Latex Modification Effects on the Impact Resistance and Toughness of Plain and Steel-Fiber-Reinforced Concretes

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The effects of latex modification and steel fiber reinforcement on the impact resistance and flexural strength and toughness of concrete materials were investigated. Two levels of latex content and two different fiber volume fractions were considered. Latex modification was particularly effective in increasing the impact resistance of plain concrete. Flexural strength was also increased in the presence of latex, but the flexural toughness of plain concrete did not receive major benefits from latex modification. Steel fibers were effective in increasing the impact resistance and flexural strength and toughness of concrete. The advantages associated with the joint use of steel fibers and latex polymers in concrete materials are assessed. Specifically, the effects of steel fiber reinforcement and latex modification on the impact resistance, flexural strength, and toughness characteristics of concrete materials are addressed. The hypothesis is that the improved adhesion capacity and ductility of concrete matrices incorporating latex polymers make them more compatible with steel fibers. The combined action of steel fibers and latex polymers produces the best performance characteristics. In the case of impact resistance and flexural toughness, the joint effects of latex and steel fibers are more than additive, indicating a positive interaction between the two. Latex modification seems to make concrete matrices more compatible with steel fibers. The increase in fiber-to-matrix bond in the presence of latex also seems to enhance the reinforcement properties of steel fibers in concrete.

Ordinary concrete suffers from relatively low flexural strength, toughness, and impact resistance. Steel fiber reinforcement and polymer modification each can partly overcome some of these problems.

Steel fibers enhance the ductility and energy absorption capacity, flexural strength, and impact resistance of concrete. Latex modification, on the other hand, improves the impermeability as well as strength and ductility characteristics of concrete.

Latex polymers in the presence of steel fibers provide a better bonding between fibers and the concrete matrix because of the formation of a monolithic polymer film that surrounds the fibers, fills the smaller voids, and links the cementitious environment to the fibers. As a result, the formation of many of the microcracks that tend to take place along the fiber-matrix interface is prevented. In addition, the resistance of fibers against pull-out action is further enhanced, resulting in improved flexural strength, toughness characteristics, and impact resistance.

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BACKGROUND

Impact Resistance

The impact resistance of concrete materials is an important factor in the design of systems such as concrete overlays on industrial floors and airfield pavements.

Latex, because of its film formation action inside the concrete matrix, gives the material some microcrack arresting properties that can potentially lead to improvements in the impact resistance of concrete (*1*). Further test data are needed for verifying the latex modification effects on the impact resistance of concrete.

Steel fiber reinforcement has also been shown in various investigations to significantly improve the impact resistance of concrete. Figure 1 (*2*) shows typical improvements in the impact resistance of concrete obtained through steel fiber reinforcement, which can be attributed to the crack-arresting action of fibers.

Flexural Performance

Latex modification of concrete provides the material with higher flexural strengths (see Figure 2) (*3*). This increase in flexural strength can be attributed to the microcrack-arresting action of polymers in concrete, and also to the bonding they provide between the matrix and aggregates. Improvements of workability through latex modification (which reduces water requirements for achieving similar workability in latex-modified concrete) is another factor contributing to flexural strength in latex-modified concrete.

Previous test results (*4*) have indicated that, at a polymer-cement ratio of 0.20, styrene-butadiene, saran, acrylic, and polyvinyl alcohol latexes provide flexural strengths of the order of 2, 3, 1.4, and 3 times, respectively, that of plain mortar after 28 days of dry curing at 50 percent relative humidity.

Steel fibers have been found to increase the first-crack and ultimate flexural strengths of concrete (*2*). They also make major contributions to the ductility and toughness (represented by the area under the flexural load-deflection curve) of the material. Steel fibers, with their desirable pull-out performance, are especially effective at relatively large deformations and crack widths.

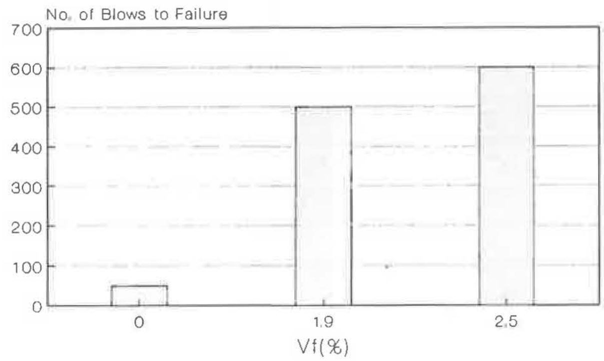

FIGURE 1 Effect of steel fiber reinforcement on the impact resistance of concrete (hooked-end steel fibers, length-to-diameter ratio = 100) (*2*).

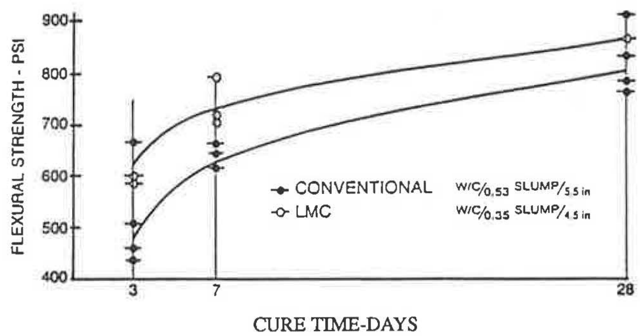

FIGURE 2 Flexural strength of plain concrete and concrete modified by latex (styrene-butadiene) versus cure time (*3*).

EXPERIMENTAL PROGRAM

The mix proportions selected for the latex-modified steel-fiber-reinforced concrete (LMSFRC) mixtures with different latex and fiber contents are presented in Table 1. The cement in all these mixes is regular Type I, the coarse aggregate is crushed limestone (see Figure 3 for gradation) with a maximum particle size of 13 mm (½ in.); the fine aggregate is natural sand with gradation satisfying the ASTM C-33 gradation requirements; the latex is BASF Styrofan 1186 styrene-butadiene dispersion (see Table 2 for properties); the steel fibers are hooked-end with a length of 30 mm (1.18 in.) and a diameter of 0.5 mm (0.0197 in.). The air-entraining agent (used only in the unmodified mixtures) was a completely neutralized vinsol resin solution.

Water content was adjusted in different mixtures, depending on the latex and fiber contents, for achieving a desirable level of workability [represented by the British Standard BS 1881 VB time of 7 to 9 sec for fibrous mixes and a slump of 76 to 127 mm (3 to 5 in.) for plain mixes]. The air content was also adjusted by varying the dosage rate of air-entraining agent.

Three cylindrical specimens 152 mm (6 in.) in diameter and 63.5 mm (2.5 in.) in height were prepared for impact tests from each of the four mixes presented in Table 1. They were moist-cured inside their molds under wet burlap coated by a polyethylene sheet for the first 24 hr and then demolded and cured in air until the test age of 28 days. The impact resistance test is performed by repeatedly dropping a 4.5-kg (10-lb) hammer on a hard steel ball supported on the cylinder from a height of 457 mm (18 in.) (*5*). The number of blows required to cause the first visible crack and the ultimate failure represents the impact resistance of the material. Ultimate failure is assumed to occur when the cracks open so far that the pieces of concrete are touching three of the four positioning lugs on the base plate. Figure 4 (*5*) shows the impact resistance test apparatus.

In addition, for each mix, three 102- × 102- × 356-mm (4- × 4- × 14-in.) prismatic flexural specimens were prepared. They were all moist-cured inside their molds under wet burlap

TABLE 1 MIX PROPORTIONS FOR EXPERIMENTAL WORK

V_f (%)	Styrenene Butadiene L/c (%)	w/c	Slump mm. (in.)	Vebe Time (sec.)	Air Content (%)
0	0	0.43	152 (6.0)	-----	5.5
0	10	0.32	190 (7.5)	-----	4.5
0.75	0	0.45	127 (5.0)	6.5	6.5
0.75	10	0.34	152 (6.0)	5.0	5.0

--- = no measurement taken
V_f = fiber volume fraction;
L/c= latex-cement ratio, by solids weight;
w/c= water-cement ratio, by weight;
s/c=2.5=sand-cement ratio, by weight; and
st./c=1.5=stone-cement ratio, by weight.

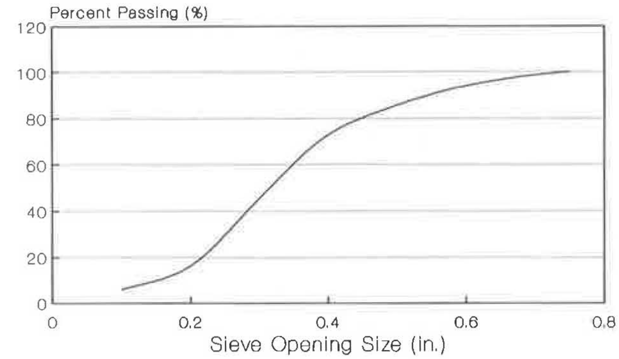

FIGURE 3 Gradation of crushed limestone coarse aggregate.

TABLE 2 PROPERTIES OF STYRENE BUTADIENE LATEX

Typical Properties	
Total solids (wt. %)	47
Specific gravity	1.01
pH (25 C)	10
Surface tension (mN/m)	38
Weight/volume , lb/U.S.gal. (kg/l)	8.3 (1.01)

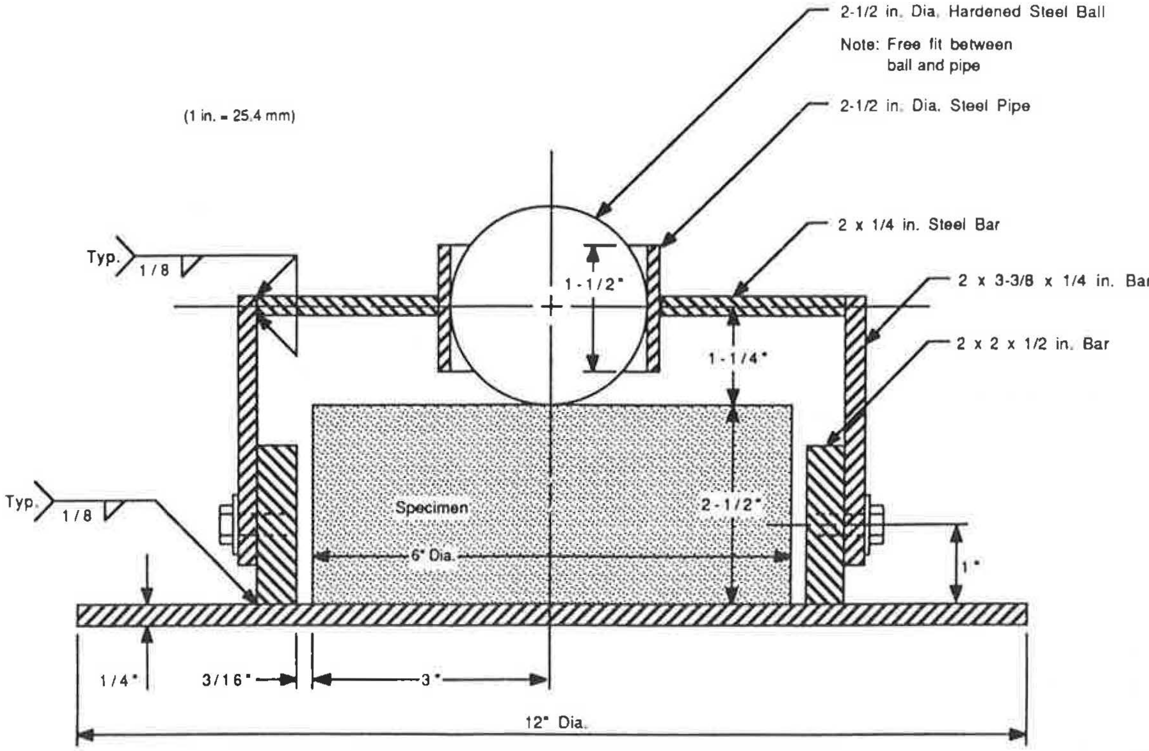

FIGURE 4 Apparatus for impact resistance test (*5*).

coated by a polyethylene sheet for the first 24 hr and then demolded and cured in air until the test age of 28 days. The flexural specimens were tested following the ASTM C-1018 and the Japanese Concrete Institute procedures (JCI-SF) by four-point loading on a span of 305 mm (12 in.). The flexural test set-up is shown in Figure 5. A computerized data acquisition system was used for load and deflection measurements, and also for the processing of the flexural test results.

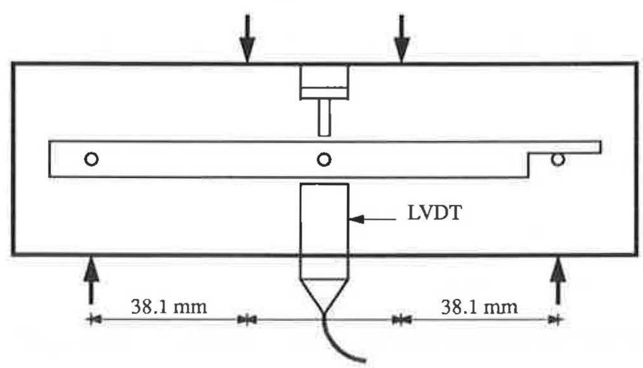

FIGURE 5 Flexural test set-up.

EXPERIMENTAL RESULTS

Impact Resistance

The impact resistance test results obtained for the mixes presented in Table 1 are presented in Table 3 and shown in Figure 6. It can be seen that latex addition increases the impact resistance of plain concrete by an average of 800 percent. Steel fiber reinforcement increases the impact resistance by an average of 370 percent. Combined use of latex polymers and steel fibers leads to major improvements in impact resistance, causing a 1,500 percent increase over plain concrete.

When both steel fibers and latex are added to the plain concrete mix, the improvements in impact resistance are superior. This effect indicates that there is an effective interaction between the steel fibers and the latex, which may result from the improved fiber-to-matrix bonding in the presence of latex polymers, and also from the increased compatibility of steel fibers and the matrix because of the reduced brittleness of the matrix incorporating latex.

When fibers are missing from the matrix, even in the presence of latex, there is only a small difference between the first crack and the failure impact resistance. This indicates that fibers, but not latex, can provide the material with post-cracking integrity.

In order to statistically investigate the effects of latex modification and steel fiber reinforcement on impact resistance, one-way analyses of variances were conducted. A one-way analysis of variance (ANOVA) performed for the cases of unmodified and latex-modified plain concretes [fiber volume fraction (Vf) of 0 percent] indicated that the effects of latex content on the impact resistance of plain concrete are significant with about 15.2 percent chances of error in this statement. A similar one-way ANOVA performed for the cases of unmodified and latex-modified steel-fiber-reinforced concrete (SFRC) (Vf = 0.75 percent) resulted in similar conclusions, with about 15.3 percent chance of error in stating that there is a latex effect on the impact resistance at Vf = 0.75 percent.

TABLE 3 IMPACT RESISTANCE TEST RESULTS FOR MIXES PRESENTED IN TABLE 1

Vf (%)	L/c (%)	Number of Blows to First Crack	Number of Blows to Failure
0	0	29	33
		25	28
		32	35
0	10	232	233
		503	503
		50	53
0.75	0	60	106
		190	247
		154	264
0.75	10	900	1065
		395	530
		148	278

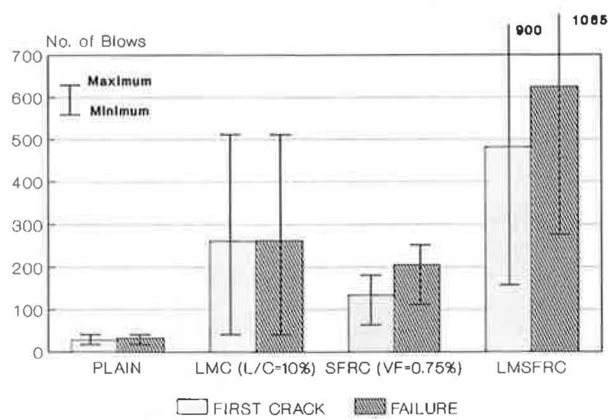

FIGURE 6 Impact resistance test results.

Similar analyses were performed to investigate the effects of steel fiber reinforcement at constant latex content on the impact resistance of the concrete matrix. For the case of unmodified concrete (latex-cement ratio L/c = 0 percent), the one-way ANOVA showed that fiber addition has a significant positive effect on the impact resistance, with only 2.6 percent chance of error in this statement. At a constant L/c of 10 percent, the corresponding one-way ANOVA revealed that there is about 24.6 percent chance of error in stating that there is a fiber effect on impact resistance of concrete at a latex-cement ratio of 10 percent.

The scatter in impact resistance test results is relatively large. This leads to conditions where, in spite of the large differences in average values of impact resistance for different mix proportions, the chance of error in stating that such a difference exists sometimes exceeds 15 percent.

Flexural Performance

The average flexural load-deflection curves for the four mix compositions considered in this investigation are presented in Figure 7. The improvements resulting from latex modification

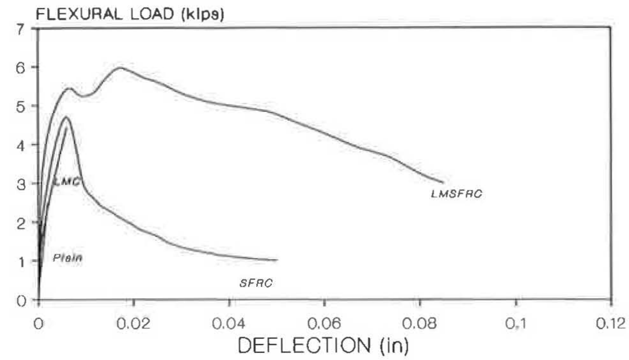

FIGURE 7 Average flexural load versus deflection relationships.

and steel fiber reinforcement, and the desirable joint effects of latex and steel fibers, are obvious in this figure. The flexural strength and toughness (defined as the area underneath the flexural load-deflection curve up to a flexural deflection equal to the span length divided by 150) test results obtained for the mixes of Table 1 are presented in Table 4.

Flexural Strength

From Table 4 and Figure 8, it can be seen that latex addition (L/c = 10 percent) increases the flexural strength of plain concrete by about 87 percent, whereas steel fiber reinforcement (Vf = 0.75 percent) increases it slightly more by about 92 percent. When plain concrete is both modified with latex polymers and reinforced with steel fibers, the improvements in flexural strength are more significant (an increase of about 150 percent over plain concrete).

A factorial analysis of variance performed on these results confirmed the significance of the effects of latex polymers, steel fibers, and their interaction, at the 5 percent level of significance. The relative significance of the effects of fibers, latex, and their interaction on the flexural strength, as indicated by the factorial analysis of variance, is presented in Table 5.

TABLE 4 FLEXURAL STRENGTH AND TOUGHNESS TEST RESULTS

Vf (%)	L/c (%)	Flexural Strength (ksi)	Flexural Toughness (k-in)
0	0	0.420	0.00003
		0.467	0.00005
		0.522	0.00002
0	10	0.880	0.0046
		0.868	0.0058
		0.775	0.0034
0.75	0	0.893	0.254
		0.869	0.207
		0.881	0.231
0.75	10	1.018	0.339
		1.235	0.425
		1.126	0.382

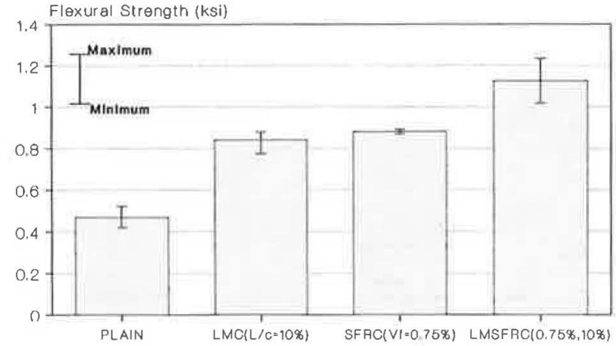

FIGURE 8 Flexural strength test results.

TABLE 5 FACTORIAL ANALYSIS OF VARIANCE OF FLEXURAL STRENGTH TEST RESULTS

Factor	Importance
Steel Fibers	**
Latex	**
Interaction	**

"**" very significant
"*" Significant

Flexural Toughness

Steel fiber reinforcement is indicated in Table 4 and Figure 9 to have positive effects on the flexural toughness of concrete, whereas the improvements in toughness resulting from latex modification are relatively small. Latex modification, however, is highly effective in improving toughness characteristics in the presence of steel fibers.

A factorial analysis of variance confirmed that the effects of latex and steel fibers on flexural toughness, as well as their interaction, are important at the 5 percent level of significance (see Table 6).

The significant improvements in flexural toughness of SFRC resulting from latex modification (noting that latex has relatively small effects on the flexural toughness of plain concrete) can be attributed to the improvements in fiber-to-matrix interfacial bond characteristics by latex polymers. In order to confirm this, microscopic pictures were taken of the steel fibers pulled out of unmodified and latex-modified steel-fiber-reinforced concretes at the fractured surfaces of the flexural specimens. As shown in Figure 10a, the steel fibers pulling

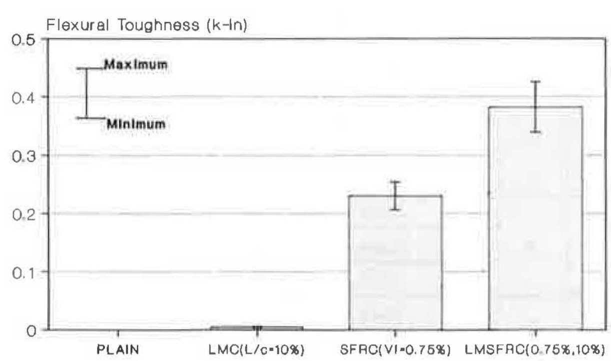

FIGURE 9 Flexural toughness test results.

TABLE 6 FACTORIAL ANALYSIS OF VARIANCE OF FLEXURAL TOUGHNESS TEST RESULTS

Factor	Importance
Steel Fibers	**
Latex	**
Interaction	*

"**" very significant
"*" Significant

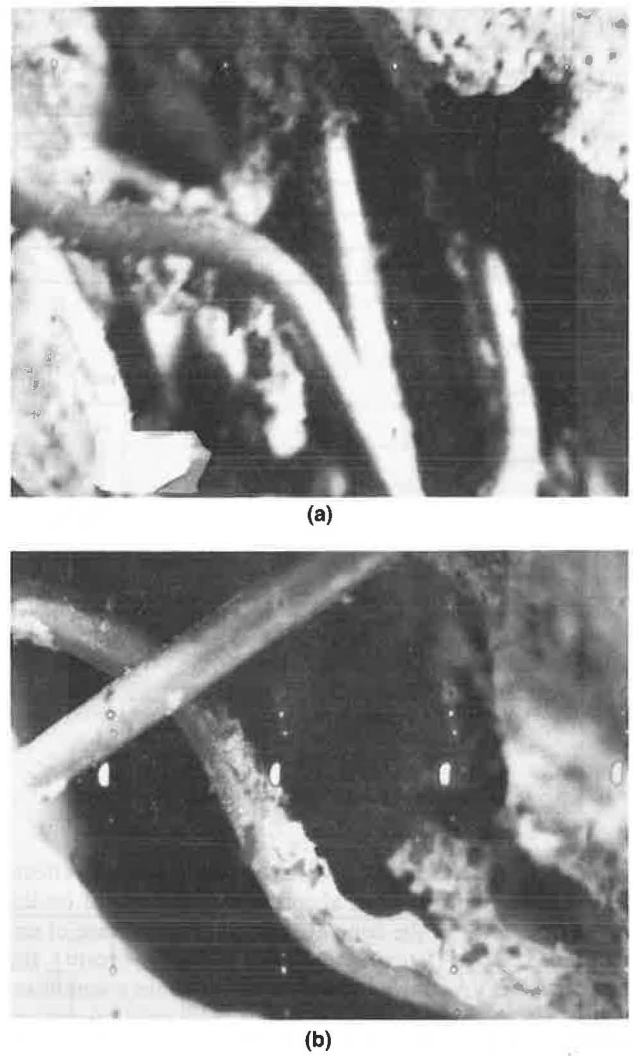

FIGURE 10 Microscopic pictures of steel fibers pulling out of (a) unmodified concrete, (b) latex-modified concrete.

out of unmodified concrete were clean, indicating an interface shear failure. The steel fibers pulling out of latex-modified concrete (Figure 10b) were partially coated with the polymer-cement comatrix, indicating that the interface shear strength was strong enough to encourage shear failure in the matrix further away from the interface zone.

SUMMARY AND CONCLUSIONS

Experimental results regarding the effects of steel fiber reinforcement and latex modification on the impact resistance

and flexural strength and toughness characteristics of concrete are reported.

From the generated test results, the following conclusions could be drawn:

1. Latex modification of steel fiber reinforcement increases the impact resistance of the concrete matrix, with superior impact strengths obtained when steel fibers and latex polymers are used simultaneously, indicating an effective interaction between latex and steel fibers resulting from the improved bonding between the fibers and the latex-modified mixtures.

2. The separate actions of latex polymers and steel fibers in concrete lead to improved flexural strength of concrete. The combined action of latex modification and steel fiber reinforcement leads to highest flexural strength values.

3. Steel fiber reinforcement is effective in increasing the flexural toughness (area underneath the flexural load-deflection curve) of concrete. Although latex modification has relatively small effects on the flexural toughness of plain concrete, it is capable of significantly improving the toughness characteristics of SFRC. These improvements can be attributed to the positive effects of latex modification on the fiber-to-matrix interfacial bond characteristics and pull-out behavior.

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