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Long-term deflection of high-strength fiber reinforced concrete beams

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Abstract. The paper presents an experimental and theoretical study on the influence of steel fibers and longitudinal tension and compression reinforcements on immediate and long-term deflections of high-strength concrete beams of 85 MPa (12,300 psi) compressive strength. Test results of eighteen beams subjected to sustained load for 180 days show that the deflection behavior depends on the longitudinal tension and compression reinforcement ratios and fiber content; excessive amount of compression reinforcement and fibers may have an unfavorable effect on the long-term deflections. The beams having the ACI Code's minimum longitudinal tension reinforcement showed much higher time-dependent deflection to immediate deflection ratio, when compared with that of the beams having about 50 percent of the balanced tension reinforcement. The results of theoretical analysis of tested beams and those of a parametric study show that the influence of steel fibers in increasing the moment of inertia of cracked transformed sections is most pronounced in beams having small amount of longitudinal tension reinforcement.

Key words: beams (supports); deflection; effective moment of inertia; flexural rigidity; high-strength concrete; immediate (instantaneous) deflection; long-term (time-dependent) deflection; reinforced concrete; steel fibers.

1. Introduction

Strength and serviceability are the two main requirements of reinforced concrete design. Considering strength requirements, design with high-strength concrete (HSC) may lead to member sizes less than those obtainable with normal-strength concrete of 21 to 42 MPa (3000 to 6000 psi). In the case of design with high-strength fiber reinforced concrete (HSFRC), both reductions in member size and amount of longitudinal tension and compression reinforcements may result. The reduction in member size is beneficial in decreasing the self-weight (dead load) of members. However, this reduction may create serviceability problem of excessive deflection due to reduced stiffness. The methods of predicting and controlling deflection in the current design codes, e.g., ACI Building Code 318-95 (ACI Committee 318 1995) are generally applicable to members of normal-strength concrete. The application of these methods to HSC and HSFRC beams needs to be examined.

The available experimental results (Paulson, Nilson and Hover 1991) show that although the creep coefficient and deflections of high-strength concrete beams are smaller than those of similar

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beams of normal-strength concrete, the influence of compression steel reinforcement on time-dependent deflections is less significant for HSC beams than for normal-strength concrete beams.

For normal-strength concrete, increase in member stiffness due to addition of fibers has been reported by a number of researchers (Alsayed 1993, Lim, Paramasivan and Lee 1987, Patton and Whittaker 1990, and Swamy and Al-Ta'an 1981). This increase in stiffness decreases the immediate deflection of fiber reinforced concrete beam. However, information on the time-dependent deflection behavior of fiber reinforced concrete (normal and high-strength) beams is presently lacking.

The authors have recently presented (Ashour, Mahmood and Wafa 1997) the results of an experimental and theoretical study on the service load deflection behavior of HSC beams and HSFRC beams. The main objective of that study was to investigate the effect of volume of steel fibers, V_f, and the ratio of compression to tension longitudinal reinforcement, ρ'/ρ, on immediate and long-term deflections. The amount of tension reinforcement was kept constant for all the nine beams tested in that study. The results of the study showed that the addition of fibers increases the flexural rigidity (stiffness) and, therefore, reduces the immediate deflection of beams. Under sustained load, the addition of fibers reduces long-term deflection due to creep and shrinkage. A similar effect on long-term deflection is also observed in beams having compression reinforcement. However, for beams having fibers and compression bars, the behavior depends on the values of two type of reinforcement and their excessive amount may have an unfavorable effect on long-term deflection.

In order to investigate the effect of longitudinal tension reinforcement ratio, ρ, the authors have further tested nine beams in a second series under sustained load. The ratio of tension reinforcement ρ provided in the beams of the previous study was 0.0125, which is about 50 percent of the balanced steel ratio considering longitudinal steel (without fibers) only. The ratio ρ in the beams of the second series is 0.0045, which is higher than the minimum required by the previous ACI Building Code 318-89 (ACI Committee 318 1989), but is slightly less than the minimum required by the current ACI Building Code 318-95 (ACI Committee 318 1995). The provision in the current code has been revised to facilitate design of flexural members using high-strength concrete.

There is not much data available on the long-term deflection behavior of normal strength or high-strength concrete beams having the minimum amount of tension reinforcement. Normal strength concrete beams tested under sustained load by Washa and Fluck (1954), Yu and Winter (1960), Corley and Sozen (1966), and Bakoss *et al.* (1982), and, high-strength concrete beams tested by Paulson *et al.* (1991) contained greater than the ACI Code's minimum tension reinforcement.

The minimum tension reinforcement is stipulated in the ACI Code to ensure that the reinforced concrete section has the computed moment strength not less than that of the corresponding plain concrete section computed from its modulus of rupture. The beams with the minimum reinforcement will, therefore, be essentially uncracked on the application of service loads. However, cracks may develop in these beams under sustained service loads due to the effect of creep and shrinkage, as observed in the beams of previous series (Ashour, Mahmood and Wafa 1997). These cracks will affect the flexural stiffness and long-term deflections. In the case of HSFRC beams with the minimum reinforcement the effect of fibers also needs to be investigated.

This paper presents and discusses the test results of eighteen beams from both series for the effect of steel fibers, tension reinforcement and compression reinforcement, on the service load deflection behavior of high-strength concrete beams. The computational procedure developed by the authors in the previous study (Ashour, Mahmood and Wafa 1997) for predicting immediate and long-term deflections of HSC and HSFRC beams is further examined and modified to cover the whole range of test variables.

2. Experimental program

Eighteen HSC and HSFRC beams were cast and tested under sustained load in two series BS and BS(L). The results of series BS were presented and discussed in the previous study (Ashour, Mahmood and Wafa 1997).

The beams in both series were simply supported and subjected to a two-point loading. The beam dimensions, reinforcement layout and loading arrangement are shown in Fig. 1. Three values of volume of steel fibers, V_f, (0, 0.75 percent and 1.5 percent), two values of tension reinforcement ratio, ρ (0.0125 and 0.0045), and three values of compression to tension steel ratio, ρ'/ρ (0, 0.5, and 1.0) were used as variables to investigate their effect on immediate and long-term deflections. The beam designations and details of steel fibers content and longitudinal reinforcement for both series are given in Table 1. A detailed description of materials and methods of casting and testing is available elsewhere (Ashour, Mahmood and Wafa 1997). However, some relevant details are also included here.

2.1. Materials

10-mm diameter reinforcing bars used in series BS have yield strength of 412 MPa (60,000 psi). 6-mm diameter bars used in series BS(L) have no definite yield region. For these bars the apparent yield strength, measured at a strain of 0.0035, is 420 MPa (60,900 psi) and ultimate strength is 575 MPa (83,400 psi). Hook ended steel fibers, made of mild carbon steel, have yield strength of 1130 MPa (159,500 psi). The fibers have average length of 60 mm (2.36 in.), nominal diameter 0.8 mm (0.03 in.), and the aspect ratio 75.

The concrete had 28-days cylinder compressive strength *fc'* equal to 85 MPa (12,300 psi). The required strength was obtained by using concrete mix proportions 1:1:2 (cement: sand: aggregate),

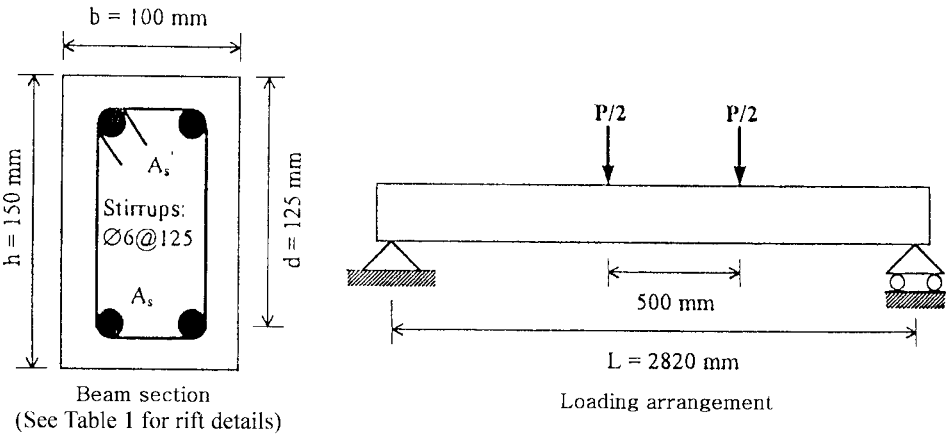

Fig. 1 Beam and loading details for series BS and BS(L) (1 mm=0.03937 in.)

Table 1 Beam designation and reinforcement details

Series	Beam Designation	Fibers Volume V_f (percent)	Longitudinal Reinforcement	
			Tension	Compression
1	2	3	4	5
BS	BS-0-0-A	0	2 ϕ 10	
	BS-0-0.5-A	0	2 ϕ 10	1 ϕ 10
	BS-0-1.0-A	0	2 ϕ 10	2 ϕ 10
	BS-0.75-0-A	0.75	2 ϕ 10	
	BS-0.75-0.5-A	0.75	2 ϕ 10	1 ϕ 10
	BS-0.75-1.0-A	0.75	2 ϕ 10	2 ϕ 10
	BS-1.5-0-A	1.5	2 ϕ 10	
	BS-1.5-0.5-A	1.5	2 ϕ 10	1 ϕ 10
	BS-1.5-1.0-A	1.5	2 ϕ 10	2 ϕ 10
BS(L)	BS-0-0-L	0	2 ϕ 6	
	BS-0-0.5-L	0	2 ϕ 6	1 ϕ 6
	BS-0-1.0-L	0	2 ϕ 6	2 ϕ 6
	BS-0.75-0-L	0.75	2 ϕ 6	
	BS-0.75-0.5-L	0.75	2 ϕ 6	1 ϕ 6
	BS-0.75-1.0-L	0.75	2 ϕ 6	2 ϕ 6
	BS-1.5-0-L	1.5	2 ϕ 6	
	BS-1.5-0.5-L	1.5	2 ϕ 6	1 ϕ 6
	BS-1.5-1.0-L	1.5	2 ϕ 6	2 ϕ 6

Note: All bar sizes in mm (1 mm=0.03937 in.)

Type I cement, 9.5 mm (3/8 in.) crushed stone (Basalt) and desert sand with a fineness modulus of 3.1. Densified silica fume (20 percent of weight of cement), a water-cement ratio of 0.23 and a superplasticizer were used to obtain the desired high strength and a slump of 45 mm (1.8 in.). With these mix proportions and the steel fibers volume of 0 (no fibers), 0.75 and 1.5 percent three concrete mixes were produced to cast three beams in each series.

For the three concrete mixes from each series, Table 2 shows the test results for modulus of rupture, splitting strength and compressive strength at 28 days and for compressive strength at 210 days. The results of shrinkage and creep tests for the three concrete mixes from the series BS, presented earlier (Ashour, Mahmood and Wafa 1997), show that the effect of adding steel fibers to high-strength concrete is more pronounced in reducing the drying shrinkage strains than the creep strains.

2.2. Beam tests

The sustained load for each beam of series BS was 7.0 kN applied through two points. This value of sustained load is about 50 percent of the average load corresponding to the initiation of yielding determined experimentally from companion beams (Ashour, Mahmood and Wafa 1997).

The sustained load for the beams in series BS(L) was 3.2 kN. This load is about 60 percent of

Table 2 Properties of concrete mixes

Series	Concrete Mix	Fiber Volume (percent)	At 28 days			At 210 days
			Splitting strength (MPa)	Modulus of rupture (MPa)	Compressive strength (MPa)	Compressive strength (MPa)
1	2	3	4	5	6	7
BS	1	0	4.71	8.97	80.19	89.23
	2	0.75	6.07	9.84	80.87	90.95
	3	1.5	7.24	14.05	82.32	91.84
BS(L)	1	0			82.23	
	2	0.75			85.86	
	3	1.5			88.16	

1 MPa=145 psi=0.145 ksi

the load corresponding to the moment capacity ignoring the effect of steel fibers.

The beams were tested at age of 28 days. The sustained load was incrementally applied through two points (Fig. 1) by using cast iron weight blocks. Mechanical dial gages were fixed at midspan to measure deflections. The deflection reading immediately after applying the full sustained load was recorded as the immediate, initial or short-term deflection (at time $t = 0$). The sustained load was applied for 180 days, and during this period deflection readings were recorded at regular intervals. The beams were regularly inspected for any cracking under sustained load. After 180 days the load was removed and deflection recovery was noted for the next 5 to 7 days.

3. Test results and discussion

As mentioned earlier, test results for the beams in series BS have already been presented and discussed (Ashour, Mahmood and Wafa 1997) and are, therefore, not repeated here. Nevertheless, the relevant results of that series are included in this paper while comparing the behavior of beams in the two series.

Visual inspection of beams in series BS(L) immediately after the application of sustained load did not reveal any surface cracks indicating that the beams were uncracked at that stage. However, cracks appeared in these beams under sustained load. These cracks affected long-term deflections of the beams, as will be discussed later.

For each group of beams in series BS(L) having constant ρ'/ρ, Fig. 2 shows the effect of steel fibers volume V_f on time versus deflection curves (t versus Δ_t curves). The curves in Fig. 2 follow the general trend observed in series BS, i.e., the addition of fibers decreases the immediate and total long-term deflections. Fig. 2 shows that in each group of beams having constant ρ'/ρ, the curve for $V_f = 0.75$ percent lies between the curves for 0 and 1.5 percent fibers. This means that the increase in V_f from 0 to 1.5 percent decreased immediate and long-term deflections. However, further increase in V_f from 0.75 percent to 1.5 percent increased immediate and long-term deflections.

Fig. 3 shows the effect of compression to tension steel ratio ρ'/ρ on time versus deflection curves (t versus Δ_t curves) for the beams in series BS(L). Fig. 3 shows that for beams having the

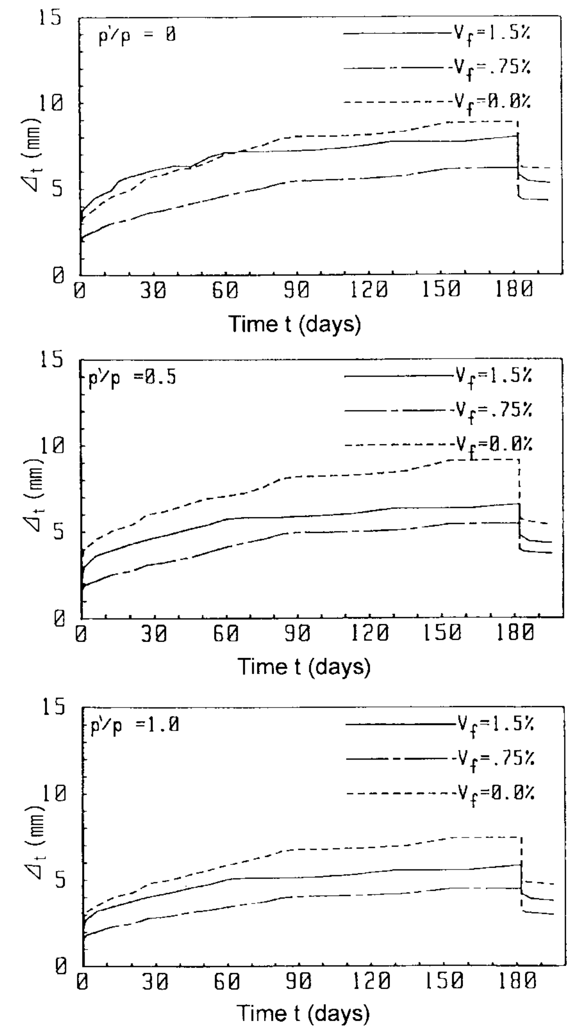

Fig. 2 Effect of V_f on the time vs. deflection curves with constant ρ'/ρ (1 mm=0.03937 in.)

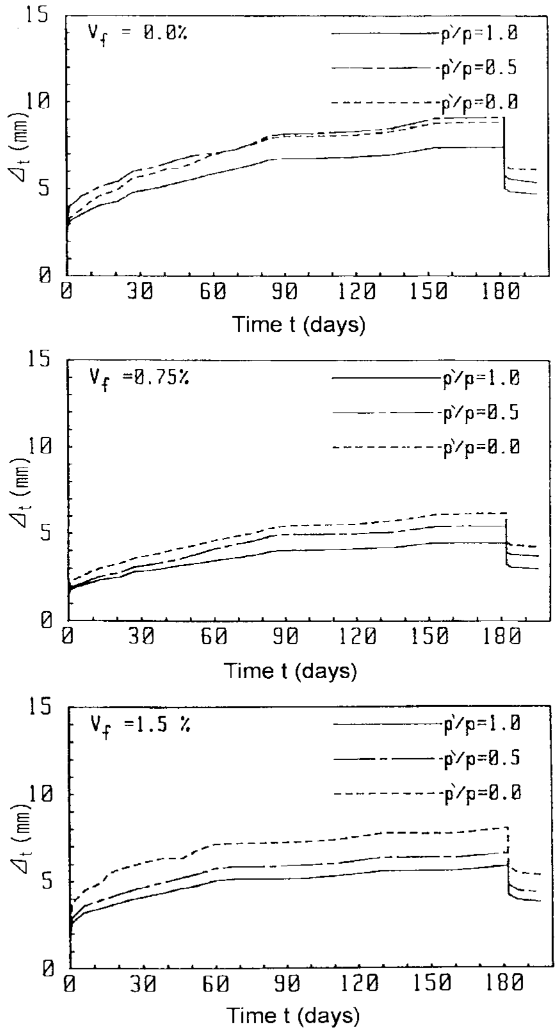

Fig. 3 Effect of ρ'/ρ on the time vs. deflection curves with constant V_f (1 mm=0.03937 in.)

same V_f, addition of compression reinforcement did not influence appreciably the immediate deflection, but reduced the long-term deflection Δ_t. The beneficial effect of compression reinforcement in reducing long-term deflections increased with increase in the ratio ρ'/ρ.

3.1. Comparison of series BS and BS(L)

For the beams in series BS and BS(L), Fig. 4 shows the effect of V_f on immediate deflection, Δ_i, total long-term deflection at 180 days, Δ_{180}, and the deflection ratio, $(\Delta_{180}\text{-}\Delta_i)/\Delta_i$. Fig. 5 shows the effect of ρ'/ρ on Δ_i, Δ_{180}, and the deflection ratio $(\Delta_{180}\text{-}\Delta_i)/\Delta_i$.

Fig. 4 shows that for the singly reinforced beams (ρ'/ρ=0) of series BS(L), although increase in V_f from 0.75 percent to 1.5 percent increased immediate and long-term deflections, the deflection

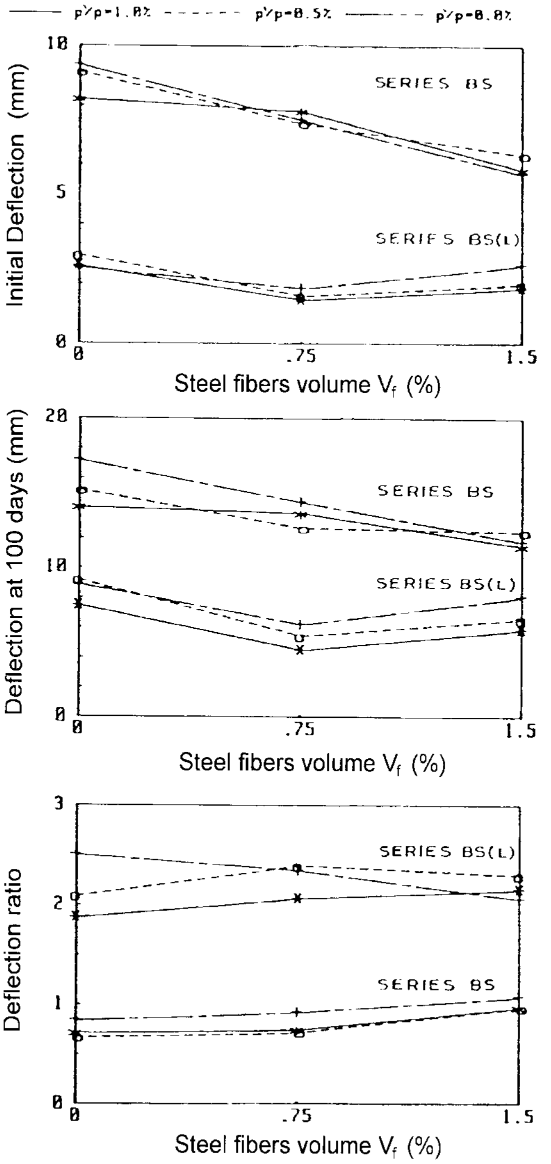

Fig. 4 Effect of V_f on immediate deflection Δ_i, long-term deflections at 180 days Δ_{180} and deflection ratio $(\Delta_{180}-\Delta_i)/\Delta_i$. (1 mm = 0.03937 in.)

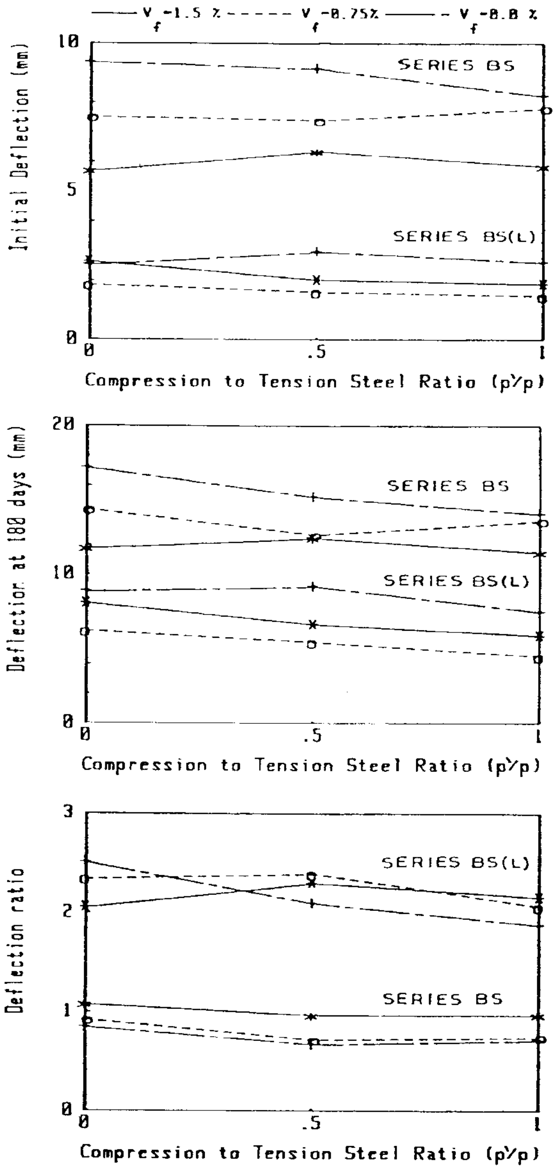

Fig. 5 Effect of ρ'/ρ on immediate deflection Δ_i, long-term deflections at 180 days Δ_{180} and deflection ratio $(\Delta_{180}-\Delta_i)/\Delta_i$ (1 mm = 0.03937 in.)

ratio $(\Delta_{180}-\Delta_i)/\Delta_i$ decreased. However, for the beams with compression reinforcement, increase in fiber content also increased the immediate and long-term deflections, and deflection ratio $(\Delta_{180}-\Delta_i)/\Delta_i$. This increase in deflection ratio with increase in fiber content is also noted in the beams of series BS.

Fig. 5 shows that for the beams without fibers ($V_f = 0$) in series BS(L), increase in the ratio ρ'/ρ reduced the deflection ratio $(\Delta_{180}-\Delta_i)/\Delta_i$. However, for beams with fibers (HSFRC beams), the minimum deflection ratio is noted for the beam with $V_f = 0.75$ percent and $\rho'/\rho = 1.0$. In the group with $V_f = 1.5$ percent, the deflection ratios for beams with $\rho'/\rho = 0.5$ and 1.0 are higher than that of the beam without compression reinforcement.

The results of the two series in Figs. 4 and 5 augment the conclusion drawn by Ashour *et al.* (1997) that for beams having steel fibers and compression reinforcement, the behavior depends on the amount of two types of reinforcement, and their excessive amount may have an unfavorable effect on the long-term deflection.

The sustained load for the beams in series BS(L) was less than that for the beams in series BS. Accordingly, the immediate and long-term deflections in the beams of series BS(L) were lower than those of the beams in series BS. However, the deflection ratios $(\Delta_{180} - \Delta_i)/\Delta_i$ for the beams in series BS(L) are appreciably higher than those for the beams in series BS as shown in Figs. 4 and 5. This is mainly due to the condition of the beams immediately after loading and under the effect of sustained load. In series BS(L) the beams were noted to be uncracked upon loading. A check of bending moments in the beams of series BS(L) under applied load also indicates these moments to be less than the theoretical cracking moment M_{cr}, based on the limiting extreme fiber tension stress equal to the modulus of rupture. However, as mentioned earlier, cracks developed under the influence of sustained load. These cracks seem to develop because of the extreme fiber tension strain reaching the limiting value under creep. The position of the nearest crack from the support in these beams indicated that it developed at a bending moment equal to about 50 percent of the theoretical cracking moment M_{cr}. These cracks reduced the beam stiffness, increased long-term deflection and the corresponding ratio $(\Delta_t - \Delta_i)/\Delta_i$. Fig. 6 presents a comparison of time versus deflection ratio (t versus $(\Delta_t - \Delta_i)/\Delta_i$ curves for some representative beams (groups of beams having same V_f) from both series. Fig. 6 shows the deflection ratios for the beams in series BS(L)

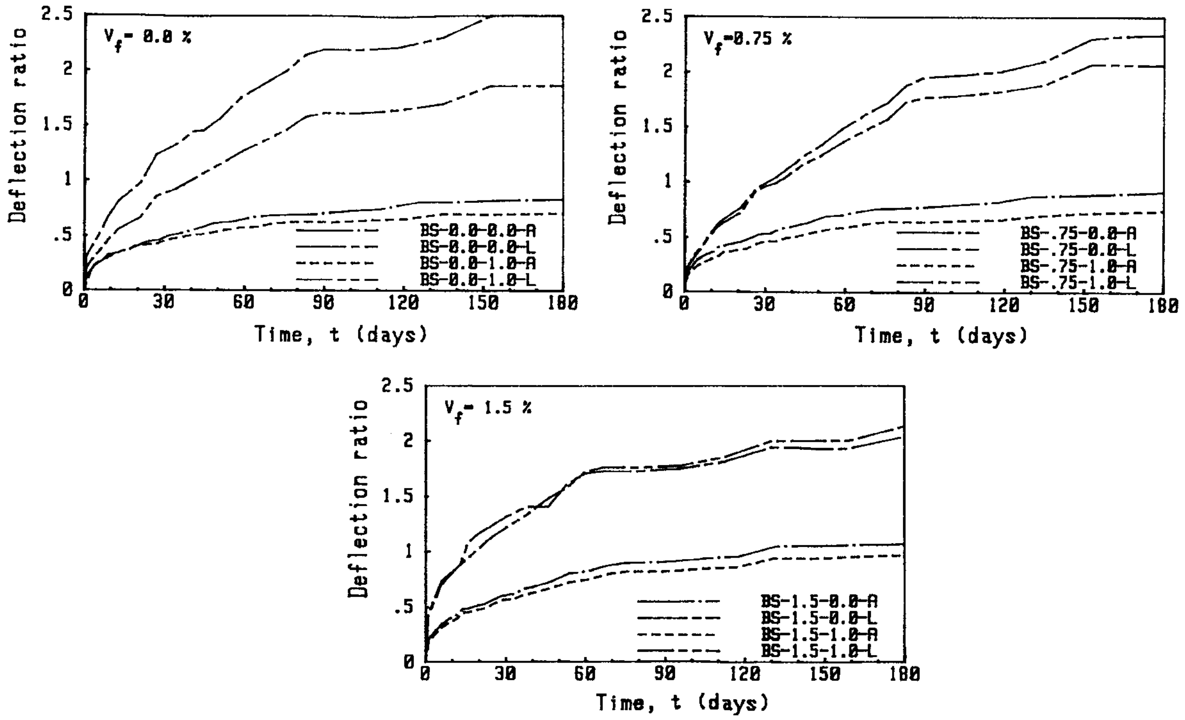

Fig. 6 Time vs. deflection ratio $(\Delta_t - \Delta_i)/\Delta_i$ curves for beams from series BS and BS(L)

increased sharply in the initial stages under sustained loading. However, after about 90 days the curves for these beams become parallel to those of series BS. Since the beams in the two series were cast from identical mixes and were kept under similar conditions, their shrinkage and creep characteristics were same. The increase in the deflection ratios for series BS(L) thus seems to be due to gradual reduction in beam stiffness, which is more pronounced in the first 90 days under sustained loading.

4. Theoretical investigation

4.1. Effect of steel fibers on moment of inertia

A procedure was developed in the previous study (Ashour, Mahmood and Wafa 1997) to include the effect of steel fibers in computing moment of inertia of the uncracked transformed section, I_u, and moment of inertia of the cracked transformed section, I_{cr}. Fig. 7 shows the transformed cracked and uncracked sections for beams having longitudinal bars and steel fibers The procedure considers the transformed area of fibers in the tension zone, but neglects their effect in the compression zone.

By using this procedure the moments of inertia of uncracked and cracked transformed sections for all the eighteen beams of series BS and BS(L) were computed (Table 3). The computed values in Table 3 show that steel fibers do not have any notable effect on the moment of inertia of uncracked transformed section I_u for the beams in both series. The same is true for the compression steel ratio ρ' on I_u and I_{cr}. However, the inclusion of steel fibers significantly increases the moments of inertia of the cracked transformed sections I_{cr}, with the increase more pronounced in the lightly reinforced ($\rho = 0.0045$) beams of series BS(L). This increase in moment of inertia is due to the decrease in the neutral axis depth that increases the tension zone and, therefore, the contribution of steel fibers.

It is also to be noted that the orientation factor α which defines the effective number (area) of fibers per unit of beam cross section depends on the length of fibers and section dimensions (Soroushian and Lee 1990). Therefore, to study further the effect of tension reinforcement ρ, volume of steel fibers V_f, and orientation factor α on the computed values of I_{cr} for HSFRC beams,

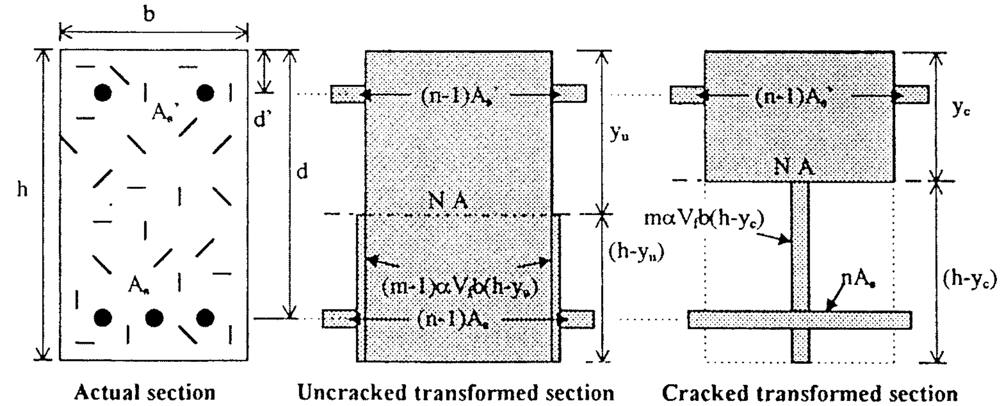

Fig. 7 Transformed uncracked and cracked sections for beams having longitudinal bars and steel fibers

Table 3 Computed moments of inertia for transformed sections of beams of series BS and BS(L)

Beam Designation	Uncracked I_u ($\times 10^4$ mm^4)	Cracked I_{cr} ($\times 10^4$ mm^4)	Ratio*
1	2	3	4
BS-0.0-0.0-A	2978	826	0.28
BS-0.75-0.0-A	3004	939	0.31
BS-1.5-0.0-A	3030	1043	0.34
BS-0.0-0.5-A	3070	831	0.27
BS-0.75-0.5-A	3098	948	0.31
BS-1.5-0.5-A	3125	1055	0.34
BS-0.0-1.0-A	3159	836	0.26
BS-0.75-1.0-A	3188	955	0.30
BS-1.5-1.0-A	3216	1066	0.33
BS-0.0-0.0-L	2876	367	0.13
BS-0.75-0.0-L	2905	524	0.18
BS-1.5-0.0-L	2933	663	0.23
BS-0.0-0.5-L	2909	367	0.13
BS-0.75-0.5-L	2939	525	0.18
BS-1.5-0.5-L	2962	665	0.22
BS-0.0-1.0-L	2942	367	0.12
BS-0.75-1.0-L	2972	525	0.18
BS-1.5-1.0-L	3001	666	0.22

Note: For all beams, I_g=2812.5$\times 10^4$ mm^4 (1$\times 10^4$ mm^4=0.024 in^4)
*Ratio of I_{cr}/I_u

a parametric study was carried out. Figs. 8 and 9 show the results of this parametric study based on the properties of steel fibers, materials and section dimensions (Fig. 1) used in the experimental program. Fig. 8 shows that for any value of ρ, increase in V_f increases the ratio of I_{cr} for sections with fibers and longitudinal steel to I_{cr} for beams with longitudinal steel only. For sections with low longitudinal tension steel ratio ρ, the addition of fibers increases the moment of inertia appreciably, but the effectiveness of fibers decreases as ρ increases. Fig. 9 shows that the addition of steel fibers in increasing moment of inertia I_{cr} may be more effective in thin members than in relatively deep members.

4.2. Immediate and long-term deflections

Immediate deflection for HSC and HSFRC beams under service load can be computed (Ashour, Mahmood and Wafa 1997) by the ACI Code (ACI Committee 318 1995) approach, using the formulas of elastic deflection with flexural rigidity equal to E_c I_e, where E_c is the short-term modulus of elasticity of concrete and I_e is the effective moment of inertia. E_c for high-strength concrete is computed by the formula presented by ACI Committee 363 (ACI Committee 363 1992). The ACI Code (ACI Committee 318 1995) formula for I_e is modified by replacing the

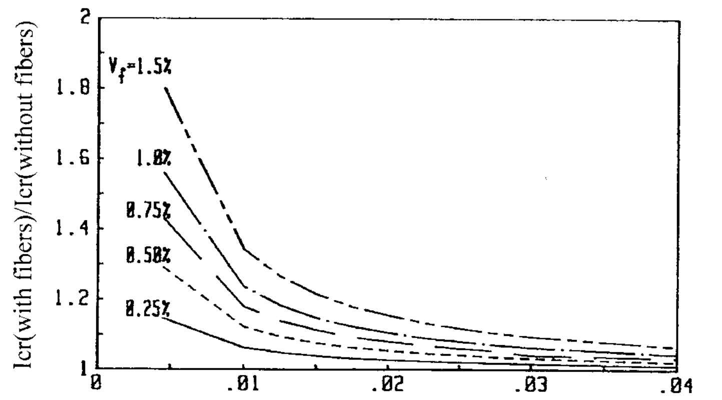

Fig. 8 Effect of fiber volume V_f on moment of inertia of cracked transformed section (b=100 mm, h=150 mm, ρ'=0)

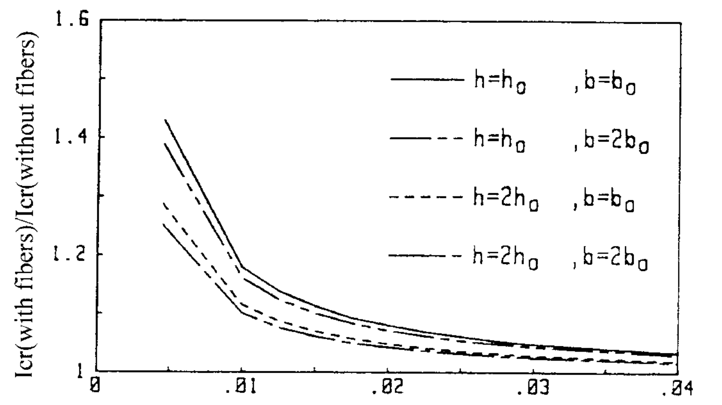

Fig. 9 Effect of beam size (section dimensions) on moment of inertia of cracked transformed section (b_0= 100 mm, h_0=150 mm, V_f=0.75 percent, ρ'=0)

moment of inertia of gross concrete section, I_g, with the moment of inertia of the uncracked transformed section, I_u. In computing I_u and I_{cr} the effect of fibers is included as mentioned earlier. The cracking moment M_{cr}, to be used in the formula for I_e, is computed by assuming the modulus of rupture equal to $0.7\sqrt{f_c'}$ (MPa), where f_c' is the compressive strength of plain concrete ($V_f = 0$).

The total long-term deflection Δ_t at any time t is the sum of the immediate deflection Δ_i and the additional (time-dependent) deflection due to the effect of shrinkage and creep under sustained load. In the ACI Code (ACI Committee 318 1995), the additional deflection is obtained by multiplying the immediate deflection by a factor λ. On the basis of the results of beams in series BS, the following modified formula for λ has been suggested (Ashour, Mahmood and Wafa 1997) for HSC and HSFRC:

$$\lambda = \frac{\mu_m \alpha_m \zeta}{1 + 50\mu_s \alpha_s \rho'} \quad (1)$$

where, ζ is the ACI Code's time-dependent factor for sustained load and ρ' is the compression steel ratio. μ_m and μ_s are material and section modifiers, respectively, for HSC. α_m and α_s are material and section modifiers, respectively, for steel fibers in HSC. Based on the results of beams in series BS, the following formulas have been suggested for μ_m, μ_s, α_m and α_s (Ashour, Mahmood and Wafa 1997):

$$\mu_m = 1.29 - 0.0000755\, f_c' \text{ (psi)} \tag{2}$$

$$\mu_s = 1.48 - 0.000107\, f_c' \text{ (psi)} \tag{3}$$

$$\alpha_m = 1 - 40\, V_f + 4000\, V_f^2 \tag{4}$$

$$\alpha_s = 1 - 40\, V_f \tag{5}$$

An attempt was made to further modify Eqs. (1)-(5) by including the results of the second series BS(L). However, considering that the range of values for V_f and f_c' for the beams in the two series was the same and that the high ratios of $(\Delta_t - \Delta_i)/\Delta_i$ observed in series BS(L) were not due to these variables, no modification in these equations was made.

4.3. Comparison of experimental and predicted deflections

Using the above procedure and the values of I_u and I_{cr} shown in Table 3, effective moment of

Table 4 Comparison of measured and predicted immediate and long-term deflections for beams of series BS and BS(L)

Beam Designation	Measured		Predicted	
	Δ_i (mm)	Δ_{180} (mm)	Δ_i (mm)	Δ_{180} (mm)
1	2	3	4	5
BS-0.0-0.0-A	9.33	17.16	7.95	15.09
BS-0.75-0.0-A	7.5	14.38	7.23	13.24
BS-1.5-0.0-A	5.67	11.73	6.67	14.46
BS-0.0-0.5-A	9.11	15.2	7.65	14.11
BS-0.75-0.5-A	7.38	12.65	6.96	12.48
BS-1.5-0.5-A	6.33	12.41	6.43	13.49
BS-0.0-1.0-A	8.2	14.04	7.36	13.23
BS-0.75-1.0-A	7.8	13.6	6.71	11.83
BS-1.5-1.0-A	5.82	11.44	6.2	12.39
BS-0.0-0.0-L	2.52	8.83	1.63	3.1
BS-0.75-0.0-L	1.85	6.18	1.62	2.97
BS-1.5-0.0-L	2.63	8.02	1.6	3.47
BS-0.0-0.5-L	2.96	9.14	1.62	3.04
BS-0.75-0.5-L	1.6	5.42	1.6	2.91
BS-1.5-0.5-L	2.0	6.59	1.59	2.89
BS-0.0-1.0-L	2.59	7.43	1.6	2.98
BS-0.75-1.0-L	1.46	4.47	1.59	2.87
BS-1.5-1.0-L	1.86	5.84	1.57	3.38

1 mm=0.03937 in.

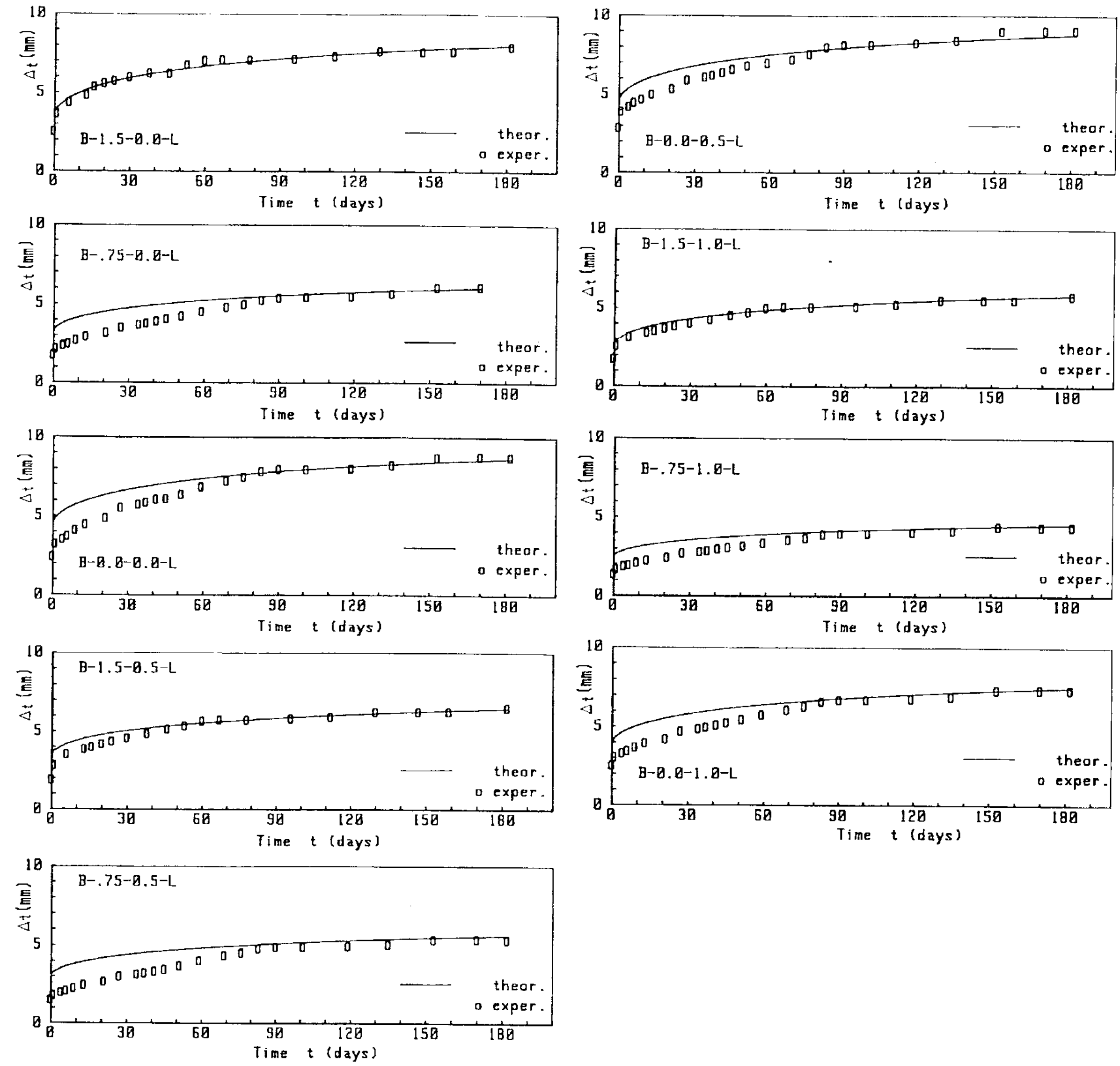

Fig. 10 Comparison of experimental and predicted time vs. deflection curves (1 mm=0.03937 in.)

inertia I_e, immediate deflection Δ_i, and long-term deflection at 180 days Δ_{180} were computed for the beams in series BS and BS(L). In computing the long-term deflection at 180 days, Δ_{180}, the effect of the self-weight of beams was also included. The ratio of cracking moment to the maximum span moment, M_{cr}/M_a, for the beams in series BS(L) is greater than 1 and therefore the deflections for these beams were computed by using I_e equal to I_u.

A comparison of the experimental and predicted deflections (Table 4) shows that the proposed procedure gives a good estimate of immediate deflections for both series and of long-term deflections for series BS. The method, however, grossly underestimates long-term deflection for series BS(L). This indicates that the quasi estimation of long-term deflections based on the immediate deflection and multiplier λ may not be valid for beams that are initially uncracked but develop cracks under sustained loading. The ratios of I_{cr}/I_u for the beams in series BS(L) are also much smaller than those for series BS (Table 3) indicating that any cracking will appreciably increase their deflection. The use of λ approach for these beams will, therefore, require an estimation of a hypothetical immediate deflection Δ_{it} that includes the effect of cracking at any time t.

For the beams in series BS(L) a hypothetical value of immediate deflection Δ_{it} was computed by using the effective moment of inertia I_e based on the values of I_u and I_{cr} from Table 3 and an experimental cracking moments ($M_{cr(\exp)}$) obtained from the bending moment diagram and the final position of cracks under sustained loading. This value of Δ_{it} and the corresponding values of λ were then used to develop time versus total deflection curves (t versus Δ_t curves) for the beams (Fig. 10). As expected, this procedure over-estimates long-term deflections in the initial stages under sustained loading, but gives a good estimate of long-term deflections after about 90 days. These results indicate that the cracking under sustained load mostly occurred during the first 90 days and then stablized. An improvement in the estimation of long-term deflections between 0 and 90 days may be made by assuming some appropriate relationship between Δ_i based on uncracked section and Δ_{it} computed by considering cracking under sustained loading.

5. Conclusions

Addition of steel fibers to high-strength concrete beams increases their flexural rigidity and reduces immediate and total long-term (immediate plus time-dependent) deflections. However, the actual behavior depends on the amount of longitudinal tension and compression reinforcements and fibers.

The beams having the ACI Code's minimum longitudinal tension reinforcement indicated a much higher ratio of time-dependent deflection to immediate deflection compared with that of the beams having about 50 percent of the balanced tension reinforcement.

Inclusion of steel fibers and compression reinforcement in high-strength concrete beams makes the long-term deflection behavior under sustained load quite complex. This behavior is affected by the values of fibers volume, and amount of compression reinforcement.

For HSFRC beams flexural rigidity and immediate deflection under service loads can be predicted by modifying the transformed sections to include the effect of steel fibers on the tension side.

The results of theoretical analysis of the tested beams indicate that the addition of fibers does not increase appreciably the moment of inertia of uncracked transformed section but may have a significant effect on the moment of inertia of cracked transformed section.

The effect of member size has not been investigated experimentally in this study. However, the results of a limited parametric study included in the paper show that the influence of steel fibers in increasing the moment of inertia of cracked transformed sections may be more pronounced in relatively thin members having small amount of longitudinal tension reinforcement.

The long-term deflection multiplier λ of ACI Code needs further modification to include the effect of steel fibers on material and section properties. However, for the beams that are uncracked on loading and show gradual cracking under sustained load the use of immediate deflection based on uncracked section and multiplier λ may grossly underestimate long-term deflections. The application of λ approach for these beams will require an estimation of a hypothetical immediate deflection Δ_{it} at any time t.

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Notations

A_s = Area of longitudinal tension reinforcement
A_s' = Area of longitudinal compression reinforcement
b = Width of beam section (also b_0)
h = Overall thickness of beam section (also h_0)
d = Effective depth
d' = Depth of compression reinforcement

E_c = Modulus of elasticity of concrete
f_c' = Compressive strength of concrete (at 28 days)
I_{cr} = Moment of inertia of cracked transformed section
I_e = Effective moment of inertia
I_g = Moment of inertia of gross concrete section ignoring reinforcement
I_u = Moment of inertia of uncracked transformed section
M_a = Maximum bending moment in the span
M_{cr} = Cracking moment
V_f = Volume of fiber, expressed as percentage of concrete volume
ζ = ACI Code time-dependent factor for sustained load
α = Fiber orientation factor
α_m = Material modifier for fibers in HSC
α_s = Section modifier for fibers in HSC
ρ = Longitudinal tension steel ratio $= A_s/bd$
ρ' = Longitudinal compression steel ratio $= A_s'/bd$
Δ_i = Immediate deflection
Δ_{it} = Hypothetical immediate deflection to include the effect of cracking at time t
Δ_t = Total (immediate plus long-tem) deflection at time t
Δ_{180} = Total deflection at 180 days
μ_m = Material modifier for HSC
μ_s = Section modifier for HSC
λ = Multiplier for additional long-term deflection