An Investigation of the Toughness and Compressive Toughness Index of Steel Fiber Reinforced Concrete

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In this paper, various methods for determining the toughness of steel fiber reinforced concrete (SFRC) are compared and evaluated using five criteria. The ASTM C1018-85 method mostly conforms to these criteria and, hence, is accepted as the foundation for China's standard test method of compressive toughness of SFRC. It is proposed that the critical-load point replace the first-crack point in defining the compressive toughness index based on an analysis of the onset and propagation of cracks in concrete under uniaxial compressive loading. The transient coefficient for load-carrying capacity (K^n) is also given to indicate the variational characteristic of toughness. Experiments were carried out to verify the validity of the recommended index.

Various indexes for defining the toughness of steel fiber reinforced concrete (SFRC) have been proposed by different organizations and reseachers in the past decade. For the purpose of developing a standard test method for SFRC, especially the compressive toughness test, the optimum method must be evaluated and supplemented with new concepts when necessary.

GENERAL REVIEW OF TOUGHNESS TEST METHODS

The standard test methods for SFRC toughness were developed by various reseach groups, separately and independently. Thus, the methods for determining toughness are multifarious and can be divided into four groups:

1. Energy method,
2. Strength method,
3. Energy ratio method, and
4. Multicharacteristic point method.

In a narrow sense, toughness is defined as the energy absorption capability of material or structure under loads up to its failure. In fact, the energy method employs the idea of toughness as expressed by the area under the load-deformation curve, but this concept has not yet been available for use in design. Figure 1 shows that the toughness of a material depends largely on its load-carrying capacity, as well as on its deformation ability. Therefore, it can be induced, in a broad sense. that toughness is equivalent to viscosity and can be evaluated by the deformation at which the load-carrying capacity remains at a required constant value. As shown in Figure 2, the ductility factor, $\mu = \delta_u/\delta_y$, is used to indicate the deformation ability of material or structure, up to failure in design, for earthquake-resisting structures; where δ_y is the deformation at which the behavior of material or structure changes from elastic to elasto-plastic and δ_u is the deformation when the load-carrying capacity begins to decrease or decreases to a given value.

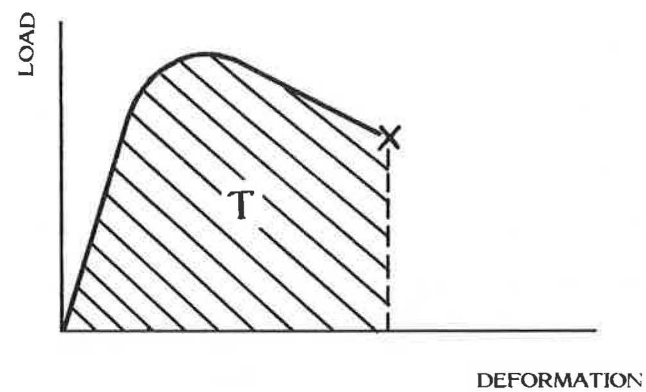

FIGURE 1 Definition of toughness.

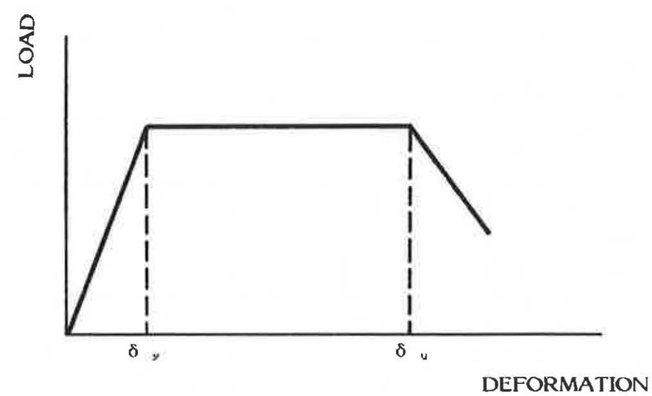

FIGURE 2 Ductility factor $\mu = \delta_u/\delta_y$.

The strength method is based on the assumption that the average equivalent strength (flexural or compressive) of a certain amount of energy absorbed up to a specific deformation can be used to access the toughness of SFRC (*1*). The flexural and compressive toughness indexes recommended by

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the JCI committee are illustrated in Figures 3 and 4 and expressed by

$$\overline{\sigma}_b = (T_b l)/(\delta_{tb} b h^2) \quad (1)$$

and

$$\overline{\sigma}_c = T_c/(\delta_{tc} A) \quad (2)$$

where l, b, h, and A are the span, width, depth and cross-sectional area of the specimen, respectively. T_b and T_c correspond to the energy absorbed (the toughness) by material up to a specified end-point deflection or deformation in flexure and compression. The advantage of this method lies in its general acceptance in design for adopting the fundamental property of material: the average equivalent strength. However, the optimum method for determining the standard deflection and deformation is still unclear. Neither the energy method nor the strength method can fully reflect the reinforcement of steel fiber on SFRC, nor can they avoid the effect of specimen size on toughness.

The proposal of ACI Committee 544 for measuring toughness can be cataloged as the energy ratio method, in which a prescribed total deflection is suggested (*2*). The toughness index was calculated as the ratio of the area under the load-deflection curve up to the mid-span deflection of 1.9 mm (for a 100 mm × 100 mm × 400 mm prismatic specimen with a span of 300 mm) to the area under the load-deflection curve up to the first-crack point. The formula is given as the following:

$$T.I. = (A_1 + A_2)/A_1 \quad (3)$$

where A_1 and A_2 are the shaded areas in Figure 5. Although some ratio systems with dimensionless indexes can be independent of specimen size and geometry, the ACI method is not, due to its definition in terms of a deflection that relates to a particular deflection. A major disadvantage of the energy method is that it is sensitive to the dislocation of the first-crack point; thus, the toughness index value can be substantially affected (*3–6*).

Consideration of practical serviceability requirements led to the development of the multiple characteristic point method, in which more than one end-point deflection is suggested (*7*). As shown in Figure 6, the characteristic point can be point A, the first-crack point; point B, at which the maximum load is achieved; point C, where the load-carrying capacity decreases to some extent (for instance, to that of 0.85 P_{max}); point D, at which the deformation increases to some extent (for instance, to that of three times of the first-crack deformation); point E, where crack widths are limited to some given values; or point F at which fracture of the specimen is supposed to occur.

The ASTM C1018-85 method originated from Johnston's definition of toughness index referenced to first-crack deflection (*8*), in which the ratio of total area (to any multiple of first-crack deflection) to the area up to the point of first crack

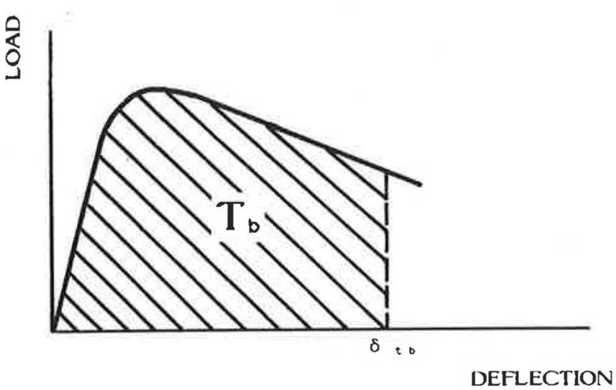

FIGURE 3 Flexural toughness coefficient σ_b.

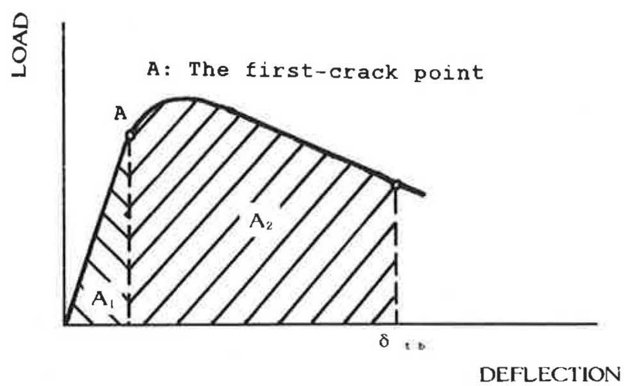

FIGURE 5 Toughness index (T.I.).

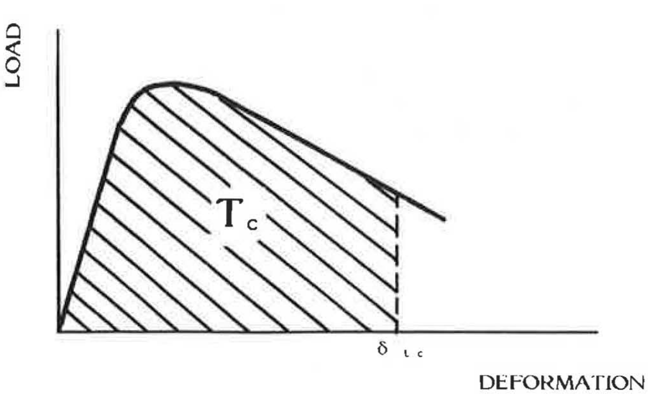

FIGURE 4 Compressive toughness coefficient σ_c.

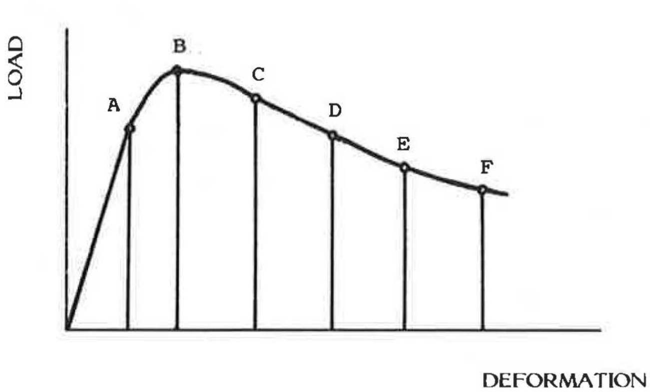

FIGURE 6 The multipoint system.

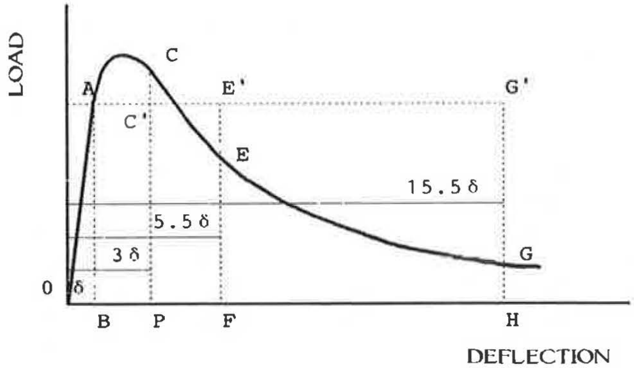

FIGURE 7 Flexural toughness indexes I_5, I_{10} and I_{30}.

was given (see Figure 7). The toughness indexes (I_5 = area *OACP*/area *OAB*, I_{10} = area *OAEF*/area *OAB*, and I_{30} = area *OAGH*/area *OAB*) enable the actual performance of material to be compared with a readily understood reference level of performance, e.g., the perfect elasto-plastic material to which the values of 5, 10, and 30 for toughness index correspond. This method proved to be better with respect to various criteria, especially the precision of the toughness index. It was previously reported that the use of multiples of first-crack deflections reduced the coefficient of variation for the toughness index (*8*).

From the above discussion, the evaluating process for toughness indexes should be based on the following criteria:

- Existence of rational and physical meaning,
- Appropriateness for engineering applications,
- Ability to indicate the influences caused by the type and shape of the added steel fibers and the fiber volume,
- Ready determination with small deviation, and
- Independence of specimen size.

COMPRESSIVE TOUGHNESS INDEX

In view of the widely recognized concept of ASTM C1018-85 and the evaluation described previously in this paper, compressive toughness indexes I_5, I_{10}, and I_{30}, which are dimensionless ratios of different areas under the load-deformation curve, were recommended (see Figure 8). For uniaxial compressive concrete, the first-crack point is not easily identifiable, due to the curvilinearity of the load-deformation curve compared with the stress-strain curve of tensile and flexural concrete (*9*). Analysis of the onset and propagation of cracks in concrete under uniaxial compressive load, as well as the reinforcement of steel fiber, provided the rationale for selecting the critical-load point as the characteristic point of compressive toughness index. Liu et al. (*10*) reported the four phases of formation and propagation of microcracks in concrete:

1. Shrinkage cracks occur around the coarse aggregates even prior to loading.
2. At loads of 30 to 65 percent of ultimate strength, stable cracks occur at the interfaces.
3. The propagation of stable cracks initiates the stretching bond cracks to bridge mortar cracks into discontinuous ones, and the propagation stops right after unloading.

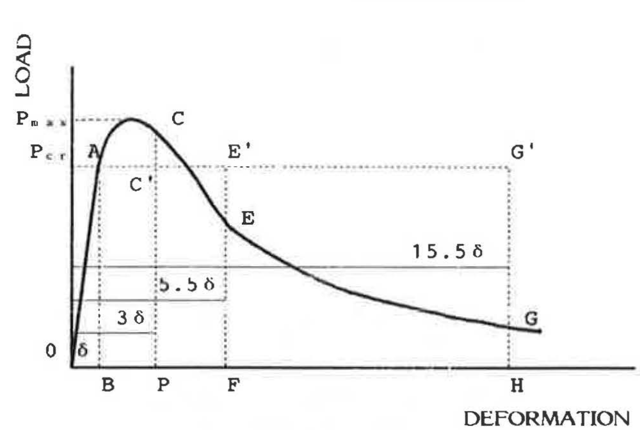

FIGURE 8 Compressive toughness indices I_5, I_{10} and I_{30}.

4. During the propagation of unstable cracks, mortar cracks increase in number and tend to form continuous cracks, which propagate automatically and lead to the collapse of concrete.

When stable crack propagation ends and unstable crack propagation begins, the load is usually 70 to 90 percent of ultimate, which is termed critical load P_{cr}. Concrete is less likely to collapse when the long-term load is smaller than P_{cr} (*11*).

As a result of the preferential distribution of steel fiber parallel to the interfaces of aggregates, steel fiber does not serve the function of arresting bond cracks in Phases 1 and 2. Apparently, the unique ability of steel fiber to bridge cracks, especially unstable cracks, is fully demonstrated in Phases 3 and 4. Thus, the critical load is less affected by the reinforcement of steel fiber. In fact, steel fiber has little influence on the increment of concrete compressive strength, and sometimes the strength even decreases in unevenly mixed concrete mixtures. It is widely accepted that the post-crack behavior of concrete after the addition of steel fiber is the most important feature (i.e., the high load-carrying capacity at large deformation).

It can be concluded from the above analysis that the critical load depends mainly on the properties of the matrix and rarely relates to the fiber content; hence, the load of 85 percent of ultimate strength was chosen as the characteristic load for specimens of various fiber content because of its easy determination from the load-deformation curve.

To indicate the trend analysis of the load-deformation curve at various deformations, as well as the difference between the post-crack behavior of a material and that of perfect elasto-plastic material, an average coefficient for load-carrying capacity (K^n) was introduced in the following formula (*3*). The formula is derived from the bi-linearized load-deformation curve shown in Figure 9:

$$K^n = (P_{cr} + \Delta P)/P_{cr} = (I_n - m)/(m - 1) \quad (4)$$

where

m = multiple of the critical-load deformation, which may be 3, 5.5, 15.5, or other multiples chosen in terms of serviceability requirements;

I_n = average toughness index of the specimens in one group (n = 5, 10, and 30);

P_{cr} = critical load, which is 85 percent of the ultimate strength; and
P = increment of load-carrying capacity at a given deformation, which is negative when the load is smaller than P_{cr}.

The transient coefficient, K^n, is at a minimum when the portion of the curve after critical load is vertical and increases from -1 through 0 to 1, and then more than one. The various values correspond to materials with behavior ranging from elastic ($K^n = -1$) to perfect elasto-plastic ($K^n = 1$) to even tougher than elasto-plastic ($K^n \geqslant 1$), are shown in Figure 10 and Table 1.

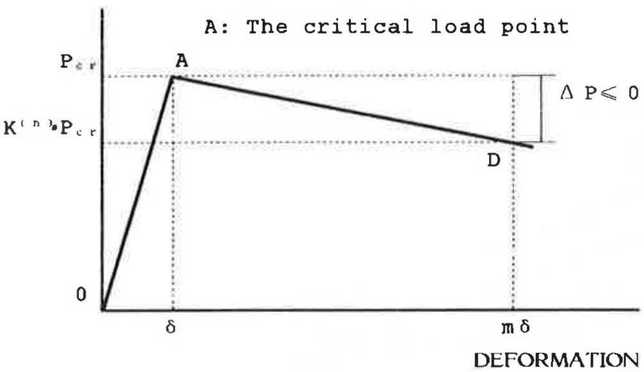

FIGURE 9 Load-deformation curve after bi-linearization.

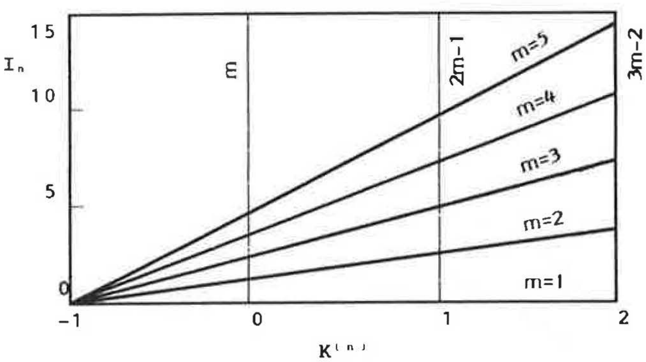

FIGURE 10 Relationship between K^n and I_n.

TABLE 1 THE VALUES OF I_n CORRESPONDING TO SOME SPECIFIC VALUES OF K^n

$K^{(n)}$	I_n
-1	1
0	m
1	2m-1
2	3m-2

EXPERIMENTAL INVESTIGATION

To verify the validity of the test method for compressive toughness index proposed in this paper, five groups of specimens were prepared with different fiber volume fractions. Ordinary portland cement with a 28-day compressive strength of 42.5 MPa was used. The coarse aggregate used was 20 mm maximum size crushed stone with a fineness of modulus of 2.63. All the specimens were 100 mm × 100 mm × 200 mm in prism. The melt-extracted carbon steel fiber (0.2 mm × 1.0 mm × 25 mm) was added into the concrete mixture with a vebe time of about 10 ± 3 sec. The mix proportions of the SFRC specimens are shown in Table 2. All uniaxial compressive tests were carried out in a universal testing machine, accompanied by two sets of oil jack as a stiffness unit. Deformation at the loading points, as well as the load were plotted by an X-Y recorder through which the load-deformation curve could be obtained automatically.

Figure 11 is the typical load-deformation curve obtained from the tests. The toughness indexes and the coefficient K^n are listed in Table 3. Figure 12 shows that the coefficient K^n can either clearly indicate the reinforcement of steel fiber on a compressive specimen or fairly describe the material behavior after cracking.

CONCLUSIONS

Based on the work presented in this paper, the following conclusions were drawn:

- The ASTM C1018-85 method has some advantages over the other existing test methods; hence, it was adopted as the basis for the standard test method of compressive toughness of SFRC.
- It was proposed that the critical-load point replace the first-crack point for measuring compressive toughness, based on the analysis of the onset and propagation of cracks in concrete.
- The toughness indexes I_5, I_{10} and I_{30}, accompanied by the coefficient K^n, can clearly reflect the post-crack behavior of SFRC.

TABLE 2 MIX PROPORTIONS OF SPECIMEN

V(%)	Contents of Materials (kg/m³)					Water-Cement Ratio	Sand Ratio
	Steel Fiber	Cement	Water	Sand	Crushed Stones		
0	0	340	170	650	1200	0.5	0.35
0.5	40	360	180	720	1080	0.5	0.40
1.0	80	380	190	790	960	0.5	0.45
1.5	120	400	200	850	850	0.5	0.50
2.0	160	420	210	910	740	0.5	0.55

TABLE 3 TOUGHNESS INDEXES I_n and K^n

		$V_f=0$	$V_f=0.5\%$	$V_f=1.0\%$	$V_f=1.5\%$	$V_f=2.0\%$
m=3	I_5	4.73	4.77	5.00	5.36	5.54
	$K^{(5)}$	0.87	0.89	1.00	1.18	1.27
m=5.5	I_{10}	7.20	8.61	9.51	10.47	11.63
	$K^{(10)}$	0.38	0.69	0.89	1.10	1.36
m=15.5	I_{30}	12.28	16.88	20.84	23,52	29.07
	$K^{(30)}$	---	0.10	0.37	0.55	0.94

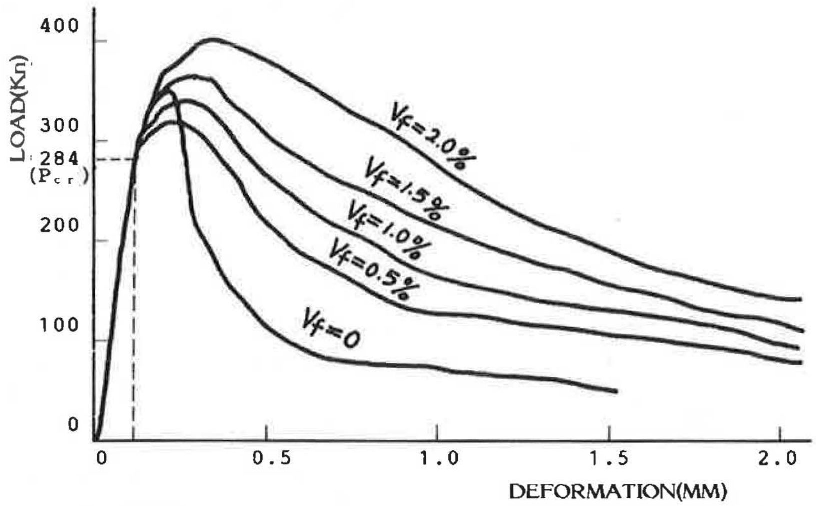

FIGURE 11 Typical compressive load-deformation curve.

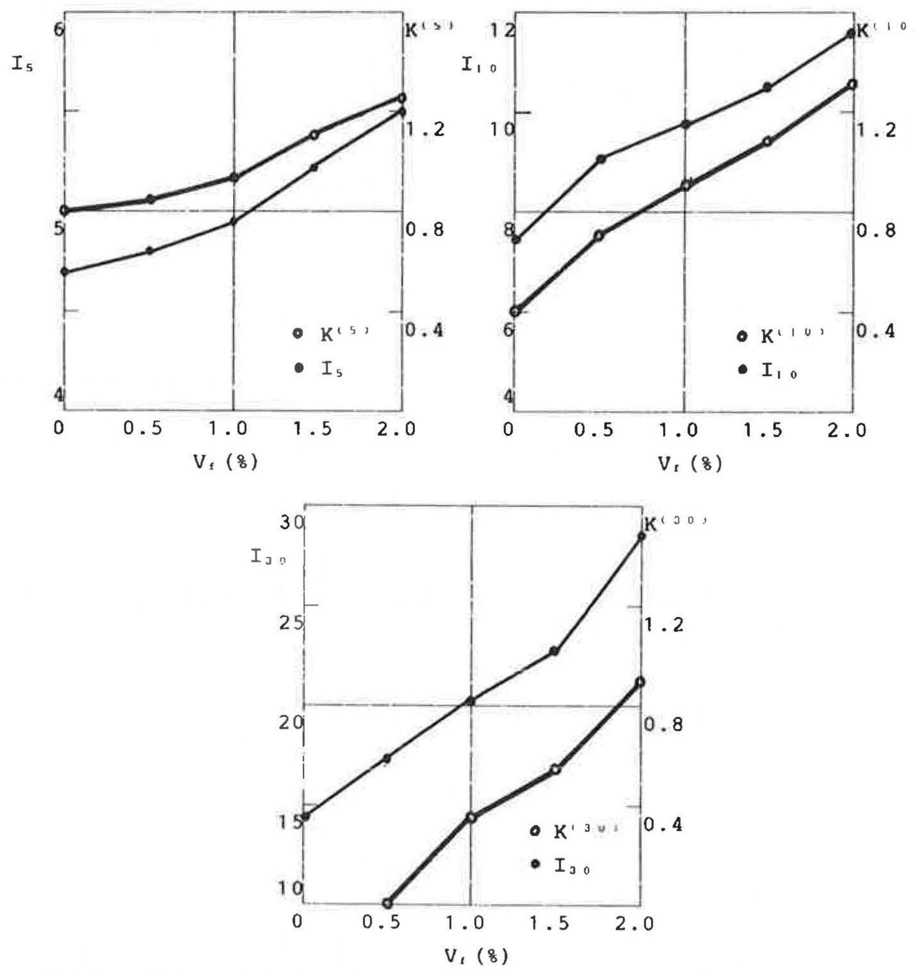

FIGURE 12 Relationship of toughness indexes, transient coefficient for load-carrying capacity, and fiber volume.

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