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Mechanical Properties of Polypropylene Fiber Reinforced Concrete and the Effects of Pozzolanic Materials

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Abstract

A comprehensive set of experimental data were generated regarding the effects of collated fibrillated polypropylene fibers at relatively low volume fractions (below 0·3%) on the compressive, flexural and impact properties of concrete materials with different binder compositions. Statistical analysis of results produced reliable conclusions on the mechanical properties of polypropylene fiber reinforced concrete, and also on the interaction of fibers and pozzolanic admixtures in deciding these properties. Polypropylene fibers were observed to have no statistically significant effects on compressive or flexural strength of concrete, while flexural toughness and impact resistance showed an increase in the presence of polypropylene fibers. Positive interactions were also detected between fibers and pozzolans. Copyright © 1996 Elsevier Science Ltd.

Key words: Compression, concrete, flexure, impact, polypropylene fibers, pozzolans, statistical analysis, strength, tests, toughness.

INTRODUCTION

Fibers in general and polypropylene fibers in particular have gained popularity in recent years for use in concrete, mainly to enhance the shrinkage cracking resistance and toughness of plain concrete. Polypropylene fibers are commercially utilized at relatively low volume fractions to control plastic shrinkage cracking of concrete. Polypropylene fibers are not expected to increase the strength of concrete, but to improve its ductility and toughness, and impact resistance. At low volume fractions, however, the fiber effects on concrete strength properties and impact resistance are relatively small, and careful statistical analysis of a sufficiently large number of tests would be required to distinguish between the actual fiber effects and the random variations in experimental results.

This study presents comprehensive experimental data and powerful statistical analyses which produce conclusions, at high levels of confidence, regarding the effects of low volume fractions of collated fibrillated polypropylene fibers on the compressive and flexural strength and toughness, and impact resistance of polypropylene fiber reinforced concrete materials.

BACKGROUND

A considerable amount of research has been performed on the mechanical properties of polypropylene fiber reinforced concrete.

Compressive and flexural strength and toughness

Contradictory test results have been reported by different investigators regarding the effects of polypropylene fibers on the compressive and flexural strengths of concrete material.[1-10] Differences in results may have been caused by the differences in matrix composition, polypropylene fiber type and volume fraction, and manufacturing conditions.

Zollo *et al.* (1984)[1] performed tests to determine compressive strength (ASTM C-39), splitting tensile strength (ASTM C-496), and flexural strength (ASTM C-78) for both plain and polypropylene fiber reinforced concretes. Fiber contents in these tests ranged from 0–0·3% by volume. The results indicated that the presence of fibers had negative effects on compressive strength, while splitting tensile and flexural strengths increased slightly with increasing fiber content. The results generated by other investigators generally agree with the earlier findings reported above.[4,6,7] Some researchers also reported evidence of small but favorable effects of fiber addition on toughness.[11,12] Mindess and Vondran (1988)[2] reported that compressive strength increased by about 25% at 0·5% volume fraction of polypropylene fibers. Test results reported by Hughes and Fattuhi (1976),[5] suggest that compressive strength decreases but flexural properties are improved with increasing fiber content.

Impact resistance

Concrete materials are subjected to impact loading in various fields of application, including pile driving, hydraulic structures, airfield pavements, protective shelters, and industrial floor overlays. Impact resistance represents the ability of concrete to withstand repeated blows and absorb energy. Since plain concrete is a brittle material, it has a relatively low energy absorption capacity under repeated impact loads.

Different test procedures have been developed for the measurement of the impact resistance of concrete. Due to the variable nature of such testing and the need to apply specialized analytical techniques to each test arrangement, cross test comparisons can not be made. Some reports indicate an increase in impact strength using polypropylene fibers,[2,8,14] while others show no improvement.[1] Tests using ACI committee 544 recommendation (drop-hammer method) have indicated that the number of blows required to obtain the first crack and the ultimate failure was increased by the addition of polypropylene fibers.[15,16]

EXPERIMENTAL PROGRAM

The mechanical properties of polypropylene fiber reinforced concrete (PPFRC) were investigated experimentally. First the effects of collated fibrillated polypropylene fibers on compressive and flexural strength and toughness were considered, and then the impact resistance of polypropylene fiber reinforced concrete was assessed.

Two experimental programs were designed for studying the compressive and flexural properties and impact resistance of polypropylene fiber reinforced concrete. In phase I, the effect of polypropylene fiber volume fraction was investigated in a one-way experimental design with five different volume fractions (0·0, 0·05, 0·1, 0·2, and 0·3%). In the second experimental design, the effects of pozzolanic materials in polypropylene fiber reinforced concrete were assessed (see Table 1).

Materials

The basic mixture ingredients of polypropylene fiber reinforced concrete (PPFRC) were: Portland cement type I, coarse aggregate, fine aggregate, water, and collated fibrillated polypropylene fibers. An air entraining agent was added to provide for freeze–thaw resistance. Superplasticizer was added to unworkable mixtures in order to maintain certain limits on water/cement ratio and slump.

The matrix composition in some mixtures was adjusted through partial substitution of Portland cement with a pozzolanic material (fly ash, slag, or silica fume). Table 2 presents the chemical compositions of the cement and pozzolanic materials used.

Collated fibrillated polypropylene fibers were used in this research. Some of the physical properties of these fibers are: tensile

Table 1. Experimental program; Phase II

Binder type	*Fiber volume fraction (%)*	
	0·0	*0·1*
Portland cement	*	*
75% Cement + 25% Fly Ash	*	*
90% Cement + 10% Silica Fume	*	*
75% Cement + 25% Slag	*	*

*2-Compression, 3-Flexural, and 10-Impact Specimens.

Table 2. Chemical compositions of binders

Binder type	*CaO*	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*SO_3*	*MgO*	*K_2O*	*C*	*Na_2O*
Cement	63·24	21·14	5·76	2·93	2·46	2·06	0·79	—	—
Fly Ash	2·6	47·00	22·10	23·40	—	0·76	2·00	4·30	—
Silica Fume	—	96·50	0·15	0·15	—	0·20	0·04	1·40	0·20
Slag	—	35·40	11·40	0·60	1·02	13·00	0·34	—	0·10

strength = 628–760 MPa (80–110 Ksi), young's modulus=3·5 GPa (500 Ksi), specific gravity = 0·9, melting point=160–170°C (320–340 °F), and ignition Point=590°C (1100 °F).

Coarse aggregates were crushed lime stone with maximum aggregate size of 19 mm (0·75 in) and specific gravity of 2·55. Fine aggregates were natural sand with fineness modulus of 3·0 and the specific gravity of 2·50. The gradation of coarse and fine aggregates met the ASTM C 33 requirements.

Mix proportioning

It was decided that the concrete mixture should provide a slump of 89±13 mm (3·5±0·5 in) for ease of handling, placing and consolidation. The basic mix proportions used in this investigation were as follows (air entraining agent was added at required dosages for achieving the target air content): Aggregate–Binder Ratio=4·5; Coarse Aggregate/Fine Aggregate Ratio=1·25; Water/Cement Ratio≤0·45. Superplasticizer was added, when necessary, to achieve the specified slump without exceeding the limit on water/cement ratio.

In some cases, where pozzolans were used, a fraction of cement was substituted with a pozzolan on equal mass basis. The cement–pozzolan binder in these mixtures had one of the following composition by weight:

(1) 75% Cement+25% Fly Ash
(2) 75% Cement+25% Blast Furnace Slag
(3) 90% Cement+10% Silica Fume

The final mix proportions for different mixtures considered in this investigation are presented in Tables 3 and 4.

Construction

All mixtures were mixed in a conventional rotary drum concrete mixer with a capacity of 0·04 m^3 (1·41 ft^3). The mixing procedure basically followed ASTM C 192. The mixer was first loaded with the coarse aggregate and a portion of the mixing water. After starting the mixer, the fine aggregate, cement (and pozzolan, if any), and the rest of water were added and mixed for 3 min. This was followed by 3 min of rest and then 2 min of final mixing. The fibers, in the case of fibrous mixtures, were added following the addition of all other mix ingredients. The admixtures (air entraining agent and/or superplasticizer, if any) were added to the mixing water.

All the specimens were covered with wet burlap and plastic 30–45 min after casting, and demolded after 24 h, and then moist cured at 23±1·7°C (73±3 °F) and 97±3% relative humidity (R.H.) for three days. They were then exposed to the interior laboratory conditions at 23±1·7°C (73±3 °F) and 40±5% R.H. until the test age of 28 days.

Table 3. Mix proportions; Phase I (lb/yd^3)*

V_f (%)	*L_f (in.)*	*Cement*	*Coarse Agg.*	*Fine Agg.*	*Water*	*AEA*	*Sup.*
0·00	—	676	1691	1353	271	0·541	—
0·05	0·75	671	1676	1341	282	0·335	—
0·10	0·75	668	1671	1336	301	0·334	—
0·20	0·75	662	1654	1323	298	0·331	0·993
0·30	0·75	661	1653	1322	297·5	0·397	1·653

*lb/yd^3=0·594 kg/m^3.

Table 4. Mix proportions, Phase II (lb/yd³)*

Matrix composition	V_f (%)	*Cement*	*Coarse Agg.*	*Fine Agg.*	*Water*	*Pozzolan*	*AEA*	*Sup.*
Cement	0·0	676	1691	1353	271	—	0·541	—
	0·1	668	1671	1336	301	—	0·334	—
Cement + 25 % F A	0·0	493	1232	985	296	164·1	1·084	0·345
	0·1	492	1230	984	295	163·9	0·984	0·394
Cement + 25 % Slag	0·0	506	1265	1012	270	168·4	0·658	—
	0·1	504	1260	1008	276	167·8	0·504	—
Cement + 10 % S F	0·0	595	1488	1191	298	66·1	0·893	1·786
	0·1	595	1487	1190	297	66·0	0·891	0·952

*lb/yd³ = 0·594 kg/m³.

TEST PROCEDURES

Compressive strength and toughness

This test was performed on 152 × 305 mm (6 × 12 in) cylindrical specimens following ASTM C 39–86 procedures. The stress–strain curves were monitored throughout the test using a computer-based data acquisition system.

The compressive toughness was calculated following the JCI-SF guidelines (area underneath the stress–strain curves up to a strain of 0·0075).[17]

Flexural strength and toughness

This test was performed on prismatic specimens with dimensions of 102 × 102 × 356 mm (4 × 4 × 14 in) using the third point loading procedure of ASTM C 78; the test was conducted in a displacement-controlled manner, and deflections were measured at the center of the specimen using the Japanese JCI-SF specifications.[17] The stress–strain curves in flexural tests were obtained using a computer-based data acquisition system.

Flexural toughness of polypropylene fiber reinforced concrete was calculated following the JCI-SF guidelines (area underneath the flexural load–deflection curves up to a mid-span deflection equal to span length divided by 150).[17]

Impact resistance

The test which described by ACI Committee 544[18] is performed on a cylindrical specimen 152 mm (6 in) in diameter and 64 mm (2·5 in) high. The test simply consists of repeatedly dropping a hammer from a height of 457 mm (18 in) on a steel ball supported by the specimen, while observing the formation of cracks and failure of the specimen. The number of blows required to cause the first visible crack on the top and the ultimate failure are both recorded.

TEST RESULTS AND DISCUSSION

Compression test results

Typical compressive stress–strain curves for different fiber volume fractions are shown in Fig. 1. The average compressive strength and toughness test results are presented in Figs 2 and 3, respectively, for different fiber volume fractions (Phase I of this Experimental Program). One-way analysis of variance of the test data revealed that the effects of polypropylene fiber volume fraction on compressive strength and toughness of concrete are not statistically significant at 95% level of confidence.

The average values of the compressive strength and toughness test results for concrete materials incorporating pozzolanic admixtures (Phase II of Experimental Program) are

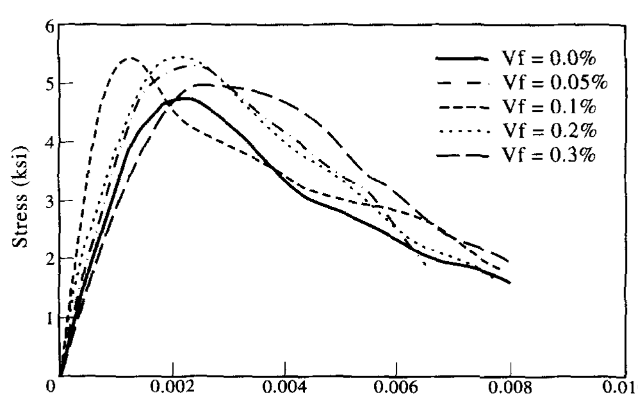

Fig. 1. Typical compressive stress–strain at different fiber volume fractions.

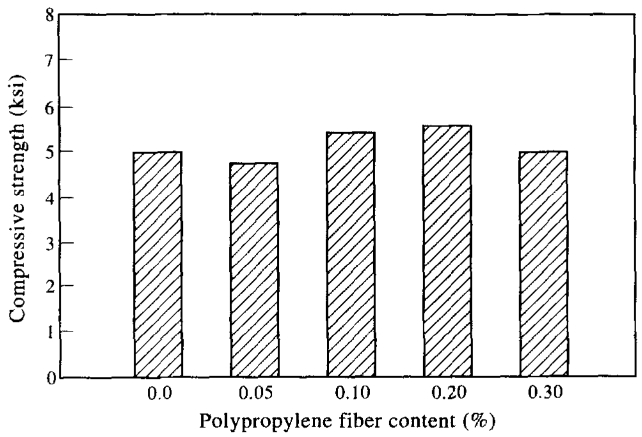

Fig. 2. Compressive strength test results at different volume fractions.

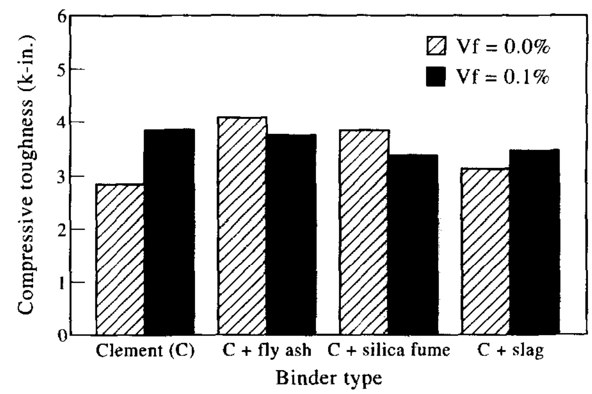

Fig. 5. Compressive toughness test results for plain and fibrous concrete materials with different binders.

presented in Figs 4 and 5, respectively. The results were analyzed by the factorial analysis of variance technique. The two factors in the analysis were the volume fraction of fibers at two levels (0·0% and 0·1%), and the binder composition at four levels (cement, fly ash, silica fume, and slag). It was concluded that compressive strength was influenced by the binder composition at 95% level of confidence, while the fiber volume fraction did not have statistically significant effects on compressive strength at the same level of confidence. On average, there were 21% and 23% increases in compressive strength with the addition of silica fume to plain and polypropylene fiber reinforced concretes, respectively. Compressive toughness was not significantly affected by either the binder composition or the fiber volume fraction at 95% level of confidence.

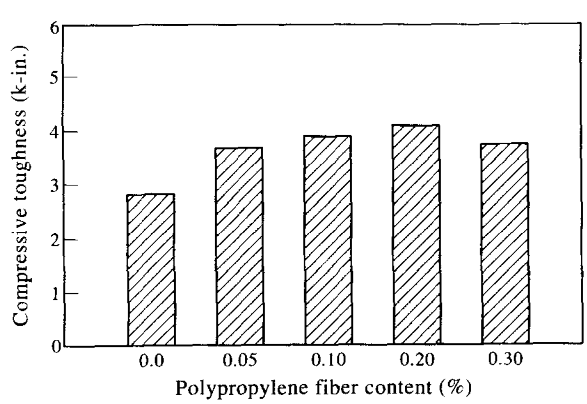

Fig. 3. Compressive toughness test results at different fiber volume fractions.

Flexural test results

Typical flexural load–deflection curves for different fiber volume fractions used in this study are shown in Fig. 6. The average values for the flexural strength and toughness test results in phase I of this part of the research are shown in Figs 7 and 8, respectively. One-way analysis of variance of test data revealed that the poly-

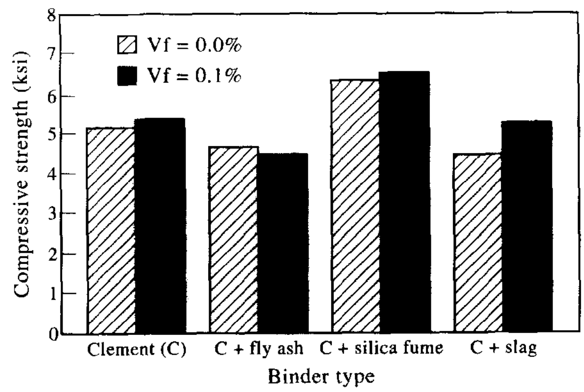

Fig. 4. Compressive strength test results for plain and fibrous concrete materials with different binders.

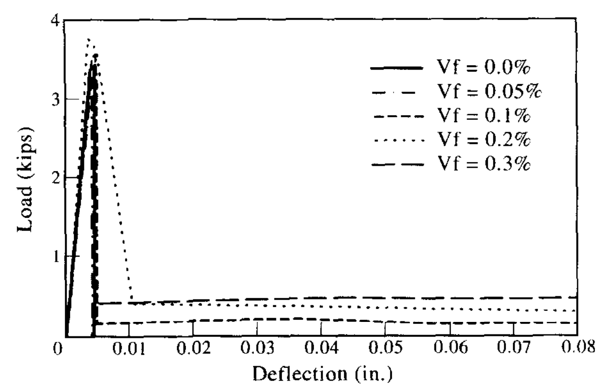

Fig. 6. Flexural load–deflection curves at different volume fractions.

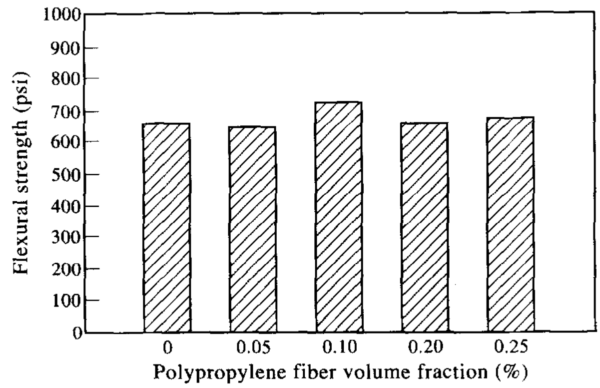

Fig. 7. Flexural strength test results of concrete at different volume fractions.

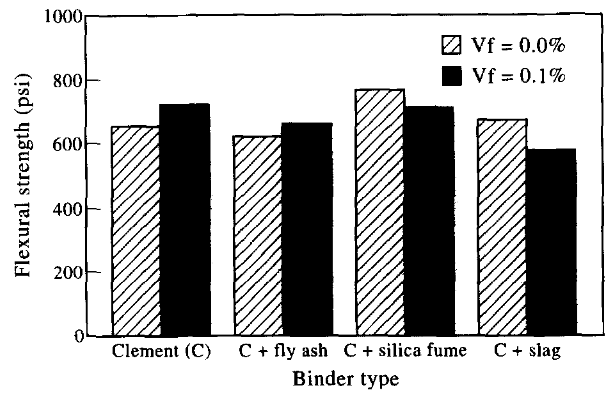

Fig. 9. Effects of pozzolanic materials and fiber volume fraction on flexural strength.

propylene fiber volume fraction did not affect the flexural strength of concrete materials at 95% level of confidence. The flexural toughness, however, was significantly affected at 99% level of confidence by the addition of polypropylene fibers. The increases in flexural toughness due to the addition of 0·1, 0·2 and 0·3% polypropylene fibers were 44, 271, and 386% over the plain concrete, respectively. Multiple comparison of results indicated that the increase in flexural toughness at 0·05% fiber fraction was not statistically significant.

The average values for the flexural strength and toughness of plain and polypropylene fiber reinforced concretes with different binder compositions are shown in Figs 9 and 10, respectively. Factorial analysis of variance (2 × 4 factorial design; two fiber volume fractions (0·0 and 0·1%) and four binder compositions (cement, fly ash, silica fume, and slag)) indicated that polypropylene fibers at 0·1% volume fraction do not affect the flexural strength (at 95% level of confidence), but the binder composition influences flexural strength at 99% level of confidence. Analysis of variance of the flexural toughness test results indicated that both polypropylene fiber volume fraction and binder composition have significant effects at 99% level of confidence. There was also a significant interaction between fibers and binder composition in the sense that the flexural toughness of, for example, silica fume and fly ash concretes improved, by 79 and 28% over that of the conventional fibrous concrete (without silica fume or fly ash), respectively.

Impact test results

In this section, the impact resistance test data will be presented together with the results of statistical analyses of the data. Due to the large variations in impact test results (which is a problem with this specific test technique), and in order to derive statistically reliable conclusions, all the data were carefully studied and the outlier were removed following the Shapiro–Wilk Normality test method.[19]

The average first crack and failure impact resistance test results are presented in Fig. 11.

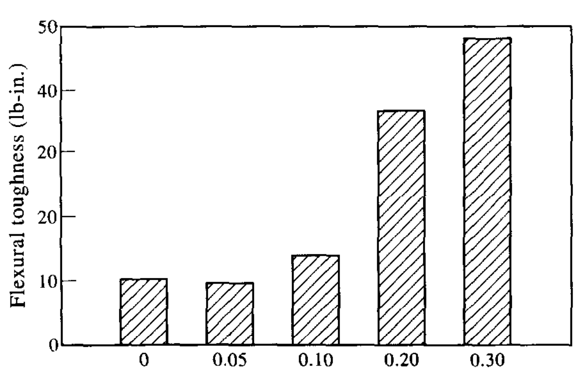

Fig. 8. Flexural toughness test results of concrete materials at different volume fractions.

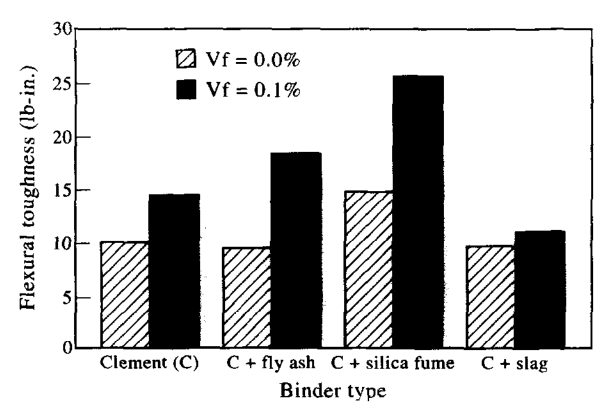

Fig. 10. Effects of pozzolanic materials and fiber volume fraction on flexural toughness.

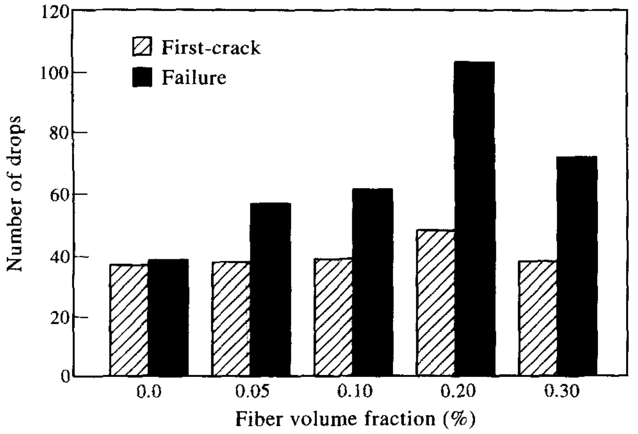

Fig. 11. Impact resistance test results for different fiber volume fractions.

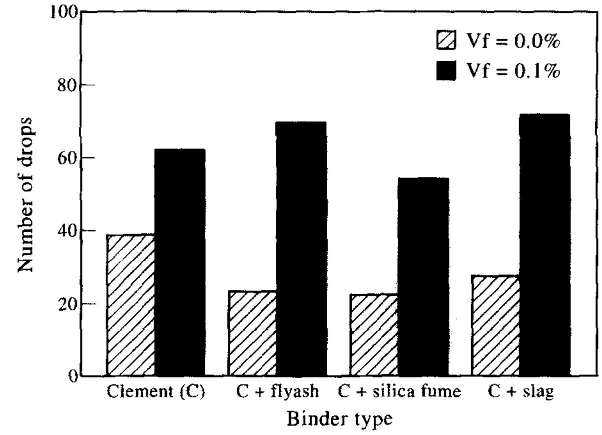

Fig. 13. Effects of pozzolanic materials and fiber volume fraction on failure impact resistance.

Analysis of variance of the data revealed that polypropylene fibers affect the first-crack and failure impact resistance at 95% and 99% levels of confidence, respectively. Multiple comparison of means of the data showed that only at 0·2% fiber volume fraction the first-crack impact resistance was different from that of plain concrete, at 95% level of confidence, for fiber lengths of 19 mm (0·75 in); the impact resistance at failure was significantly different from plain concrete only with the addition of 0·1% and 0·2% (but not 0·05% and 0·3%) fiber volume fractions, at 95% level of confidence.

The average values for the first-crack and failure impact test results for concrete materials incorporating pozzolanic admixtures (Phase II of Experimental Program) are shown in Figs 12 and 13, respectively. Analysis of variance of the data indicated that, at 99% level of confidence, polypropylene fibers at 0·1% volume fraction

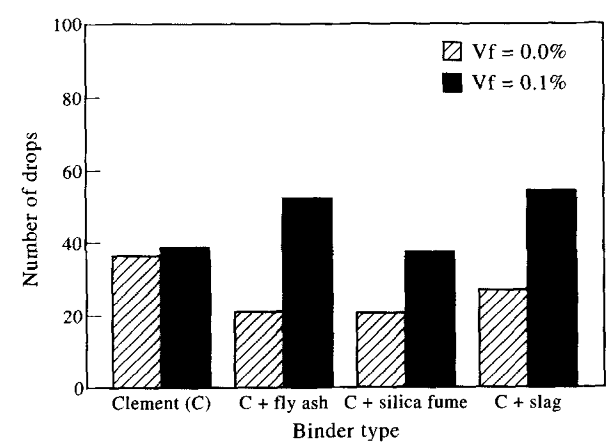

Fig. 12. Effects of pozzolanic materials and fiber volume fraction on failure impact resistance.

improved both the first-crack and failure impact resistances of concrete, while pozzolanic materials damaged the impact resistance. A positive interaction was also found between the fibers and pozzolan effects, in the sense that fibers produced a larger increase in the impact resistance of pozzolan concrete when compared with plain concrete. On average, polypropylene fibers increased the first-crack impact resistance of fly ash, slag and silica fume concretes by 151%, 78% and 91%, respectively; the corresponding improvements in failure impact resistance were 202%, 145%, and 164%, respectively. Pozzolans damaged the impact resistance of plain concrete; fly ash, slag and silica fume reduced the failure impact resistance of plain concrete by 40%, 42%, and 28%, respectively. The damage of pozzolans to impact resistance could be caused by the denser microstructure of concrete in their presence where strength is enhanced at the cost of reduced toughness. Increased effectiveness of fibers in the presence of pozzolans could be caused by the improved fiber to matrix bonding associated with the action of pozzolans in concrete.

SUMMARY AND CONCLUSIONS

The effects of collated fibrillated polypropylene fibers at volume fraction ranging from 0·05% to 0·30% on the compressive and flexural strength and toughness, and impact resistance of conventional concrete materials and concretes incorporating different pozzolanic materials were investigated experimentally. Sufficient replicated test data were produced in order to confirm the validity of the following conclusions at 95% (or higher) level of confidence:

(1) Polypropylene fibers have no statistically significant effects on the compressive strength and toughness of conventional concrete at the volume fractions used in this investigation. The presence of silica fume, however, increased the average compressive strength by 17% and 23% of plain and fibrous concretes.
(2) Polypropylene fibers have no effects on flexural strength at the volume fractions used in this study.
(3) Polypropylene fibers affect the flexural toughness significantly at 95% level of confidence. On the average, the addition of 0·1%, 0·2%, and 0·3% volume fraction of fibers increases the flexural toughness by 44%, 271% and 387%, respectively. Silica fume increases the flexural toughness by 48% and 79% in the case of plain and fibrous concretes, respectively.
(4) Polypropylene fibers increase the first-crack and failure impact resistance of concrete. The impact resistance at failure is increased by 48%, 62%, 171% and 90% with the addition of 0·05, 0·1, 0·2 and 0·3% fiber volume fraction, respectively, for fiber length of 19 mm (0·75 in).
(5) While pozzolans generally reduce the impact resistance of concrete, the positive interactions between polypropylene fibers and pozzolans (fibers are more effective in the presence of pozzolans) leads to enhanced impact resistance of fibrous concrete with pozzolans. The impact resistance at failure of conventional fibrous concrete was increased by 82%, 42% and 90% with the addition of fly ash, silica fume and slag, respectively.

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