80EA	175	350	50	721	963	80	40	2.8	2.6
10F80EA	175	350	50	721	963	80	80	2.8	2.6

*1 Water, *2 High Early strength Portland Cement, specific gravity = 3.14, *3 Fine aggregate, specific gravity = 2.64,
*4 Coarse aggregate, specific gravity = 2.64, G_{max} = 20 mm, *5 Expansion agent, specific gravity = 3.14
*6 Steel fibers, specific gravity = 7.85, *7 Air entraining agent, type 775S, specific gravity = 1.025
*8 Superplasticizer, high performance water reducing agent, type SP8N, specific gravity = 1.05

Fig. 1 Steel fibers layout

Table 2 Properties of concrete

Concrete Type	f_c' *1 [N/mm^2]	f_t *2 [N/mm^2]
C	34.8	2.4
0F80EA	4.0	0.9
05F80EA	29.7	3.0
10F80EA	31.1	3.4

*1 compressive strength of concrete
*2 tensile strength of concrete

were used as summarized in Table 1. The strength of each concrete mix was measured at the day of testing and they are presented in Table 2.

2.2. Reinforcement

The characteristics of the reinforcement are listed in Table 3. The specifications are according to JIS G 3112. The meanings of “Tensile reinforcement 1” and “Tensile reinforcement 2” will be explained in the subsequent chapters.

2.3. Steel fibers

Steel short fibers used in this study are with crimped ends, as it can be seen in Fig. 1. The length is L_f = 30 mm and the diameter is d_f = 0.6 mm. The material properties are: tensile strength f_u = 1000 N/mm^2 and Young’s modulus $E = 2.1 \cdot 10^5$ N/mm^2.

2.4. Expansion agent

The amount of expansion agent was to replace a part of the fine aggregate mass and not of the cement mass. This was based on the fact that in case of ASR the silica in the aggregate reacts with the alkali in the cement to create the ASR gel. Thus, the expansion agent is considered to be the reactive fine aggregate.

3. TEST PROGRAMS

The test specimens consisted in a total number of eight beams. For each concrete mix in Table 1 there were two beams: one designed to fail in flexure and one to fail in shear. The longitudinal “Reinforcement 1” in Table 3 refers to the reinforcement for the beams designed to fails in flexure and “Reinforcement 2” denotes the reinforcement for the beams designed to fail in shear.

“C” in Table 1 is considered to be the control case. “0F80EA” uses expansion agent to induce the formation of random cracks while “05F80EA” and “10F80EA” are similar to “0F80EA” to which steel fibers were added in 0.5% and 1% in volume respectively in order to control the cracking. Moreover, each specimen was named according to the designed mode of failure, an additional group of letters “SH” and “FL” being added in front of concrete type name for shear and flexure, respectively.

The sizes of the beams and the reinforcement layout are showed in Fig. 2. In case of specimens designed for flexure and shear mode of failure, the longitudinal reinforcement ratios are 1.08% and 4.3%, respectively. Both types of specimens have an a/d ratio of 2.71

After casting, the formworks where covered in wet cloth and kept at room temperature for 24 hours. The second day, the specimens were taken

Table 3 Reinforcement properties according to JIS G 3112

Reinforcement type	Bar size	Nominal diameter [mm]	Grade	Yield strength, f_y [N/mm^2]
Reinforcement 1	D13	12.7	SD295A	295
Reinforcement 2	D25	25.4	SD345	345
Stirrups	D6	6.25	SD295A	295

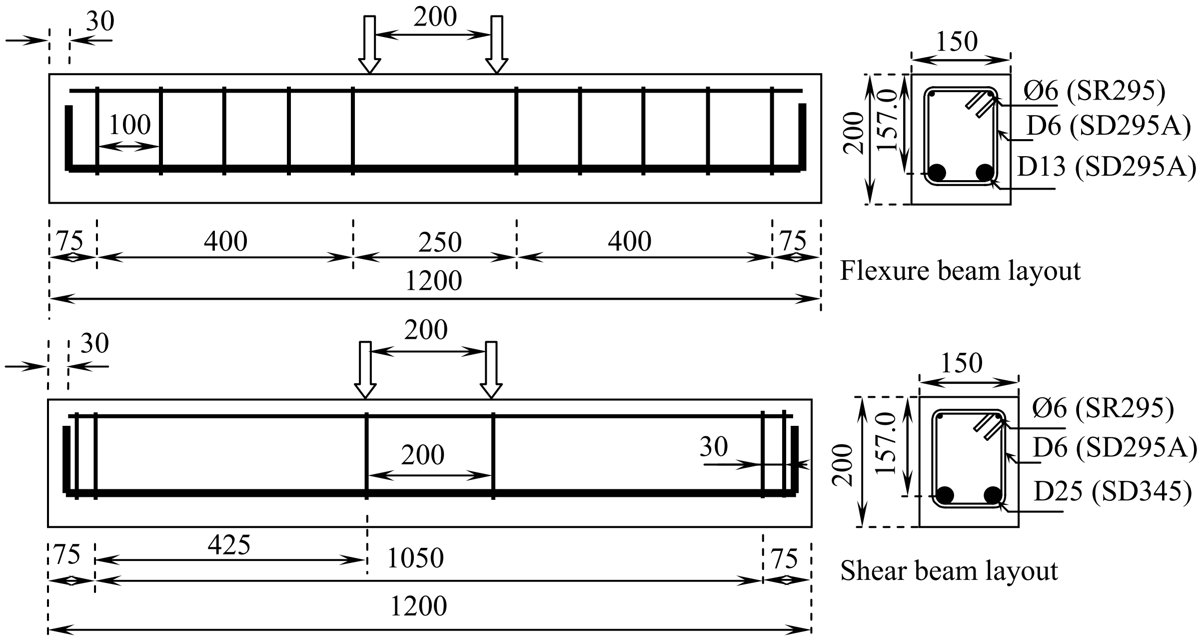

Fig. 2 Beam sizes and reinforcement layout

out of the formwork and for the next six days, they were kept at 20ºC constant temperature and 75% relative humidity. The strain induced in the beams was measured with the help of strain gages attached to the longitudinal reinforcement and recorded by a data logger at 30 minutes interval.

At 7 days the beams were tested for flexure and shear. The results obtained from testing as well as the strain history during the curing period of time are presented further on.

4. RESULTS AND DISCUSSION

4.1. Results from material testing

Figure 3 is a close up image of one of the cylinders for 0F80EA case that was tested for compressive strength. It can be clearly seen how the expansion created random cracks on the surface of the cylinder. Subsequent testing revealed the fact that the concrete was, indeed, very weak because its compressive strength was 4.0 N/mm^2 as it can be seen from Table 2. It should be pointed out that neither of the cylinders for the mixes containing fibers showed any visible evidence of surface cracks nor were any of the beams, with or without steel fibers.

The results obtained from uniaxial compression tests and from splitting tests (Table 2) on 0F80EA are not reliable, in this case, because they measure the strength of the unconfined concrete subjected to expansion. However, the concrete in the RC beams has a different strength due to the confining effect of the reinforcement. This effect cannot be simulated on cylinders and thus direct testing on the concrete from RC beams was necessary. A nondestructive Schmidt hammer test was conducted on beams made out of 0F80EA to approximate the strength of concrete confined by the reinforcement. The obtained average value was 21 N/mm^2. Even though this method is an empirical one and its results only approximate the results from the uniaxial compression tests for normal concrete (i.e. without expansion agent), it gave a more reasonable value for the strength of the concrete confined by the reinforcement in the beam.

Figures 4 and Fig. 5 show the steel strain history, given by the strain gage at mid-span, for all the concrete mixes containing expansion agent for the cases of flexure and shear, respectively. The negative values for the strain show that the steel is in compression as if some kind of prestressing were applied to it. This phenomenon was termed “chemical prestressing”.

Fig. 3 Close up image of micro-cracking

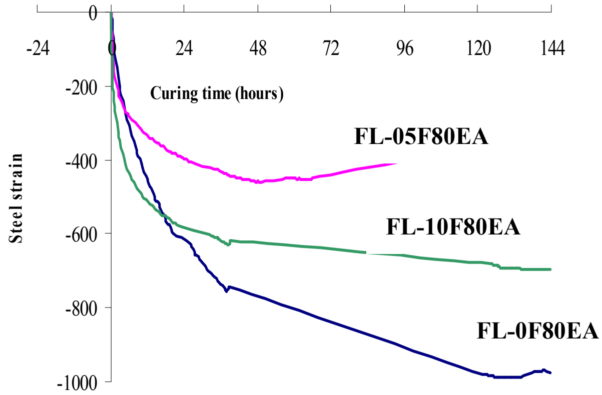

Fig. 4 Steel strain history at mid-span for the case of flexure

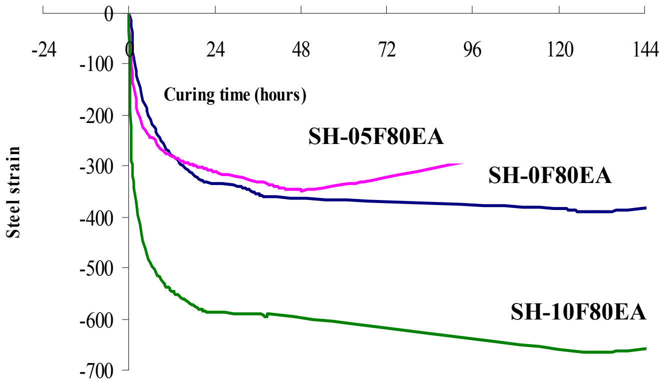

Fig. 5 Steel strain history at mid-span for the case of shear

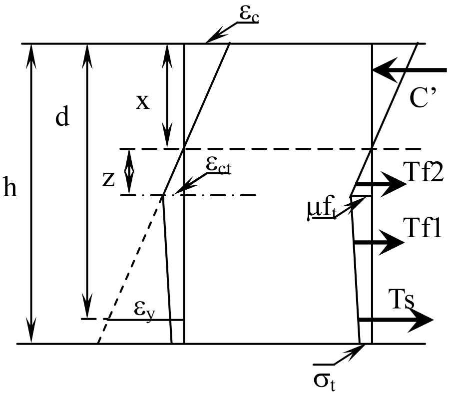

Fig. 6 Strain and stress distribution in SFRC at yielding stage

4.2. Flexure testing and flexure carrying capacity prediction

In the case of beams failing in flexure the prestressing force was taken into account by the means of M_0 which is the bending moment that creates a strain in the steel such that combined with the strain created by the prestressing the final results would be 0. It is also known as decompressing moment. For the beams having steel fibers, the model used is the one presented in Fig. 6. For normal concrete, its contribution in the tensile zone is considered to be 0 from the first cracking stage. In case of SFRC, even at the yielding stage there is the contribution of steel fibers. The depth of $x+z$ in Fig. 6 is the level where the tip of the flexural crack is located. The concrete above it still behaves elastically, thus its strain is smaller or equal to $\varepsilon_{ct} = \dfrac{f_t}{E_c}$ In Fig. 6, σ_t is computed according to Eq. 1 where μ is a reduction factor considered to be 0.55, f_t is the tensile strength of concrete taken from Table 2, ω is the crack opening and ω_k is the maximum crack opening given by Eq. 2. Tf1 is the tensile force given by the steel fibers at the crack opening and Tf2 is the tensile force given by the fibers in the uncracked tensioned concrete.

$$\sigma_t = \mu \cdot f_t \cdot \left(1 + \frac{\omega}{\omega_k}\right) \quad (1)$$

$$\omega_k = 1.4 + \frac{100}{f'_c} \quad (2)$$

Figure 7 shows the load-displacement curves for flexure case. As someone might expect by looking at Table 2, the concrete having 80 kg/m^3 of expansion agent and no fibers at all should exhibit the lowest peak load.

The results obtained following the above method for the ultimate stage, when the compression force taken over by the concrete is computed by using the equivalent stress block, are presented in Table 4 (all values are in kN). Taking into account both the prestress and the fiber effect can tremendously improve the accuracy of predicting the ultimate load in case of flexure as it can be seen from the P_{cal}/P_{exp} ratio from Table 4.

Table 4 Influence of the prestress and steel fibers on the peak load for flexure beams

	FL-0F80 EA	FL-0F80 EA*1	FL-05F8 0EA	FL-10F80 EA
P_{cal}	54.2	75.5	83.6	85.2
P_{exp}	84.1	84.1	80.8	85.4
P_{cal}/P_{exp}	0.64	0.90	0.85	0.99

*1 concrete strength is given by the Schimdt hammer test.

Table 5 Influence of the prestress and steel fibers on the peak load for shear beams

	SH-0F80EA	SH-0F80EA*1	SH-05F80EA	SH-10F80EA
β_n	2	1.74	1.49	1.89
P_{cal}	97.9	147.8	160.0	219.9
P_{exp}	173.1	173.1	183.2	215.8
P_{cal}/P_{exp}	0.57	0.85	0.87	1.02

*1 concrete strength is given by the Schimdt hammer test

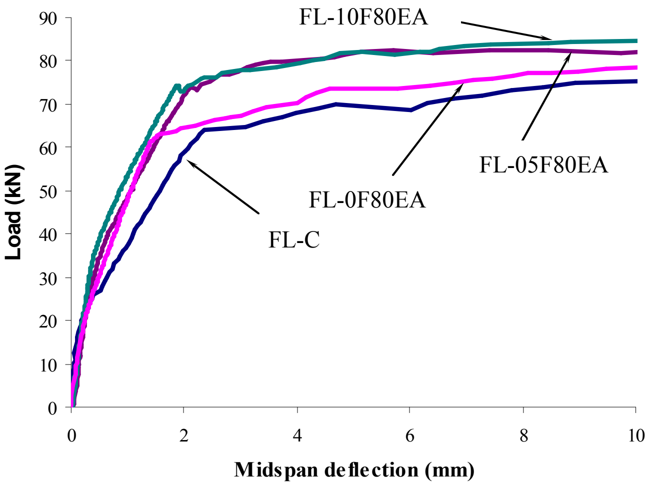

Fig. 7 Load-displacement curve in case of flexure

4.3. Shear testing and shear carrying capacity prediction

Fig. 8 depicts the load-displacement diagrams for all the specimens tested for shear. As someone might expect by looking at the values from Table 2, the specimen from 0F80EA mix should have the lowest peak load. Even by the rough estimation of the strength of confined concrete in the beam by the Schmidt hammer test the peak load should have been smaller.

However, if some sort of "chemical prestress" occurred indeed, as can be deduced from the steel strain history diagrams, it should have increased the maximum load that the beams can withstand. In order to be able to predict the ultimate load for shear the following assumption has been made: the total shear carrying capacity is comprised by the shear carrying capacity of the concrete, as given by Eq. 3 proposed by Niwa and Okamura in 1986, the shear carrying capacity due to prestressing (taken into account by the factor β_n from Eq. 4) and the shear carrying capacity given by the use of steel fibers. The calculation of β_n is carried out by means of Eq. 5 whereas the effect of fiber by means of Eq. 6.

$$V_c = 0.2 \cdot f'^{1/3}_c \cdot p_w^{1/3} \cdot d^{-1/4} \cdot b_w \cdot d \cdot \left(0.75 + \frac{1.4 \cdot d}{a}\right) \quad (3)$$

where p_w is the longitudinal reinforcement ratio equal to 4.3%, d is the effective depth and b_w is the thickness.

$$V_p = V_c \cdot \beta_n \quad (4)$$

$$\beta_n = 1 + \frac{2 \cdot M_0}{M_u} \quad (5)$$

where M_u is the ultimate resisting moment of the beam and M_0 is as defined in Section 4.2. The values of β_n should be greater than 0 but smaller than 2.

The effect of fibers is considered by means of the empirical Eq. 6 as given in [5] and [6].

$$v_u = 0.37 \cdot \tau \cdot V_f \cdot \frac{L_f}{d_f} \quad (6)$$

where τ is the bond strength equal to 4.15 N/mm^2 for crimped end fibers in the absence of any pull out tests [5] and V_f is the volume of fibers.

The values for the ultimate load, computed using this method, are presented in Table 5. Looking at the values of β_n it can be observed that the prestressing force plays an important role in the overall shear capacity of beams. These results were obtained by combining Eqs. 4, 5 and 6. Even though they were developed in different conditions and different material characteristics, they give a reasonably good approximation of the experimental results. However, further improvement of the method is suggested.

As is can be seen from Fig. 8, there is no big increase in the load carrying capacity of the SH-10F80EA beam as compared to SH-0F80EA. This could be explained by the fact that fibers add more confinement to the concrete and thus the chemical prestressing force decreases.

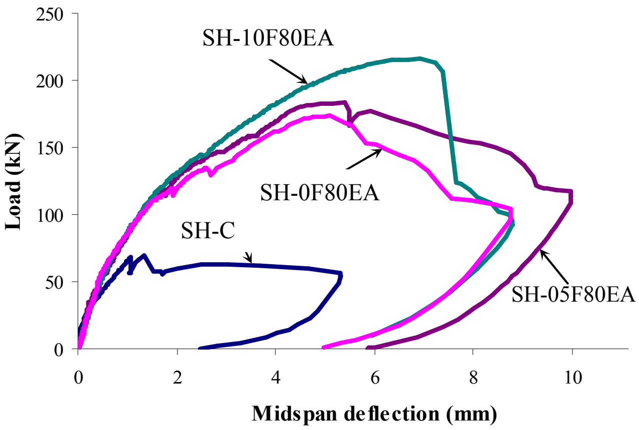

Fig. 8 Load-displacement curve in case of shear

5. CONCLUSIONS

1) Short steel fibers act to inhibit the propagation of cracks given by the expansion agent. This was clearly visible in the case of compression and splitting cylinders. The unconfined concrete from 0F80EA mix presented random cracking whereas the cylinders made from 05F80EA and 10F80EA mixes exhibited no cracks at all. Moreover, because of the addition of fibers the concrete compressive strength was almost similar to that of the control case with a slight increase in the tensile strength. The slightly lower compressive strengths means that there was micro-cracking inside the cylinders but fibers stopped the occurrence of macro-cracking.
2) There was a clear difference between the strength on concrete in cylinders made from 0F80EA mix and the beams made from the same mix. Uniaxial compression test showed a concrete strength on 4 N/mm^2 whereas the Schmidt hammer test conducted on the concrete from the beams showed an average strength of 21 N/mm^2. The confining role of the rebars was made clearly visible from this fact.
3) The use of the expansion agent gave good results for the formation of map cracking in the unconfined specimens, i.e. in the compression and splitting cylinders made with concrete 0F80EA. A sharp decrease in both compressive and tensile strength was observed as shown in Table 2. On the other hand, in the RC beams, the use of expansion agent created some kind of "chemical prestress", which, together with the use of fibers, showed an increase in the peak load and ductility for the RC beams.
4) The shear behavior of the beams, as presented in Fig. 8 show that fibers add more confinement to the concrete and thus reduce the strain in the rebars. By this, they play an important role on the chemical prestressing force that affects the overall behavior of the beams.
5) Taking into account the effect of the chemical prestress and that of the addition of fibers, showed an increase in the accuracy of predicting the ultimate loads both for flexure and shear as it can be seen in Tables 4 and 5, respectively. This is especially valid for 05F80EA and 10F80EA concrete mixes. However, for the case of 0F80EA the accuracy of the prediction is quite poor especially if the compressive strength value from the uniaxial compression test is considered. The use of the strength value given by the Schmidt hammer test leads to an improvement of the accuracy mostly because the test is performed directly on the confined concrete from the beam. The expansion of the beam is limited due to the presence of reinforcement and thus the concrete strength is different than the one from the unconfined cylinders. The value of the latter is better approximated by the Schmidt hammer test than the uniaxial compression test.

REFERENCES

[1] Smaoui, N. et al., Effects of Alkali Addition on the Mechanical Properties and Durability of Concrete, Cem & Concrete Res. 35, 2005, pp. 203-212

[2] Diamond, S., Alkali Silica Reactions – Some Paradoxes, Cem & Concrete Comp. 19, 1997, pp. 391-401

[3] Karihaloo, B.L and Lange-Kornbal, D., Tension Softening on Fiber Reinforced Cementitous Composites, Cem. & Concrete Comp. 19, 1997, pp. 315-328

[4] Collepardi, M. et al., Effects of Shrinkage Reducing Admixtures in Shrinkage Compensating Concrete under Non-wet Curing Conditions, Cem. & Concrete Comp. 27, 2005, pp. 704-708

[5] Swamy, R. N., Jones, R. and Chiam, A.T.P., Influence of Steel Fibers on the Shear Resistance of Lightweight Concrete T-Beams, ACI Structural Journal, 1993, 90(1), pp. 103-114

[6] Lok, T.S. and Xiao, J.R., Flexural Strength Assessment of Steel Fiber Reinforced Concrete, ASCE Journal of Materials in Civil Engineering, August 1999, pp. 188-196