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Mechanical Properties of Steel Fiber-reinforced, High-strength, Lightweight Concrete

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Abstract

This paper presents basic information on the mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete with compressive and flexural strengths up to 85.4 MPa and 11.8 MPa, respectively. The influence of steel fiber on modulus of elasticity and Poisson's ratio of concrete are investigated, and flexural fracture toughness is calculated. Test results show that the effect of fiber volume fraction (V_f) *and aspect ratio* (l_f/d_f) *on flexural strength and fracture toughness is extremely prominent, compressive strength is only slightly improved, and tensile/compressive strength ratio is obviously enhanced. It is observed that the flexural deflection corresponded to ultimate load increased with the increase of* V_f *and* l_f/d_f*, and due to fiber arresting cracking, the shape of the descending branch of load-deflection tends towards gently. © 1997 Elsevier Science Ltd. All rights reserved.*

Keywords: steel fiber, lightweight concrete, flexural strength, toughness, tensile strength.

INTRODUCTION

Recently, with the rapid development of super high building, larger sized and larger span concrete structure, requirements of concrete performance are higher strength, lightweight, higher toughness and others. In some cases, the density of the concrete is often more important than the strength. In concrete construction, self-weight represents a very large proportion of total load on the structure, and there are clearly considerable advantages in reducing the density of concrete. A decreased density of concrete for the same strength level permits a saving in dead load for structural design and foundation. Therefore, more information is available on properties of high-strength, lightweight concrete in recent years[1–8]. Zhang and Gjorv[9] reported that the tensile/compressive strength ratio was lower for high-strength, lightweight concrete than that for high-strength, normal weight concrete, and the lightweight concrete becomes more brittle for increasing strength level. Slate, Nilson, and Martinez[10] found that the stress–strain curve in uniaxial compression was steeper and more linear to a higher stress–strength ratio for the high-strength, lightweight concrete than for the low strength lightweight concrete. Simazaki et al.[11] found that the compressive toughness of high-strength, lightweight concrete was smaller than that of normal weight concrete.

With the increased strength of high-strength, lightweight concrete, this has been used widely as major construction materials, but problems, such as low tensile/compressive strength ratio, low flexural strength, low fracture toughness, high brittleness and larger shrinkage, prevented its use in concrete structure. The addition of steel fiber to high-strength, light-weight concrete has important effects on the improvement on properties of high-strength, light-weight concrete, especially for improving tensile/compressive ratio, behavior of earthquake resistance, resistance to cracking and fracture toughness. However, the published literature

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contains very little information on properties of steel fiber reinforced high-strength, lightweight concrete. This paper presents basic information on the compressive strength, tensile strength, flexural strength, modulus of elasticity, Poisson's ratio and flexural toughness of steel fiber reinforced high-strength, lightweight concrete with a compressive strength up to 85.4 MPa and a flexural strength up to 11.8 MPa, corresponding to a density of 1963 kg/m^3.

EXPERIMENTAL PROCEDURE

Materials

Cement

A Portland cement was used, with a Blaine surface area of 3560 cm^2/g and a density of 3.15 g/cm^3.

Silica fume (SF) with a N_2 surface area of 25 m^2/g and density of 2.24 g/cm^3 was used. The chemical compositions of cement and silica fume are listed in Table 1.

Admixture

A superplasticizer, based on naphthalene, was used.

Coarse aggregate

An expanded clay aggregate with a round but irregular shape, a maximum aggregate size of 15 mm, a particle density of 1.46 g/cm^3, a density of 810 kg/m^3 and water absorption, within the first 1 h, of 10% was used.

Fine aggregate

Medium sand with a fineness modulus of 2.70 and an apparent specific gravity of 2.63 g/cm^3 was used.

Table 1. Chemical compositions of cement and silica fume

Materials	*Chemical compositions (%)*						
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	*IL*
Cement	22.06	5.36	5.13	65.37	1.06	2.03	—
Silica fume	93.38	0.12	0.50	0.39	—	—	3.78

Table 2. Mix proportions of concrete

Mix no.	*Cement (kg/m^3)*	*SF (kg/m^3)*	*W/(C+ SF)*	*Agg., fine*	*(kg/m^3) coarse*	*Steel fiber (kg/m^3)*
A	520	50	0.28	530	580	0
B	517	50	0.28	527	576	47
C	515	50	0.28	525	574	78
D	512	50	0.28	522	571	117
E	510	50	0.28	519	568	156

Steel fiber

The rectangular fibers with lengths of 20 mm, 25 mm, 30 mm and aspect ratios of 46, 58, 70, respectively, were used.

Mix proportions

The mix proportions are shown in Table 2 in this study. The volume fractions of steel fiber in concrete were 0, 0.6, 1.0, 1.5, 2.0 vol%, respectively. All mixes had 1.5% of superplasticizer by weight of cement.

Test methods

Before mixing, the moisture content of the coarse aggregate was measured. The total water in the mix was the water of mix proportion and the water absorbed by aggregate within the first hour. The first, cement, silica fume and fine aggregate, were pre-mixed for about 5 min, and the second, the coarse aggregate and steel fiber, were added and mixed for 5 min; then, the water together with superlasticizer was added and mixed for another 3–5 min. The concrete specimens were cast in steel molds and compacted on a vibration table. After demolding at 24 h, the specimens were kept in temperature 20 ± 3°C and humidity over 90% until time of testing. The compressive strength (f_c) and the splitting tensile strength (f_{st}) were measured on $100 \times 100 \times 100$ mm cubes, the flexural strength (f_{sw}) was tested on $100 \times 100 \times 400$ mm specimens with four-point flexural loading. The modulus of elasticity (E_c) and Poisson's ratio were tested on $100 \times 100 \times 300$ mm prisms. The modulus of elasticity (E_c) was calculated, based on the stress corresponding to 40% of the ultimate strength and the longitudinal strain produced by this stress. The flexural toughness was calculated based on ASTM-C1018-85. All tests were carried out at 28 days.

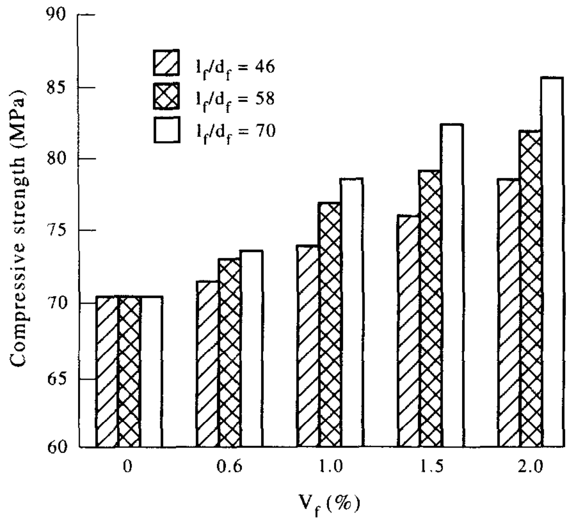

Fig. 1. Effect of V_f and l_f/d_f on compressive strength.

RESULTS AND DISCUSSION

Compressive strength

Figure 1 shows the relationship between the compressive strength and steel fiber volume fraction and aspect ratio. It clearly demonstrates that the compressive strength increases with increasing fiber volume fraction and aspect ratio. However, it shows a relatively lower rate of increase. Test results show the compressive strength varied from 70.2 to 85.4 MPa, corresponding to a density of 1850–1966 kg/m^3 for the various fiber volume fractions and aspect ratios. For high-strength, lightweight concrete, the weakest component in concrete is the coarse lightweight aggregate rather than the hardened cement paste and the transition zone between cement paste and lightweight aggregate. The ultimate strength of concrete is mainly controlled by the strength of the lightweight coarse aggregate itself. Under uniaxial compressive, vertical compressive strain and transverse tensile strain occurred in concrete compressive strength test specimens, and the concrete deformation continuously increased with increasing in load. When transverse tensile strain extended to the ultimate tensile strain of coarse aggregates, cracks occurred in coarse aggregates in concrete. When the compressive load was increased further, cracks that occurred in coarse aggregate were promoted to extend and propagate into cement paste; in addition, at more position, tensile strain reached the ultimate tensile strain of coarse aggregates. When the compressive load reached a certain level of strength, concrete failure occurred.

The incorporation of steel fiber into matrix serves to increase the ultimate compressive strength by the resultant arresting growth of cracks based on the bond of steel fiber and cement paste. In the test, it was found that the dispersion of fiber became very difficult, when the fiber volume fraction was further increased to 2.5%, and for this reason, concrete was not fully compacted. Concrete compressive strength increased with increasing aspect ratio of the fiber, as previously recounted. It is proposed that the larger the aspect ratio of steel fiber, the more effective crack arresting in the range of critical aspect ratio of steel fiber. For the type of lightweight aggregate, it is noted that the compressive strength only reaches a certain level of strength, and the compressive strength does not benefit very much from a further improvement in matrix strength[9].

Density

It can be seen from Fig. 2 that the density was not affected by the aspect ratio of steel fiber. The fresh concrete density was mainly affected by fiber volume fraction. The relationship between the density and fiber volume follows the equation

$$D_c = D_m(1 - V_f) + D_s V_f \tag{1}$$

where D_c = density of steel fiber reinforced, high-strength, lightweight concrete; D_m = density of high-strength, lightweight concrete; and

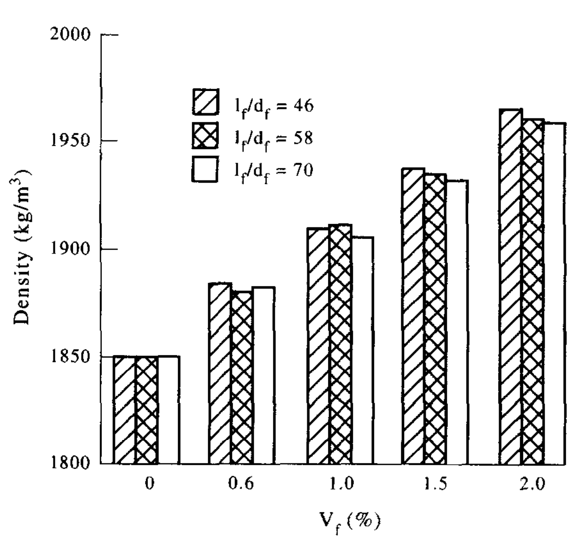

Fig. 2. Effect of fiber volume fraction on density.

D_s = density of steel fiber. Increasing the aspect ratio of steel fiber would create mixing problems and may result in concrete of a lower density for the same fiber volume fraction.

Splitting tensile strength

When the fiber volume fraction increased from 0% to 2%, the splitting tensile strength increased from 4.95 to 8.8 MPa. The rate of increase of splitting tensile strength is 9–78%, depending on the various fiber volume fraction and aspect ratios. For a lower fiber volume fraction, any improvement in the splitting tensile strength of concrete is hardly effective. Therefore, in order to improve the splitting tensile strength of steel fiber-reinforced, high-strength, lightweight concrete, it is considered that the fiber volume fraction must be over 1 vol% fraction. Figure 3 shows the relationship between splitting tensile strength and fiber volume fractions and aspect ratios. It has been shown that the splitting tensile strength increases linearly with the addition of fibers and is linear functions of the term $V_f l_f/d_f$. For steel fiber-reinforced, high-strength, lightweight concrete, test results show that the splitting tensile strength follows the relationship

$$f_{st}=0.94f_t(1-V_f)+3.02V_f l_f/d_f \qquad (2)$$

where f_t = splitting tensile strength of high-strength, lightweight concrete; and f_{st} = splitting tensile strength of steel fiber-reinforced, high-strength, lightweight concrete. eqn 2 gives an approximation for the tensile strength of high-strength, lightweight concrete at $V_f = 0$.

Flexural strength

When the fiber volume fraction increased from 0 to 2%, flexural strength increased from 6.2 to 11.8 MPa. The rate of increase of flexural strength is 9.6 to 90%, depending on the fiber volume fraction and aspect ratio. The fracture process of steel fiber-reinforced concrete consists of progressive debonding of fiber, during which slow crack propagation occurs. Final failure occurs due to unstable crack propagation when the fiber pull out and the interfacial shear stress reach the ultimate bond strength[12]. The reason for the increase in flexural strength is that, after matrix cracking, fibers will carry the load that the concrete sustained until cracking by interfacial bond between fibers and matrix. At higher aspect ratios, the advantage of fibers in increasing flexural strength of concrete seems to be more pronounced. Figure 4 clearly demonstrates that flexural strength increased with fiber volume fraction and aspect ratio. The relationship between ultimate flexural strength and the term $V_f l_f/d_f$ follows the equation

$$f_{sw}=0.92f_w(1-V_f)+4.19V_f l_f/d_f \qquad (3)$$

where f_{sw} = flexural strength of steel fiber-reinforced, high-strength, lightweight concrete; and f_w = flexural strength of high-strength, lightweight concrete. For steel fiber reinforced concrete, Swamy and Mangat[12] have reported a similar relationship for the flexural strength of

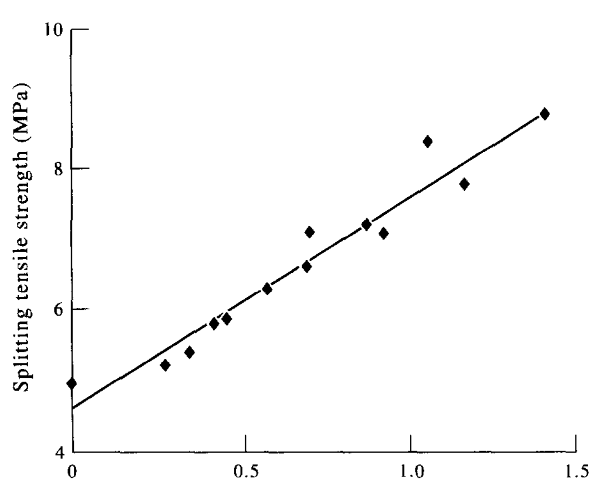

Fig. 3. Effect of $V_f l_f/d_f$ on splitting tensile strength.

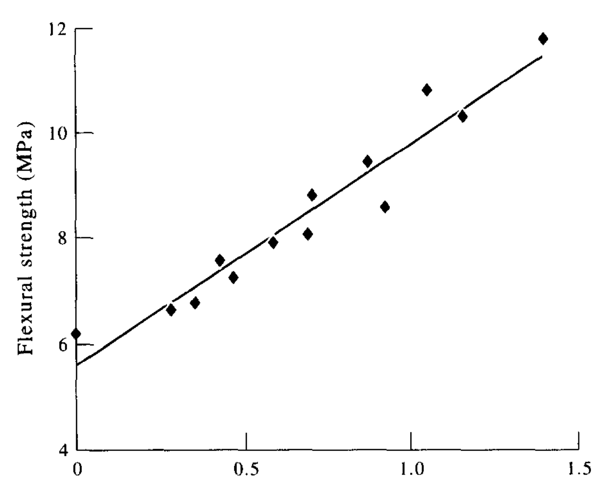

Fig. 4. Effect of $V_f l_f/d_f$ on flexural strength.

steel fiber-reinforced concrete, which is described by

$$f_{sw} = 0.97 f_w (1 - V_f) + 3.41 V_f l_f / d_f \qquad (4)$$

When eqn 3 is compared to eqn 4, it is found that the strengthening effect of steel fiber to lightweight concrete is larger than that of normal concrete.

High-strength, lightweight concrete, because of the high interfacial bond strength between the lightweight aggregate and mortar, fails because of cracks passing straight through the lightweight aggregate. Fracture planes of specimens were smoother.

Flexural load-deflection curves

Figure 5 shows typical flexural load-deflection curves of steel fiber-reinforced, high-strength, lightweight concrete with fiber volume fractions of 1% and 2% and aspect ratios of 70 and 58, respectively. The curves presented in these figures were averages of three test results on identical mix specimens. The test results show that the load-deflection curve for steel fiber-reinforced, high-strength, lightweight concrete are similar to the curves for steel fiber-reinforced concrete described by Gao[13]. It is observed that the deflection corresponded to ultimate load increases with the increase of fiber volume fraction and aspect ratio, and the descending branch of the flexural load-deflection curves tends towards gently after maximum load for high steel fiber volume fraction and aspect ratio. This may be attributed to the influence of fiber arresting cracking. Figure 5 also shows that the initial liner elastic part of the curve before matrix microcracking increased with the addition of steel fibers. Due to inadequate machine stiffness, it was impossible to measure the descending branch of the high-strength, lightweight concrete.

Flexural toughness

One of the major roles of fiber in fiber concrete is to provide toughness, i.e. increasing the energy required for the fracture process by the resultant crack arresting process[14,15]. The flexural behavior of steel fiber-reinforced, high-strength, lightweight concrete is similar to steel fiber reinforced concrete, but compared to steel fiber-reinforced concrete, cracks first occur in lightweight aggregate rather than cement paste under load. In general, fibers serving as crack arrests or barriers increase the tortuosity of an advancing crack; therefore, the addition of steel fibers to concrete effectively increases the post-cracking behavior of the steel fiber reinforced, high-strength, lightweight concrete.

The total area under the load-deflection curve indicates the energy absorbed by the flexural specimens. The flexural fracture toughness has been defined as the total area under the load-deflection curve according to ASTM-C1018-85. Figure 6 shows the relationship between toughness and the term $V_f l_f / d_f$. The increase in the value of the flexural fracture toughness is because of fiber pull-out and fiber debonding in the fracture process. However,

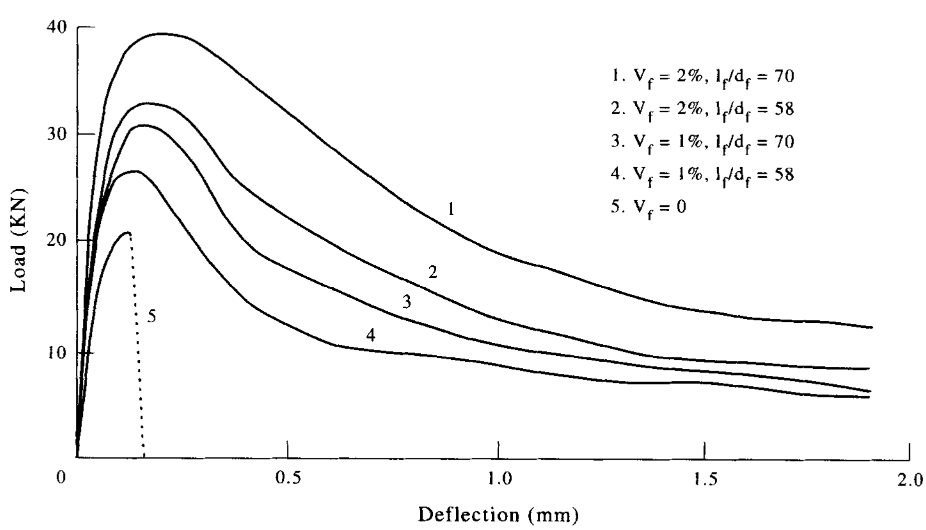

Fig. 5. Typical flexural load-deflection curves of steel fiber-reinforced, high-strength, lightweight concrete.

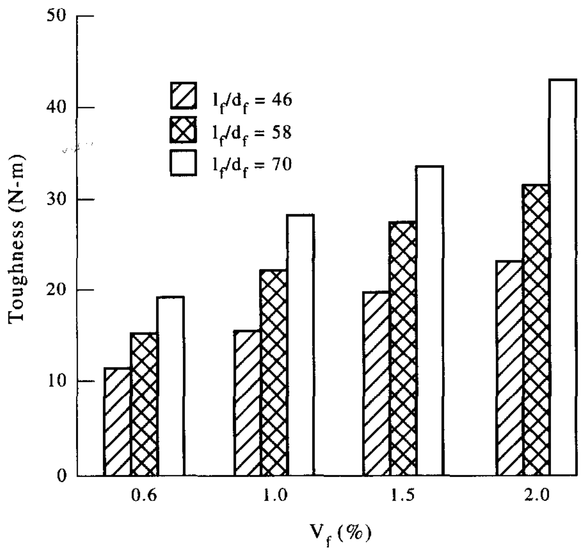

Fig. 6. Effect of V_f and l_f/d_f on flexural toughness.

fiber pull-out appears to be the most significant process concerning fracture behavior of cement-based composites.

The increase in fracture toughness with increasing fiber volume fraction stems from a great number of fibers forming a bridge in the crack and a more tortuous crack propagation path.

Modulus of elasticity and Poisson's ratio

Figure 7 shows the relationship between the static modulus of elasticity of the steel fiber-reinforced, high-strength, lightweight concrete and steel fiber volume fraction and aspect ratio. In general, the modulus of elasticity of concrete is primarily affected by the stiffness and volume of components. Since lightweight aggregates in this study are porous, the modulus of elasticity of aggregate is lower than that of natural aggregate, a greater volume of concrete is occupied by lightweight aggregate, and the modulus of elasticity of concrete is largely affected by lightweight aggregate. As the addition of steel fiber to high-strength, lightweight concrete, the modulus of elasticity of concrete gradually increased with increasing steel fiber volume fraction; this may be due to the higher modulus of elasticity of steel fiber and the decrease in the number original shrinkage cracks owing to the fiber arresting the cracking.

The relationship between the modulus of elasticity and the term $V_f l_f/d_f$ follows the equation

$$E_c = E_m(1+0.173V_f l_f/d_f) \tag{5}$$

where E_c = modulus of elasticity of steel fiber-reinforced, high-strength, lightweight concrete; and E_m = modulus of elasticity of high-strength, lightweight concrete. For steel fiber-reinforced, high-strength, lightweight concrete in this study, it is observed that Poisson's ratio tends to decrease with increasing steel fiber volume fraction (see Fig. 8). This may be attributed to the influence of the fiber arresting deformation. The relationship between Poisson's ratio and the term $V_f l_f/d_f$ follows the equation

$$\varepsilon_c = \varepsilon_m(1-0.172V_f l_f/d_f) \tag{6}$$

where ε_c = Poisson's ratio of steel fiber-reinforced, high-strength, lightweight concrete; and

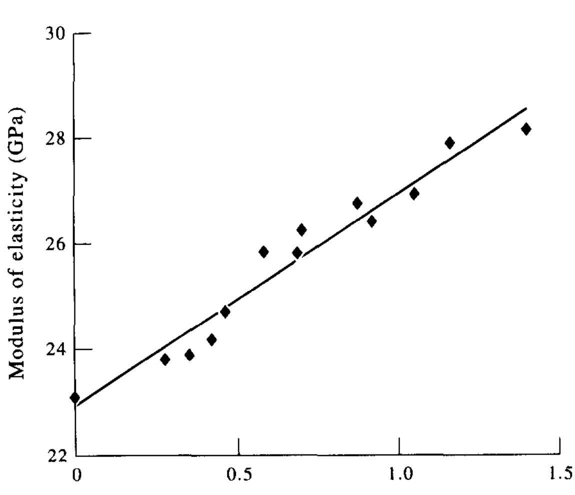

Fig. 7. Effect of $V_f l_f/d_f$ on modulus of elasticity.

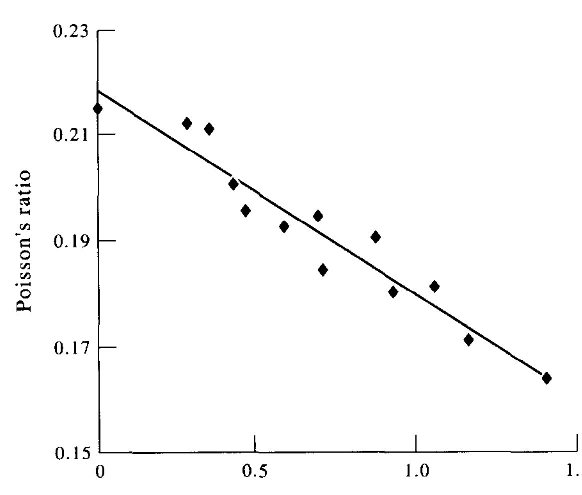

Fig. 8. Relationship between Poisson's ratio and $V_f l_f/d_f$.

ε_m = Poisson's ratio of high-strength, lightweight concrete.

CONCLUSIONS

(1) The compressive strength of high-strength, lightweight concrete was only slightly improved with the addition of steel fiber. However, splitting tensile and flexural strength were largely improved, and the flexural and splitting tensile strength varied from 4.95 to 8.8 MPa and from 6.2 to 11.8 MPa, respectively. The tensile/compressive strength ratio was obviously enhanced. These were attributed to the effect of the steel fiber arresting cracking.

(2) For steel fiber-reinforced, high-strength, lightweight concrete, the modulus of elasticity varied from 23.1 to 27.9 GPa depending on V_f and l_f/d_f, which was lower than that of steel fiber-reinforced normal concrete. The Poisson's ratio varied from 0.215 to 0.166 for different V_f and l_f/d_f.

(3) The effect of steel fiber on flexural behavior was extremely prominent, the deflection corresponding to the ultimate load increased with the increase in V_f and l_f/d_f, the shape of the descending branch of load-deflection curves tended towards gently, and flexural fracture toughness was largely improved because the fiber pull-out and debond increased the value of the fracture energy.

(4) It is important to recognize that strength and density are comprehensively taken into account in the mix design of steel fiber reinforced high-strength lightweight concrete. Therefore, the addition of steel fiber with 1–1.5% volume fraction to high-strength light weight concrete is extremely effective in improving the strength and fracture toughness in practice.

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