中正嶺學報 第三十二卷 第一期 民國 92.11
JOURNAL OF C.C.I.T. VOL.32 NO.1 Nov. 2003

Impact Resistance of Polypropylene Fiber-Reinforced Concrete

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ABSTRACT

This paper investigated the impact resistance improving properties of polypropylene fibers in normal strength concrete. The impact resistance of polypropylene fiber-reinforced concrete and normal strength concrete was measured by using a drop-weight test and analyzed by using statistical procedures. The first-crack strength of the polypropylene fiber-reinforced concrete had a mean of 188 blows, a coefficient of variation of 35%, and a 95% confidence interval of 166 to 210 blows, compared to 168 blows, 36%, and 146 to 190 blows for that of the normal strength concrete. The failure strength of the polypropylene fiber-reinforced concrete had a mean of 207 blows, a coefficient of variation of 32%, and a 95% confidence interval of 185 to 229 blows, as opposed to 177 blows, 34%, and 155 to 189 blows for that of the normal strength concrete. The Kolmogorov-Smirnov test with significance level 0.05 indicates that both types of concrete approximately followed normal distributions in the first-crack and failure strengths, and in the percentage increase in number of post-first-crack blows. Finally, prediction models were established for both concretes, which predict the number of blows for failure strength and the related 95% confidence interval.

Keywords: polypropylene fiber, impact resistance, first-crack strength, failure strength.

聚丙烯纖維混凝土抗衝擊性之研究

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摘　要

本文旨在探討聚丙烯纖維加入普通混凝土內對其抗衝擊性提昇之效果。聚丙烯纖維混凝土及普通混凝土之抗衝擊性以落錘實驗求取，並以統計方法分析。聚丙烯纖維混凝土之初裂強度的平均衝擊數為 188 次，變異係數 35%，95%信賴區間之衝擊數為 166 至 210 次，普通混凝土初裂強度則分別為 168 次，36%及 146 至 190 次。聚丙烯纖維混凝土之破壞強度的平均衝擊數為 207 次，變異係數 32%，95%信賴區間之衝擊數為 185 至 229 次，普通混凝土破壞強度則分別為 177 次，34%及 155 至 189 次。利用 K-S 檢定在顯著水準 0.05 下，兩者混凝土之初裂、破壞強度及初次裂縫後之衝擊數增加百分率均近似常態分佈。最後，並建立兩者混凝土之破壞強度預測模式，該等模式可預測破壞強度及 95%信賴區間之衝擊數。

關鍵字：聚丙烯纖維，衝擊阻力，初裂強度，破壞強度。

文稿收件日期 91.6.7；文稿修正後接受日期 92.7.28.

Manuscript received June 7, 2002; revised July 28, 2003.

I. INTRODUCTION

Concrete generally registers low tensile strain capacity and brittle nature, and therefore, develops susceptibility to the presence and development of cracks in plastic as well as hardened state. To inhibit the crack formation, polypropylene fibers were popularly added throughout the crack prone concrete [1,2]. The cracks in the polypropylene fiber concrete are blocked and prevented from further development, minimized in size and even nullified in the pre-visual stage [3,4]. The crack blocking action arises because the fibers throughout the concrete improve the plastic concrete's resistance to the internal stresses created during plastic shrinkage, and therefore, increase the concrete's extensibility. Besides, the fibers transfer across the crack the external stresses applied on the hardened concrete and thus benefit the concrete's ductility [5].

The engineering characteristics of polypropylene fiber-reinforced concrete (PFRC) have been investigated in the concrete literatures, including compressive [6], tensile [7,8], flexural strengths [9,10] and shrinkage [11]. However, the impact resistance of this concrete was scarcely touched upon. Practically, the impact resistance of fiber reinforced concretes pronouncedly carried statistical variations due to various factors [12-14]. The major factors include: a) local variations in the fiber density at the interior of the mixes; b) possible inconsistency in the bond strength at the interface of fiber and cementitious matrix; c) potential re-orientation of fibers during construction.

This paper measured the impact resistance of polypropylene fiber-reinforced concrete by using a drop-weight test, evaluated the variations of the impact resistance by employing statistical procedures, and gained better understanding of the impact-resistance contributing potential of polypropylene fibers in concrete. Further, impact resistance prediction models were developed for the polypropylene and normal strength concretes, which establish the failure strength by using the accompanying first-crack strength.

II. EXPERIMENTAL PRODCEDURES

Normal type I cement was used for the current concrete mix. The coarse aggregate was the gravel with a maximum size of 2.54 cm. The fine aggregate was the river sand with a fineness modulus of 2.9. The normal strength concrete (NSC) of 21MPa compressive strength was made using 300, 194, 1050, and 850 kg/m^3 of cement, mixing water, coarse aggregate and fine aggregate, respectively. The 19 mm long fibrillated polypropylene fibers with 500 Deniers were added to the normal-strength concrete mixture at a rate of 0.9 kg/m^3. The resulting propylene fiber-reinforced concrete registered a 28-day compressive strength of 22.1MPa, about 1.05 times that of the normal strength concrete.

The mixing procedures were performed according to the following sequences.

1. The fine and coarse aggregates were placed in a mixer, followed by a 1-min mixing.
2. The cement was added to the mixed aggregate, followed by a 1-min mixing.
3. The mixing water was introduced to the cement and aggregate, followed by a 2-min mixing.
4. The polypropylene fibers were evenly sprinkled on top of the wet mixture, followed by a 3-min mixing to distribute the fibers throughout the concrete mixture.

The freshly mixed polypropylene fiber-reinforced concrete was fed into cylindrical molds to cast 150×300 mm cylinders. The cylinders were stripped from their molds the day after casting and stored in lime water at 25±1°C. Each cylinder was cut into four 150 mm diameter, 64 mm thick discs at the age of 28 days for a drop weight test.

The drop weight test conducted followed from the test technique suggested by the ACI committee 544 on fiber reinforced concrete [15]. This test rests a disc on the base plate within four positioning lugs. The disc bottom has received a thin layer of heavy grease to reduce the friction between the disc and the base plate. The positioning bracket of the base plate is bolted in place. Then, a 4.54-kg hammer consecutively falls from a 457-mm height onto a 63.5 mm diameter steel ball standing at the center of the disc, subjecting the disc to repeated impact blows. The number of blows developing the first visible crack on the disc top is the first-crack strength. The falling operation continues to trigger the ultimate failure of the disc containing cracks. The ultimate failure is the opening-up of the disc to touch three of the four lugs. The number of blows triggering the ultimate failure is the failure strength.

III. RESULTS AND DISCUSSION

Table 1 presents the drop-weight test results on 32 discs of NSC, revealing that the first-crack strength was 84 to 338 blows with the failure strength being 88 to 346 blows. Table 2 presents the drop-weight test results on 32 discs of PFRC, revealing that the first-crack strength ranged from 102 to 419 blows and the failure strength ranged from 114 to 432 blows. Tables 3 and 4 present the analyses of drop-weight test results on the concretes, from the SPSS statistical software package.

A. First-crack strength

Table 3 indicates that the first-crack strength of 32 NSC discs had a mean of 168 blows, a standard deviation of 60 blows, and coefficient of variation of 36%. The standard error of the mean was 11 blows. And the 95% confidence interval on the mean ranged between 146 and 190 blows, which implies that with a probability of 0.95, this interval 146 to 190 blows contains the true average first crack strength.

Table 1 Drop-weight test results and predicted failure strength for NSC

Specimen No.	Drop-weight test results			Predicted failure strength		
	First-crack strength (blows)	Failure strength (blows)	Percentage increase in number of post-first-crack blows	Failure strength (blows)	95% confidence interval for failure strength(blows)	
					Lower prediction bound	Upper prediction bound
1	153	164	7.2	161	154	169
2	190	206	8.4	198	191	206
3	142	147	3.5	150	143	157
4	126	135	7.1	134	127	141
5	112	120	7.1	120	112	127
6	145	152	4.8	153	146	160
7	131	136	3.8	139	132	146
8	193	200	3.6	201	194	209
9	88	96	9.1	96	88	103
10	190	193	1.6	198	191	206
11	264	277	4.9	273	265	280
12	280	283	1.1	289	281	297
13	84	88	4.8	92	84	99
14	204	211	3.4	212	205	220
15	104	111	6.7	112	104	119
16	108	114	5.6	116	108	123
17	189	194	2.7	197	190	205
18	155	165	6.5	163	156	171
19	113	118	4.4	121	113	128
20	287	292	1.7	296	288	304
21	133	140	5.3	141	134	148
22	180	184	2.2	188	181	196
23	163	172	5.5	171	164	179
24	338	346	2.4	347	339	355
25	142	155	9.2	150	143	157
26	179	188	5.0	187	180	195
27	172	183	6.4	180	173	188
28	115	123	7.0	123	115	130
29	237	254	7.2	246	238	253
30	171	181	5.9	179	172	187
31	175	187	6.9	183	176	191
32	123	134	8.9	131	124	138

Table 2 Drop-weight test results and predicted failure strength for PFRC

Specimen No.	Drop-weight test results			Predicted failure strength		
	First-crack strength (blows)	Failure strength (blows)	Percentage increase in number of post-first-crack blows	Failure strength (blows)	95% confidence interval for failure strength (blows): Lower prediction bound	95% confidence interval for failure strength (blows): Upper prediction bound
1	121	133	9.9	138	125	152
2	201	212	5.5	220	206	233
3	246	265	7.7	265	252	279
4	149	164	10.1	167	153	180
5	106	117	10.4	123	109	137
6	163	185	13.5	181	168	194
7	419	432	3.1	442	426	457
8	239	267	11.7	258	245	272
9	105	114	8.6	122	108	136
10	238	259	8.8	257	244	271
11	154	175	13.6	172	158	185
12	131	148	13.0	148	135	162
13	124	129	4.0	141	128	155
14	233	248	6.4	252	239	266
15	131	145	10.7	148	135	162
16	193	216	11.9	211	198	225
17	255	277	8.6	275	261	288
18	132	150	13.6	149	136	163
19	102	128	25.5	119	105	132
20	200	228	14.0	219	205	232
21	105	120	14.3	122	108	136
22	284	299	5.3	304	290	318
23	200	209	4.5	219	205	232
24	157	170	8.3	175	162	188
25	188	211	12.2	206	193	220
26	177	198	11.9	195	182	209
27	217	237	9.2	236	223	249
28	201	232	15.4	220	206	233
29	202	223	10.4	221	207	234
30	206	230	11.7	225	211	238
31	231	250	8.2	250	237	264
32	209	238	13.9	228	215	241

Table 3 Summary of statistical measures of impact strength for NSC

	First-crack strength (blows)	Failure strength (blows)	Percentage increase in number of post-first-crack blows
Mean (x)	168	177	5
Standard deviation (σ)	60	61	2
Coefficient of variation (σ/x), %	36	34	40

Table 4 Summary of statistical measures of impact strength for PFRC

	First-crack strength (blows)	Failure strength (blows)	Percentage increase in number of post-first-crack blows
Mean (x)	188	207	10
Standard deviation (σ)	65	67	4
Coefficient of variation (σ/x), %	35	32	40

Table 4 indicates that the first-crack strength of 32 PFRC discs had a mean of 188 blows with a standard deviation of 65 blows, and a coefficient of variation of 35%. The standard error of the mean was 11 blows. And the 95% confidence interval extended from 166 to 210 blows. The means indicate that for the first-crack strength, PFRC resisted 1.1 times more impact blows than NSC did.

Figures 1 and 2 show the frequency distribution of first-crack strength for NSC and PFRC, respectively. In Figure 1, the appearance of the histogram marginally resembled that of the normal approximation curve, implying that the distribution of first-crack strength of NSC was marginally normal. In Figure 2, the appearance of the histogram roughly resembled that of the curve, implying that the distribution of first-crack strength of PFRC was roughly normal.

To be subjective, The normality of the first-crack-strength distribution was investigated by using the null hypothesis that the average first-crack-strengths of the two concretes were approximately equal, and a two-tailed test procedure of the hypothesis was performed using the Kolmogorov-Smirnon (K-S) test at significance level 0.05. In the K-S test, the p-value achieved refers to the smallest level of significance at which the null hypothesis would be rejected. This test yielded a p-value of 0.054 for NSC, which lies slightly above the significance level 0.05, confirming that the distribution of first-crack strength of NSC is barely normal. The p-value is 0.20 for PFRC, indicating the distribution of first-crack strength for PFRC was roughly normal. Figures 3 and 4 present the normal probability plots for the distribution of first-crack strength of NSC and PFRC, respectively. Figure 3 shows the data points falling close to the straight line, implying that the distribution of first-crack strength of NSC was barely normal. Figure 4 shows a narrow extent to which most of the data points spread out about the straight line, displaying that the distribution of first-crack strength of PFRC was roughly normal.

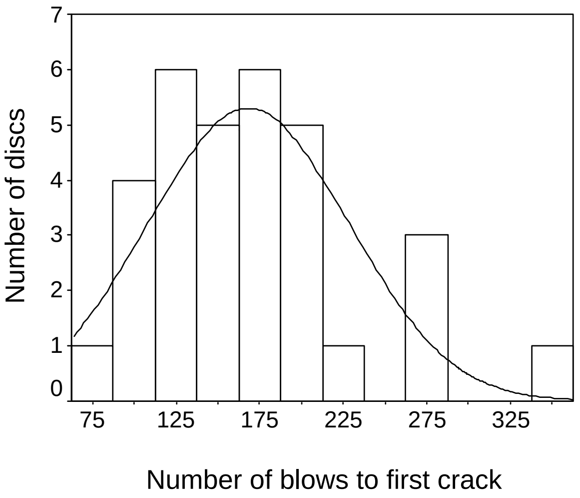

Figure 1. Frequency distribution for first-crack strength of NSC.

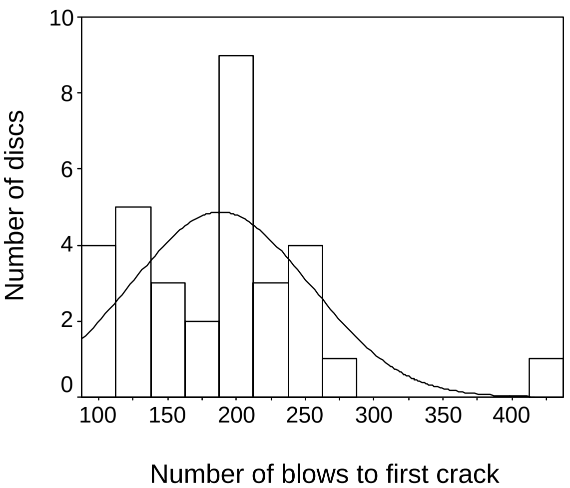

Figure 2. Frequency distribution or first- crack strength of PFRC.

B. Failure Strength

Table 3 indicates that the failure strength of 32 NSC discs had a mean of 177 blows, a standard of 61 blows, and a coefficient of variation of 34%. The standard error of the mean is 11 blows, and the 95% confidence interval for the mean ranged from 155 to 199 blows. Table 4 indicates that the failure strength of the 32 PFRC discs had a mean of 207 blows, a standard deviation of 67 blows, and a coefficient of variation 32%. The standard error of the mean is 12 blows, and the 95% confidence interval for the mean ranged from 183 to 231 blows. The failure strength of PFRC was 1.2 times that of NSC.

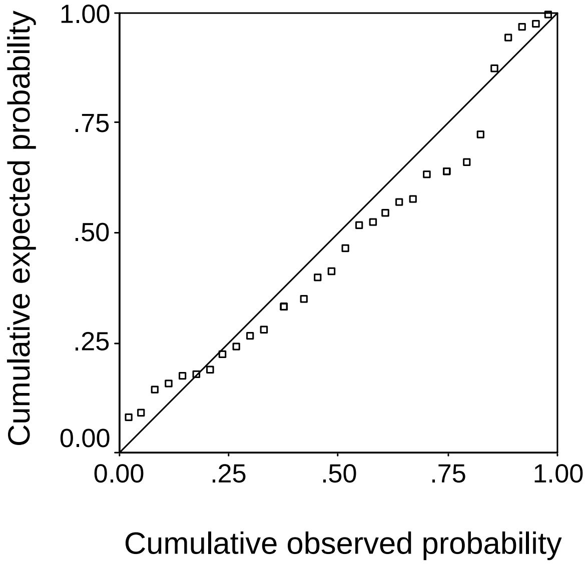

Figure 3. Normal probability plot for first-crack strength of NSC.

Figure 5 and 6 exhibit the frequency distribution of failure strength of NSC and PFRC discs, respectively. In Figure 5, the appearance of the histogram slightly followed that of the normal approximation curve, indicating an approximate normality of distribution of failure strength for NSC. In Figure 6, the appearance of the histogram roughly followed that of the curve, implying a seeming normality of distribution of failure strength for PFRC. Further, the K-S test yielded a p-value of 0.136 for NSC. This value lies above the significance level 0.05, confirming the approximate normality for distribution of failure strength. This test yielded a slightly higher p-value of 0.2 for PFRC, indicating the approximate normality for the distribution of failure strength. Figures 7 and 8 contain the normal probability plots for the distribution of failure strength of NSC and PFRC. In Figure 7, the plot shows a large percentage of data points falling close to the straight line, implying an approximately normal distribution for failure strength of NSC. Figure 8 exhibits a roughly linear pattern, indicating an acceptable normality for distribution of failure strength of PFRC.

C. Percentage increase in number of post-first-crack blows

Table 3 displays for NSC the percentage increase in number of post-first-crack blows, which denotes the blows to ultimate failure of the disc after the first visible crack appeared._____The percentage increase had a mean of 5 blows, a standard deviation of 2 blows, and a coefficient of variation of 40%. The standard error of the mean was 1 blow, and the 95% confidence internal on the mean ranged between 3 and 7 blows. Tables 4 gives the percentage increase in number of post-first-crack blows for PFRC. The percentage increase had a mean of 10 blows, a standard deviation of 4 blows, and a coefficient of variation of 40%. The standard error of the mean was 1 blow, and the 95% confidence for the mean ranged between 8 and 12 blows. The comparison of the percentage increase in numbers of post-first-crack blows indicates that PFRC was 2 times higher than NSC in withstanding the post-first-crack blows. Figures 9 and 10 show the frequency distribution of the percentage increase in number of post-first-crack blows for NSC and PFRC. In each figure, the appearance of the histogram resembled that of the normal approximation curve, indicating the seemingly normal distributions of the percentage increase for NSC and PFRC. The K-S test yielded a p-value of 0.20 for NSC and PFRC, which lies far above the significance level 0.05. Figures 11 and 12 contain the normal probability plots of the percentage increase in number of post-first-crack blows for NSC and PFRC. Each figure shows a large percentage of data points falling close to the straight line, and thereby, displays the approximately normal distribution of the percentage increase in numbers of post-first-crack blows.

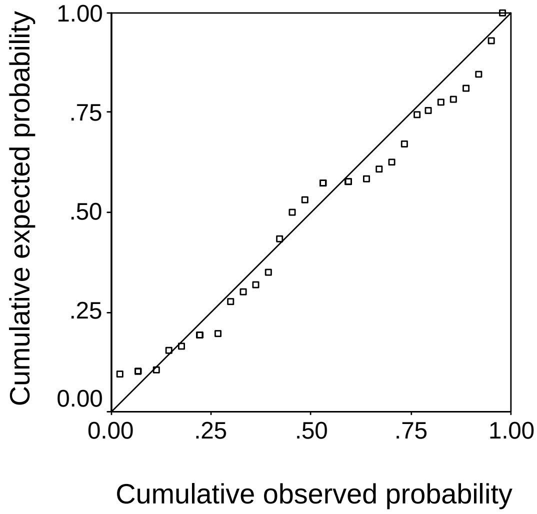

Figure 4. Normal probability plot for first-crack strength of PFRC.

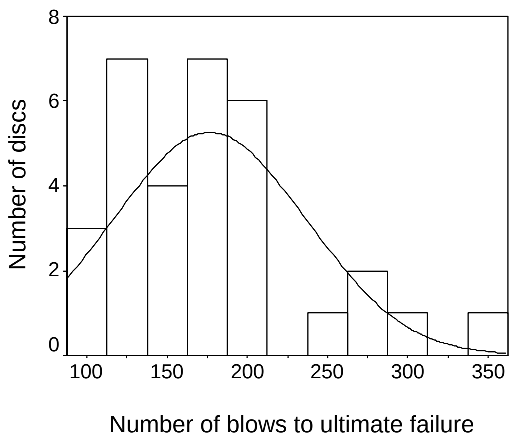

Figure 5. Frequency distribution for failure strength of NSC.

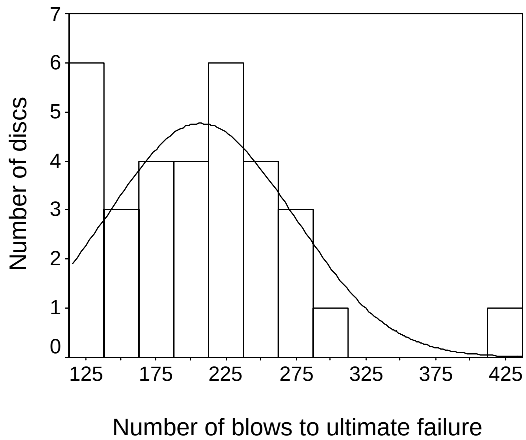

Figure 6. Frequency distribution for failure strength of PFRC.

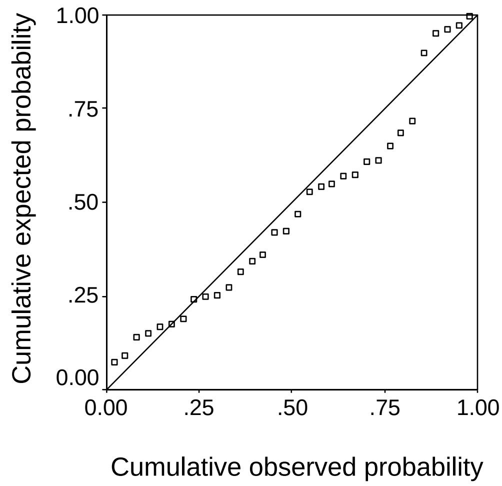

Figure 7. Normal probability plot for failure strength of NSC.

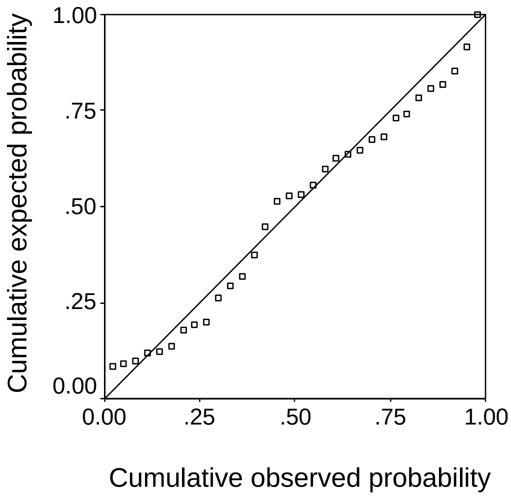

Figure 8. Normal probability plot for failurestrength of PFRC.

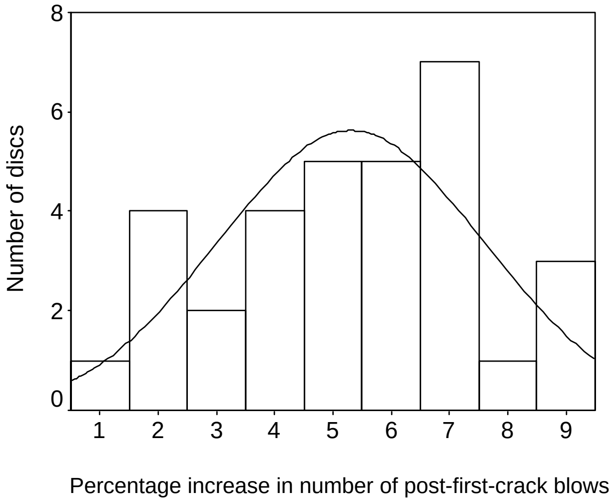

Figure 9. Frequency distribution of percentage increase in number of post-first-crack blows for NSC.

D. Prediction of failure strength

For the NSC, the correlation coefficient describing the relationship between the first-crack and failure strengths was 0.998, relative to 0.996 for the PFRC; each value indicates a strong linear dependency between the two strengths. Figures 13 and 14 are the scatter plots of failure strength versus first-crack strength for NSC and PFRC. In each Figure, the plot exhibits an approximately linear pattern. The linear dependency between failure and first crack strengths for NSC and PFRC can be described using a linear regression model [16]

$$N_2 = a + b N_1 + \varepsilon \tag{1}$$

Where N_2 and N_1 denote the number of blows for the failure strength and the first-crack strength, respectively; *a* and *b* are unknown constants; and ε is the random error assumed to be normally distributed with a mean zero and a constant variance. The values of *a* and *b* can be determined by employing a least square analysis and fitting the model to the drop-weight test data. The regression model is

$$\hat{N}_2 = 7.195 + 1.006 N_1 \tag{2}$$

for NSC and

$$\hat{N}_2 = 14.968 + 1.018 N_1 \tag{3}$$

for PFRC

In equations (2) and (3), $\hat{N}_2$ is the response variable to be predicted for the predictor variable N_1 which is experimentally established. Equations(2) and (3) carried very high values of 0.997 and 0.991, respectively, for the coefficient of determination. These values approach unity, indicating the good fit of equations(2) and (3) to the drop-weight test data. For the NSC and PFRC, the failure strength predictions can be made by using the respective first-crack strength to replace the predictor variable N_1 in equations(2) and (3). Using the failure strength predicted, the corresponding 95% prediction interval can be determined. Tables 1 and 2 display for the NSC and PFRC the predicted failure strength and the upper and lower bounds of the corresponding 95% prediction interval.

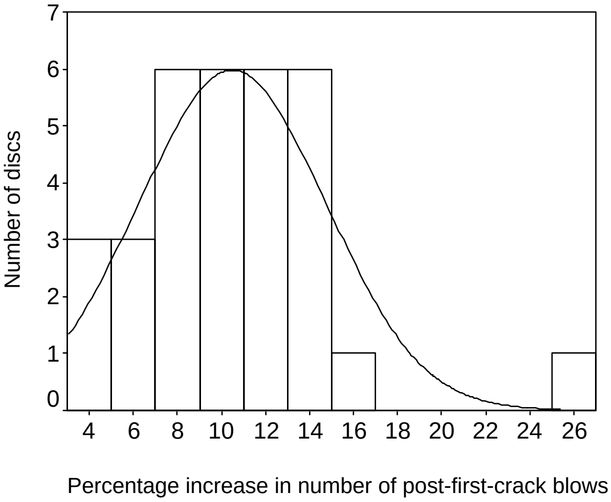

Figure 10. Frequency distribution of percentage increase in number of post-first-crack blows for PFRC.

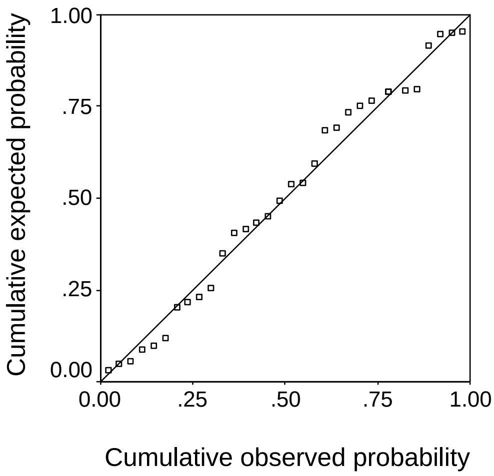

Figure 11. Normal probability plot of percentage increase in number of post-first-crack blows for NSC.

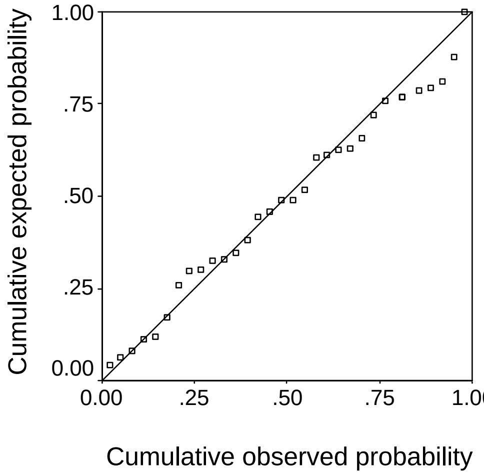

Figure 12. Normal probability plot of percentage increase in number of post-first-crack blows for PFRC.

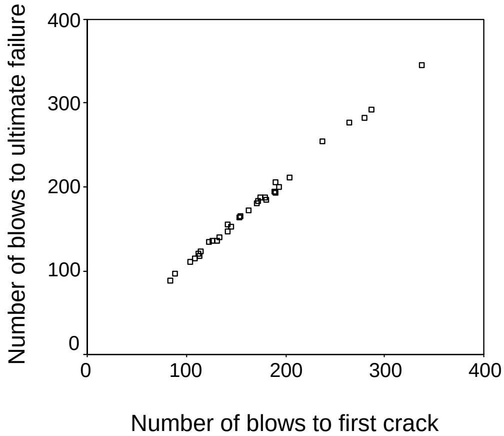

Figure 13. Scatter plot of failure strength versus first-crack strength for NSC.

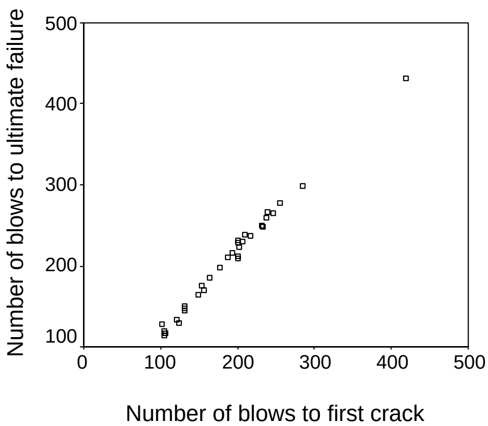

Figure 14. Scatter plot of failure strength versus first-crack strength for PFRC.

V. CONCLUSIONS

1. The polypropylene fiber-reinforced concrete outperformed the normal strength concrete in the impact strength. The polypropylene fiber-reinforced concrete was 1.1 and 1.2 times higher in first-crack strength and failure strength, respectively, than the normal strength concrete.

2. The polypropylene fiber-reinforced concrete performed better than the normal strength concrete in impact resistance after the first visible crack appeared. The polypropylene fiber-reinforced concrete was 2 times higher than the normal strength concrete in percentage increase in number of post-first-crack blows.

3. The impact resistance models established for polypropylene fiber-reinforced concrete and normal strength concrete provide an estimate for the failure strength and the 95% confidence interval on the mean failure strength.

REFERENCES

[1] Hogan, D. J., "Fiber Reinforced Comes of Age," Concrete, Vol. 12, No. 4, pp. 18-20, 1987.

[2] Vittone, A., "Fibrillated Polypropylene Reinforced Cement-Based Products," Concrete International, Vol. 9, No. 9, pp. 44-45, 1987.

[3] Baggott, R., and Gandhi, D., " Multiple Cracking in Aligned Polypropylene Fibre Reinforced Cement Composites," Journal of Material Science, Vol. 16, No. 1, pp. 65-74, 1981.

[4] Swamy, R. N., and Hussin, M. W., " Woven Polypropylene Fabrics-An Alternative to Asbestos for Thin Sheet Application," Fiber Reinforced Cements and Concrete: Recent Development, Elsevier, pp. 90-100, 1989.

[5] Dave, N. J., and Ellis, D. G., "Polypropylene Fiber Reinforced Cement," International Journal of Cement Composites, Vol. 1, No.1, pp. 19-28, 1979.

[6] Fanella, D. A., and Naaman, A. E., "Stress-Strain Properties of Fiber Reinforced Mortar in Compression," ACI Material Journal, Vol. 82, No. 4, pp. 475-483, 1985.

[7] Keer, J. G., and Thorne, A., "Performance of Polypropylene-Reinforced Cement Sheeting Elements," Fiber Reinforced Concrete-International Symposium, SP-81, American Concrete Institute, Detroit, Michigan, pp. 213-231, 1984.

[8] Baggott, R., "Polypropylene Fibre Reinforcement of Light Cementitious Matrices," The International Journal of Cement Composites and Lightweight Concrete, Vol. 5, No. 2, pp. 105-114, 1983.

[9] Mackley, M. R., and Parker, A. R., "The Mechanical Response of Polypropylene Fibre Cement Composite and its Analogy with Bone," Materials Science and Engineering, Vol. 45, No. 1, pp. 117-122, 1980.

[10] Gardiner, T., and Currie, B., "Flexural Behaviour of Composite Cement Sheets Using Woven Polypropylene Mesh Fabrics," The International Journal of Cement and Lightweight Concrete, Vol. 5, No. 3, pp. 193-197, 1983.

[11] Dahl, P. A., "Influence of Fibre Reinforcement on Plastic Shrinkage Cracking," In Brittle Matrix Composites-I, ed. A. M. Brandt and I. H. Marshall. Proc. European Mechanics Colloquium 204, Elsevier Applied Science Publishers, pp. 435-441, 1986.

[12] Soroushian, p., Nagi, M., and Alhozaimy, A., "Statistical Variations in the Mechanical Properties of Carbon FIiber Reinforced Cement Composites," ACI Materials Journal, Vol. 89, No. 2, pp. 131-138, 1992.

[13] Nataraja, M. C., Dhang, N., A. P. Gupta, A. P., " Statistical Variations in Impact Resistance of Steel Fiber-Reinforced Concrete Subjected to Drop Weight Test," Cement and Concrete Research, Vol. 29, No. 8, pp. 989-995, 1999.

[14] Ramakrishnan, V., Brandshaug, T., Coyle, W. V., and Schrader, E. K., " A Comparative Evaluation of Concrete Reinforced with Straight Steel Fibers and Fibers with Deformed Ends Glued Together into Bundles," ACI Materials Journal, Vol. 77, No. 3, pp. 135-143, 1980.

[15] ACI Committee 544, "Measurement of Fiber Reinforced Concrete," ACI Materials Journal, Vol. 85, No. 6, pp. 583-593, 1988.

[16] Neter, J., Kutner, M. H., Nachtsheim, C. J., and Wasserman, W., "Applied Linear Regression Models," 3rd Edition, Irwin, New York, pp.85-90, 1996.