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Properties of Steel Fibre Reinforced Concrete Containing Larger Coarse Aggregate

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Abstract

This paper describes an experimental investigation to study the properties, such as tensile, compressive, flexural strength, flexural toughness and flexural fatigue strength, of steel fibre reinforced concrete containing larger aggregate with maximum size of 40 mm. More than 400 specimens were tested, the results of the tests showed that the properties of the fibre concrete might approach those of fibre concrete containing small aggregate, when the size of steel fibre and the grading of aggregates were rationally selected for the mixture of fibre concrete. Based on the test results, some formulae were proposed to predict the properties of steel fibre concrete with larger crushed stone and a field trial project was carried out in Dalian harbour.

Keywords: steel fibre reinforced concrete, matrix concrete, coarse aggregate, grading, optimum, compressive strength, tensile strength, flexural strength, flexural toughness, fatigue endurance.

INTRODUCTION

Steel fibre reinforced concrete has been used throughout the world in pavements and slabs on ground. Some properties, such as tensile, flexural strength, fatigue endurance, impact resistance, capacity of inhibiting crack and energy absorption are substantially improved. This allowed reduced pavement thickness and increased joint spacing and led to better performance.

However, up to now the steel fibre reinforced concrete used extensively is rich concrete with small coarse aggregate of maximum size of 10, 15 or 20 mm. The increase of cement content certainly causes the increase of shrinkage and cost of the concrete. Small and less coarse aggregate in concrete is also unfavourable for the abrasion resistance. These may in some degree counteract the favourable effect of steel fibre on the concrete.

It is known that the strengthening effect of steel fibre increases with the ratio of fibre length to size of coarse aggregate. Typical ratio values are in the range from 1·5 to 2·0; beyond this range the reinforcing effect of steel fibre on concrete may be lower. The reason is that, on the one hand, some steel fibres tend to arrange in a coarse aggregate–mortar interface, moreover, the microcracks develop also in this interface. Therefore, if the fibres are short, they will not be across microcracks and thus arrest them; on the other hand, if the fibres are too long, the workability of mixture may get worse and the properties of fibre concrete will consequently be worse. However, some experimental observations have shown that the steel fibres in the matrix are discrete in a random way and are not totally concentrated on the surfaces of crashed stone. Also, the cracks were frequent across some stones when the rich concrete failed. It is thus obvious that so long as the steel fibres with proper length and crushed stone with acceptable size, exceeding the limit of 20 mm, are used in concrete, the steel fibres may still have a reinforcing role. Based on this thought, the authors have carried out a series of experiments to study the properties, e.g. compressive, tensile and flexural strength, toughness and fatigue performance of the fibre concrete containing larger crushed stone with a maximum size of 40 mm. The reinforcing effect of steel fibre on the fibre concrete has thereby been evaluated; the length of steel fibre, the size of coarse aggregate and the grading of coarse aggregate have been chosen to obtain an optimum reinforcing effect. After the experimental study the field trial has been carried out in Dalian harbour.

EXPERIMENTAL PROGRAM

The experimental program consisted of two parts. The first part was a static experimental program to study the effect of steel fibre, the size of aggregate on concrete properties and to choose the mixture proportion. The second part was a fatigue experimental program .

Details of test specimens

The test specimens were made from the following materials: plain portland cement with standard strength 42·5 MPa, river sand with middle fineness modulus, crushed limestone with maximum size 20 or 40 mm, a composite type of water-reducing admixture and the melt extract carbon steel fibre made by QingAn Steel Factory in China. This kind of fibre was divided into three types:

(I) 25 mm in length with aspect ratio 43,
(II) 35 mm in length with aspect ratio 60,
(III) 45 mm in length with aspect ratio 77.

The concrete mixture with 0·5 water–cement ratio was used to cast the specimens. The volume percentage of fibres was varied from 0 to 2%. The crushed stone was divided into two ranges: medium stone with sizes from 20 to 40 mm and fine stone with sizes from 5 to 20 mm. In the static test specimens, the proportions of fine stone to medium stone were 10:0, 6:4, 5:5 and 4:6. In the mixture for fatigue test specimens, the proportions were taken as 10:0 and 6:4. The specimens were numbered to represent the type of fibre, the aggregate state and the percentage of fibre by volume. For example, a specimen number II–64–10 represents the II-type of steel fibre, a proportion of fine stone to medium stone of 6:4 and 1·0% of fibre by volume used in the mixture for casting the specimen. The proportion of the mixture without steel fibre is shown in Table 1; other proportions of mixture with different volume fractions of the fibre may be obtained from this proportion. In general, the addition of 0·5% of steel fibre by volume leads to increasing cement of 20 kg/m^3 and ~3–5% of sand ratio for getting adequate workability of the mixture.

Cubes (150 mm) were used in the compressive and the splitting tensile test. Beams (150 × 150 × 550 mm) were used in the flexural test and the fatigue flexural test. In total, 210 cubes and 105 beams were prepared for static testing and 120 beams for fatigue testing.

Test methods

The methods of tests, e.g. compressive, tensile and flexural test, followed the standard of test methods for steel fibre reinforced concrete.[1,2] The splitting tension method used to test the tensile strength of fibre concrete was debatable, but recent researches have shown that the method is also suitable for fibre concrete.

An electro-servo hydraulic structural fatigue test system was used in flexural static and fatigue tests. The static test was controlled by displacement and the fatigue test by load. Test control with an analog controller is conventional and accurate with an error of dynamic load or displacement being within 0·5%. A sine waveform with ~5–20 Hz frequency for loading up the specimen was generated by the function generator and adjusted by the servo-controller in the analog controller. Three computer programs developed by the authors were used for monitoring the load, calibrating the measurement meters and acquiring data.

The flexural test set-up is shown in Fig. 1. Strains over the depth of the cross-section in mid-span were measured at different load levels or cycles with strain gauges of 100 mm in length, the mid-span deflection and the tensile

Table 1. Brief proportion of concrete mixture

Max. size of agg., 20 mm			*Max. size of agg., 40 mm*		
W/C	*Sand ratio*	*Cement (kg/m^3)*	W/C	Sand ratio	Cement (kg/m^3)
0·50	0·40	350	0·50	0·35	310

deformation were synchronously measured with clip-extensometers.

STATIC TEST RESULTS

Compression

The effect of steel fibres on the compressive strength of concrete containing aggregate with maximum size 40 mm is similar to that of concrete containing aggregate with maximum size 20 mm. Increasing range is from a negligible quantity to 20% and in most cases the compressive strength increases with steel fibre content, but decreases for concrete containing 2% by volume of fibre, because of the poorer workability of its mixture. The effect of aggregate maximum size on the compressive strength of concrete is negligible.

Splitting tension

Figure 2 shows the relationship among splitting tensile strength, content of steel fibre and ratio of fine stone to medium stone. The influence of steel fibre on tensile strength of concrete is greater than that on compression, the increasing range from a negligible quantity to 58%. The strengthening effect of steel fibre is different depending on the content of steel fibre and the ratio of fine stone to medium stone; the effect of higher content of fibre is greater than that of

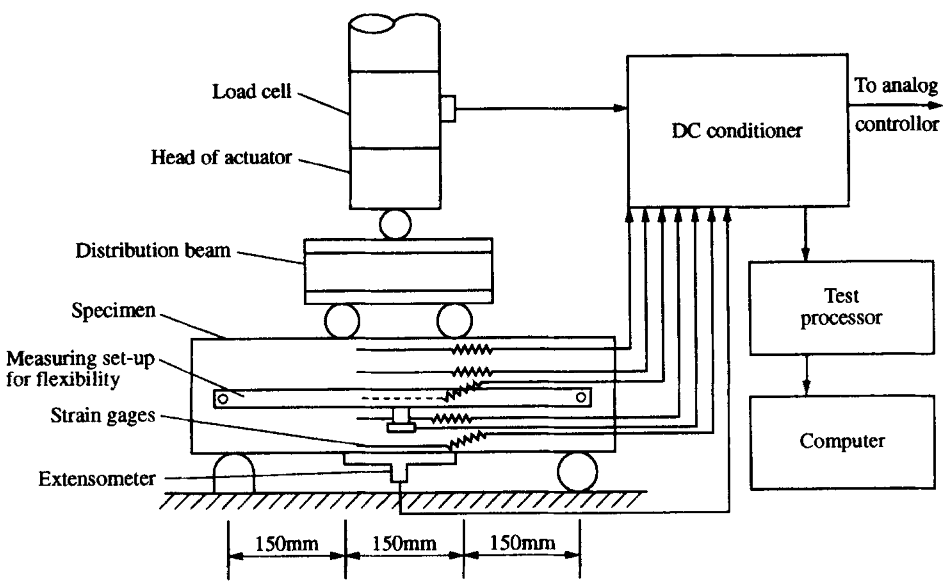

Fig. 1. Test set up.

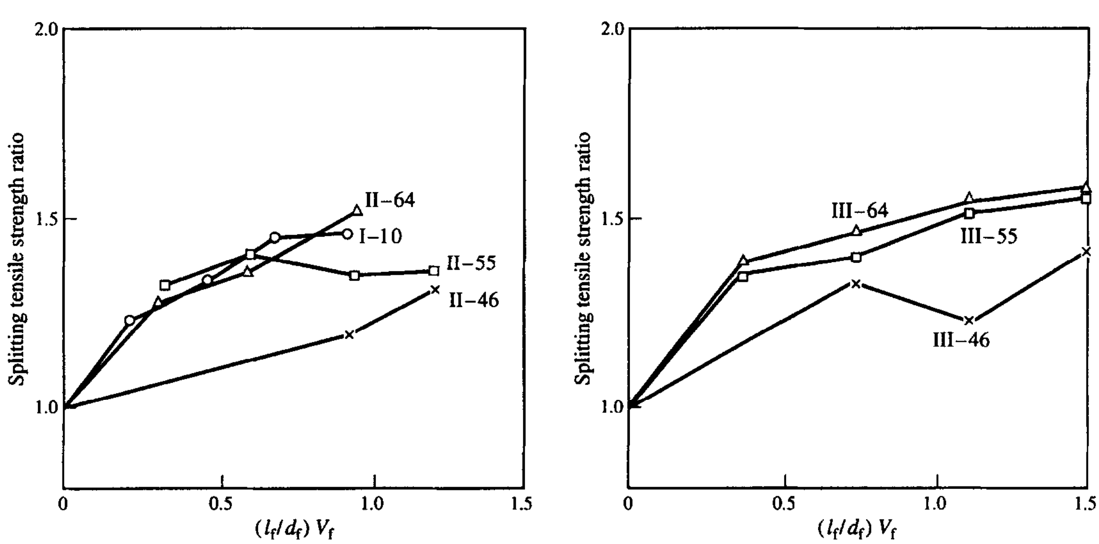

Fig. 2. Test results of tensile strength.

lower content of fibre. At the same fraction of steel fibre by volume, tensile strength decreases with the increase in the ratio of medium stone of size 20–40 mm. The strengthening effect of steel fibre on concrete with a medium stone to fine stone ratio of 6:4 is the best and approaches that on concrete with a smaller aggregate of maximum size 20 mm.

The tensile strength is also affected by aspect ratio of steel fibre: the longer the steel fibre, the higher the tensile strength (Fig. 3).

Flexure

It can be seen in Fig. 4 that the addition of fibres to concrete containing larger coarse aggregate with a maximum size of 40 mm substantially improves ultimate flexural strength, and the improvement of the strength at the same volume fraction of the fibres is slightly reduced as the content of medium crushed stone increases from 20 to 40 mm.

Two types of equation to predict ultimate flexural strength of fibre concrete were developed based on the regression analysis.[3,4] One of the equations obtained from test data of small specimens (102 × 102 × 305 mm) is as follows:[3]

$$f_{cr} = 0{\cdot}97 f_r V_m + 3{\cdot}4 V_f l_f / d_f \qquad (1)$$

Where f_{cr} and f_r are the ultimate composite flexural strength of the composite and the matrix, respectively; V_m and V_f are the volume fraction of the matrix and the fibres, respectively; and l_f/d_f is the ratio of the length to the diameter of the fibres (aspect ratio).

Because the bond stress between matrix and fibres is related to the strength of the matrix, another equation was suggested by the authors.[4]

$$f_{cr} = f_r(1 + \alpha_r V_f l_f / d_f) \qquad (2)$$

Where α_r is a strengthening effect coefficient of different fibres on the ultimate flexural strength.

Based on the regression of large amounts of test data, the coefficient α_r was determined as 0·51 and 0·73 for melt extract fibre and sheared fibre, respectively, used in fibre concrete containing small aggregate. The experimental

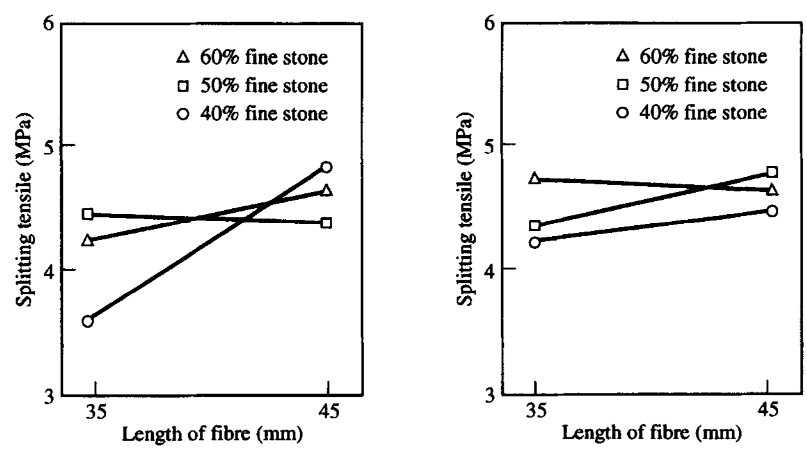

Fig. 3. Relationship between tensile strength and length of steel fibre.

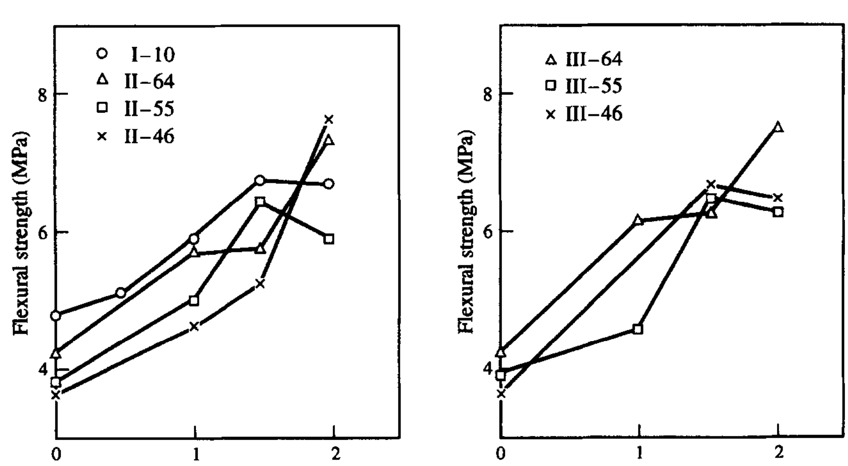

Fig. 4. Flexural test results.

flexural strengths proved eqn (2) and the values of α_f to be also applicable for the fibre concrete containing larger aggregate with maximum size up to 40 mm.

Flexural toughness

Typical experimental load–deflection curves are plotted in Fig. 5. It is shown that the addition of fibres improves significantly the flexural toughness for every group of specimens. The toughness indices I_{10}, defined in ASTM C 1018, were calculated and plotted against volume fraction of the fibres in Fig. 6. The index I_{10} is obtained by dividing the area under the load–deflection curve, determined at a deflection 5·5 times the first-crack deflection, by the area under the curve up to the first crack. The volume content of fibre greatly affects the toughness but the effects of fibre length and aggregate size on the toughness are slight in the test scope.

Optimal proportion of particle fractions of crushed stone

In pavement application in China the crushed stone used in conventional concrete was gen-

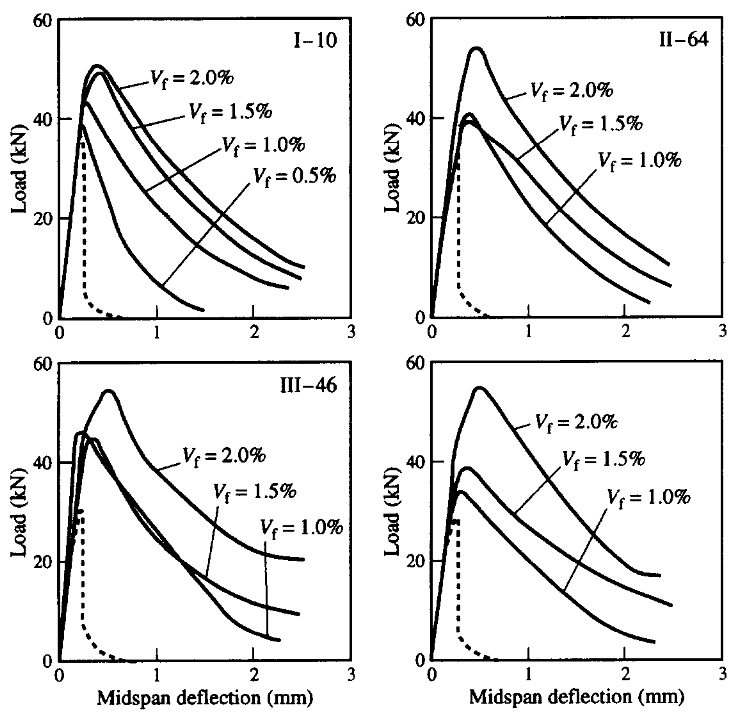

Fig. 5. Typical experimental load–deflection curves.

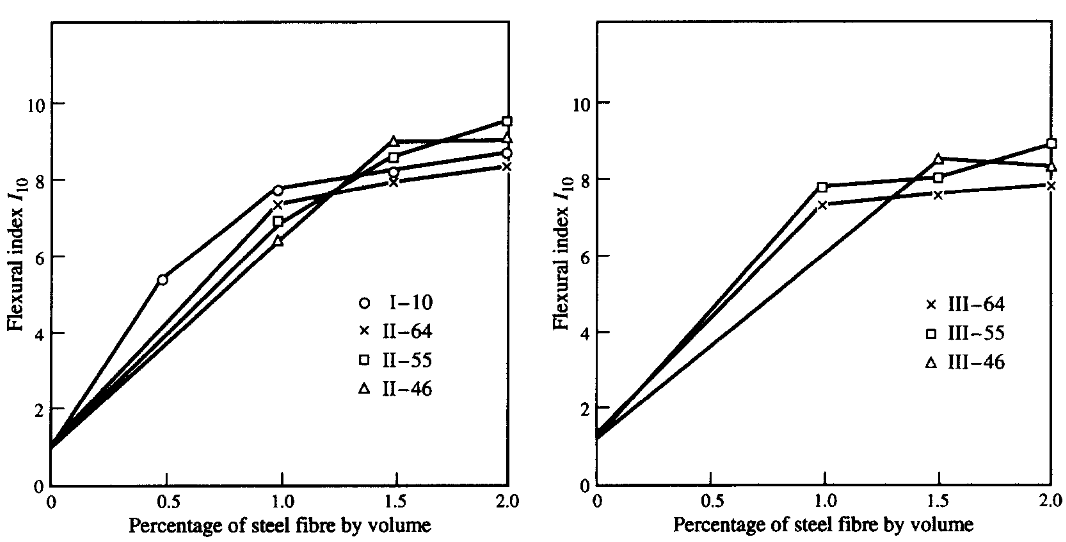

Fig. 6. Curves of toughness index against volume fraction of fibres.

erally divided into two particle fractions: medium particles with nominal size from 20 to 40 mm and fine particles with nominal size from 5 to 20 mm. The weight fractions of medium crushed stone in all graded aggregate that met the grading requirements for conventional concrete were 40–70%. But for fibre concrete, according to above mentioned test results, the reinforcing effect of steel fibres on concrete was in some degree reduced with the increase of medium crushed stone in the concrete. It is also reasonable, however, that the proportion of fine crushed stone to medium stone of 6:4 should be considered as an optimum proportion. The reason is that the tensile and flexural strengths of the fibre concrete containing crushed stone with this proportion are similar to those with small crushed stone at the same water–cement ratio and the same production of aspect ratio by volume fraction of the fibres. Therefore, this proportion was used in the mixture of fibre concrete to prepare the fatigue test specimens.

FATIGUE TEST RESULTS

Fatigue strength

Figure 7 shows that the steel fibres have also substantially improved the flexural fatigue strength of concrete. At the same stress ratio the fatigue life has been extended with increase of fibre content, for instance, at stress ratio 0·8 the fatigue life of the specimen with 1·5% of steel fibre by volume is about 60 times that of the specimen without steel fibre.

By means of regression analysis using the data a fatigue equation has been obtained as follows:

$$S = (0{\cdot}944 - 0{\cdot}77\ \lg N)(1 + 0{\cdot}154\, l_f/d_f V_f) \quad (3)$$

Where N is the fatigue life, i.e. limit number of load cycles, of the fibre concrete containing larger aggregate with a maximum size of 40 mm; and S is the stress ratio, i.e. ratio of the peak value of fatigue stress to the static ultimate flexural strength.

The mean value of ratios of measured to calculated stress by eqn (3) is 1·203 with a coefficient of variation of 5·06%. Equation (3) is conservative and corresponds to the equation for plain concrete pavement in the design standard of China,[5] so it can be used in the design for fibre concrete pavement.

Figure 8 shows the fatigue test result, part of which is taken from Sun and Gao.[2] In Sun and Gao's test, the test method, the materials and the proportion of the mixture are the same as that in our test but the type of steel fibre is different. In their test sheared fibre with rectangular cross-section was used and the bond of the fibre with the matrix was higher than that of melt extract fibre. Figure 8 indicates that fatigue strength of the fibre concrete with larger crushed stone is almost the same as that of the fibre concrete with small crushed stone.

Deformation behaviour

In the full fatigue test process, peak values of mid-span deflection, maximum tensile elongations at the specimen bottom of mid-span, were measured for every specimen by a computer with a high rate data acquisition system. The typical process curves are shown in Figs 9 and 10, respectively.

The curves are similar to each other and can be divided into three stages: initial plastic deformation stage, stable growing stage of elastic deformation and unstable deformation stage.

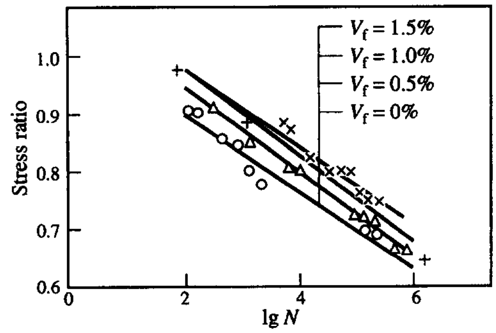

Fig. 7. Stress ratio — fatigue life relationship.

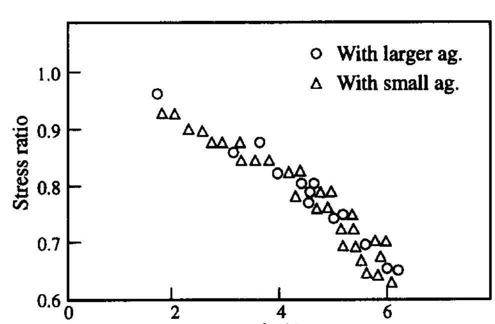

Fig. 8. Stress ratio — fatigue life relationship for two types of fibre concrete.

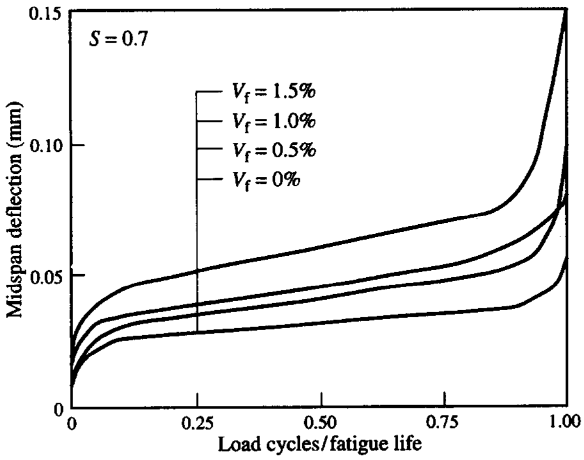

Fig. 9. Mid-span deflection in fatigue test process.

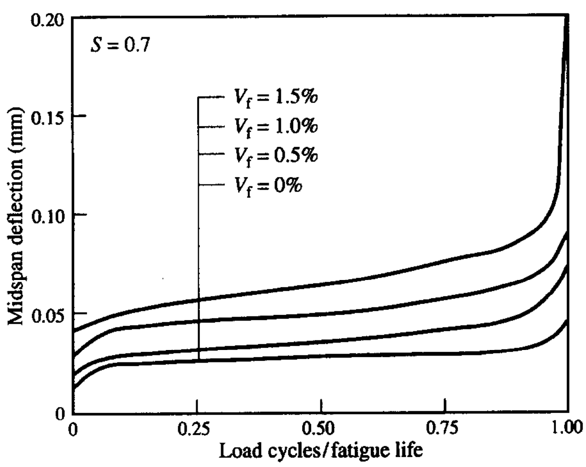

Fig. 10. Tensile elongation at the specimen bottom in fatigue test process.

The first stage and the last stage are short and within about 5% of total loading cycles.

It is well-known that the addition of steel fibre affects the flexural elastic modulus of concrete slightly, but why the deformations of the specimens with different contents of steel fibres so different from each other? The reason is that the peak values of fatigue stress are different for the specimens with different contents of steel fibres, although at the same stress ratio. Special attention to the tensile deformation and crack opening should be paid since large tensile deformation may lead to the deterioration of serviceability and to the failure of the specimens under fatigue load. However, when the unstable tensile deformation and crack opening take place, the specimen will soon rupture and the number of load cycles is closed to the fatigue life both for fibre concrete and plain concrete. It is also reasonable that the rupture of a specimen (or member, pavement) of fibre concrete is regarded as its failure.

FIELD TRIAL

The field trial project of full depth pavement of fibre concrete containing larger aggregate was complete in August 1992 at Dalian harbour. The 90 m long × 12 m wide × 150 mm thick pavement was placed, with joint spacing of 12 m, on a 300 mm roller compacted crushed stone base. For comparing performances the pavement was divided into two parts: the first part containing larger aggregate with maximum size of 40 mm and cement content 350 kg/m^3; the second part containing small aggregate with maximum size of 20 mm and cement content 400 kg/m^3. All the concrete mixture had a melt extract fibre content of 78 kg/m^3 of 0·5 mm equivalent diameter × 30 mm long. For a day after placement a slight crack about 6 m long had appeared on the surface of the end in the second part of the pavement. It was longitudinal and in the center of the pavement. The pavement had borne heavy traffic and endured severe temperature stress for six months; three transverse cracks appeared in three sections at about 10 cm from the joints. They opened about 2–5 mm and the adjacent joints still remained closed. This problem may be caused by an inadequate construction procedure. In general, a construction joint, i.e. the seam between the section of hardened concrete pavement and the section of fresh concrete pavement, should coincide with a designed construction joint or expansion joint. In this placement, in fact, because of inadequate construction procedure, the construction joint was apart from the designed contraction joint by about 10 cm. It is not strange that a contraction crack appeared at the construction joint and the designed contraction joint still remained closed although it had been cut at the surface. However, the pavement is still performing satisfactorily. The long term performance will be examined in the future.

CONCLUSIONS

Based on the static and fatigue test results and the observation on the field trial, the following conclusions have been drawn:

(1) Steel fibres are not only used to reinforce fine stone concrete but also used to reinforce the concrete containing larger aggregate with maximum size of 40 mm, provided that the steel fibres are not shorter than 35 mm.
(2) The proportion of medium crushed stone to fine crushed stone is in relation to the reinforcing effect of steel fibre on the concrete. The optimum proportion is about 4–6, at which the reinforcing effect is similar for fine stone concrete.
(3) The fibre concrete containing larger crushed stone demonstrated a good fatigue performance in both laboratory test and field trial.
(4) An equation is proposed to predict the fatigue flexural strength of fibre concrete containing larger crushed stone. This equation gives good and conservative prediction for the fatigue strength of the tested specimens.
(5) The deforming process of fibre concrete under fatigue loading is divided into three stages: initial plastic deforming stage, linear stage and unstable deforming stage; the last stage is very short so that fibre concrete shows a good serviceability.

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