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Strength and Fracture Toughness of Fiber Reinforced Concrete

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ABSTRACT: In this paper, the effects of using fibers on the compressive, splitting tensile and flexural strengths as well as fracture toughness of concrete were investigated experimentally. Rebound numbers and pulse velocities were also measured. Steel, polypropylene and glass fibers were tested at 0.5% for the steel fibers and 0.1% for the polypropylene and glass fibers by volume of concrete. Two water-cement ratios (w/c=0.65 and 0.45) and two different curing (air and moist) conditions were used. Slight increases in strengths were obtained by the use of fibers. Steel fibers were the most effective in increasing the strengths. Glass fibers performed better in splitting tensile and flexural strengths whereas polypropylene fibers were better in compressive strength. Fracture toughness of steel fiber concrete was much higher than the other mixtures at both water-cement ratios. Other fibers helped to improve the fracture toughness slightly compared to the control mix without fibers.

1 INTRODUCTION

Mechanical properties of fiber-reinforced concrete (FRC) have been investigated for decades (ACI Committee 544, 1996). Generally, the contribution of fibers to compressive strength was not very significant. However, the tensile and flexural strengths were reported to be more affected by the presence of fibers (Thomas & Ramaswamy, 2007; Topçu & Canbaz, 2007; Song & Hwang, 2004; Sivakumar & Santhanam, 2007; Köksal et al., 2008; Yazıcı et al., 2004). Steel fiber is the most popular one among the fibers used in concrete. Steel fiber reinforced concrete (SFRC) has highly improved flexural toughness and fracture properties, which makes it very useful as plain concrete is a brittle material (Song & Hwang, 2004; Sivakumar & Santhanam, 2007; Atiş & Karahan, 2009; Trottier & Banthia, 1994). The performance of SFRC is established well with its relatively old use. However, the performances of polypropylene fiber reinforced concrete (PFRC) and glass fiber reinforced concrete (GFRC) are less investigated compared to SFRC. Previously, the parameters used were the fiber type, fiber content and fiber aspect ratio (Topçu & Canbaz, 2007; Sivakumar & Santhanam, 2007; Yazıcı et al., 2007). Research on FRC of various water-cement ratios and curing conditions can be significant to evaluate the effect of concrete quality in fiber reinforced concrete. In the present study, the compressive, splitting tensile and flexural strengths as well as fracture energy properties were investigated for concretes with no fibers and with steel, polypropylene and glass fibers produced with two water-cement ratios and cured differently.

2 EXPERIMENTAL PROGRAM

In the present study, fresh and hardened concrete properties of fiber reinforced concrete mixes were compared to the control (without fiber) concrete mix. The fibers used were steel, polypropylene, and glass fibers. The fiber addition rates were selected according to their manufacturers' recommendations as the commonly used rates in construction practice: 0.5% for steel fibers, 0.1% for polypropylene fibers, and 0.1% for glass fibers by volume of concrete. Two water-cement ratios (w/c=0.65 and 0.45) were used in the study. The specimens were demoulded one day after casting and cured until testing in two different conditions: air curing in laboratory and moist curing in lime saturated water.

2.1 Materials

Portland cement CEM I 42.5 R, crushed limestone coarse aggregate having 19 mm maximum size, river sand and crushed sand were used. Superplasticizer (SP) was polynaphthalene sulphonate high range water reducing admixture. Steel fibers were cold drawn wire fibers with hooked ends and glued in bundles. Polypropylene fibers were multi-filament fibers. Glass fibers were multi-filament alkali-resistant fibers. General properties of the fibers are given in Table 1.

Table 1. General properties of fibers

	steel	polypropylene	glass
Length (mm)	35	13	12
Diameter (mm)	0.55	0.022	0.014
Length/Diameter	64	591	857
Density g/cm^3	7.85	0.91	2.68
Tensile strength (MPa)	1100	400	1700
Modulus of elasticity (GPa)	200	3.5-3.9	72
Number of fibers/kg	14500	224 million	2.1 million

2.2 Concrete mixes and test specimens

Compositions of the concrete mixes are given in Table 2. For all mixes, the target slump (17±2 cm) was achieved by first determining the superplasticizer content in the control mixes and then increasing it to reach the same slump in the fiber containing concretes. Density and air content were also measured.

Table 2. Concrete mixes

kg/m^3	w/c = 0.65	w/c = 0.45
Cement	310	400
Water	201.5	180
Coarse aggregate No 1	581	575
Coarse aggregate No 2	473	468
Sand	560	554
Crushed sand	237	235
Superplasticizer for control concrete	1.9	7
Steel fiber and Superplasticizer*	39.25 – 3.5	39.25 – 9
Polypropylene fiber and Superplasticizer	0.91 – 3.8	0.91 – 9
Glass fiber and Superplasticizer	2.68 – 5.2	2.68 – 10.2

* Fiber and superplasticiser contents are written in the same row for each concrete mix.

Six cylindrical specimens of 100×200mm were cast for each mix at each curing type. Three of them were tested in compression to measure the modulus of elasticity and compressive strength. The other three specimens were used first to measure the rebound number and pulse velocity and then the splitting tensile strength. Three beam specimens of 100×100×500mm for each mix were tested for flexural strength and fracture toughness. Beam specimens were only moist cured. All specimens were tested at 28 days after casting.

3 RESULTS AND DISCUSSION

3.1 *Fresh concrete properties*

The slump, unit weight and entrapped air content were measured for the fresh concrete mixtures and the results are given in Table 3. The results indicated that the use of fibers required higher dosage of superplasticizer to realize the target slump. Whereas the unit weights were not too different, the measured entrapped air was higher in fiber concretes, especially at low w/c concretes.

Table 3. Fresh concrete properties

w/c = 0.65	control	steel	polypropylene	glass
SP (kg/m^3)	1.9	3.5	3.8	5.2
Unit weight (kg/m^3)	2684	2724	2665	2667
Entrapped air %	3.1	2.6	3.1	3.1
w/c = 0.45	control	steel	polypropylene	glass
SP (kg/m^3)	7	9	9	10.2
Unit weight (kg/m^3)	2723	2735	2710	2696
Entrapped air %	2.2	3.0	3.7	3.8

3.2 *Hardened concrete properties*

The variations of compressive strength (f_c), splitting tensile strength (f_{sp}), flexural strength (f_{fl}), rebound number (RN) and pulse velocity (PV) in fiber reinforced concretes with respect to the control mixture are given in Table 4. The coding of the mixes include the concrete type (C: control, S: steel, P: polypropylene, G: glass), the water-cement ratio (65 and 45 for w/c = 0.65 and 0.45, respectively) and the curing type (a: air cured and m: moist cured).

Table 4. Percent variation of the hardened concrete properties

	f_c	f_{sp}	f_{fl}	RN	PV
C65a	0	0	-	0	0
S65a	2	8	-	-1	-2
P65a	2	6	-	-4	2
G65a	-13	-12	-	-3	0
C65m	0	0	0	0	-
S65m	25	33	-7	0	-
P65m	8	15	1	2	-
G65m	0	4	-19	4	-
C45a	0	0	-	0	0
S45a	10	0	-	-2	-1
P45a	-7	-14	-	-6	1
G45a	4	-8	-	-8	0
C45m	0	0	0	0	-
S45m	15	9	26	12	-

P45m	14	-11	6	-7	-
G45m	-3	6	1	2	-

The results of the compressive and splitting tensile strength tests are shown in Figs. 1 and 2, respectively. Fiber reinforced concretes had higher f_c and f_{sp} than those of the control concrete in most of the tested mixes. The significance of the improvement by fiber addition depended on the curing type, w/c and fiber type. The contribution of fibers to fc and f_{sp} was more significant at 0.65-w/c and in moist curing. SFRC had the highest f_c and f_{sp} results. The increases in compressive and splitting tensile strengths of moist cured specimens were 25% and 33% and 15% and 9%, respectively, for 0.65 and 0.45 water-cement ratio concretes. However, the increase by steel fiber addition diminished for air cured specimens showing even no increase in f_{sp} at low water-cement ratio concretes. PFRC had higher fc and f_{sp} compared to the control specimens at 0.65-w/c in moist curing, by 8% and 15% respectively. In air curing, the increase by polypropylene fiber addition was lower. At 0.45-w/c, there was an increase in moist curing by 14% and a decrease in air curing by 7% for f_c. In both curing conditions, decreases were recorded at 0.45-w/c for f_{sp} (14% in air and 11% in moist curing). GFRC had lower f_c and f_{sp}, particularly in air curing at 0.65-w/c (by 13% and 12% respectively). However, the results in moist curing were closer to the control specimen or slightly better for GFRC.

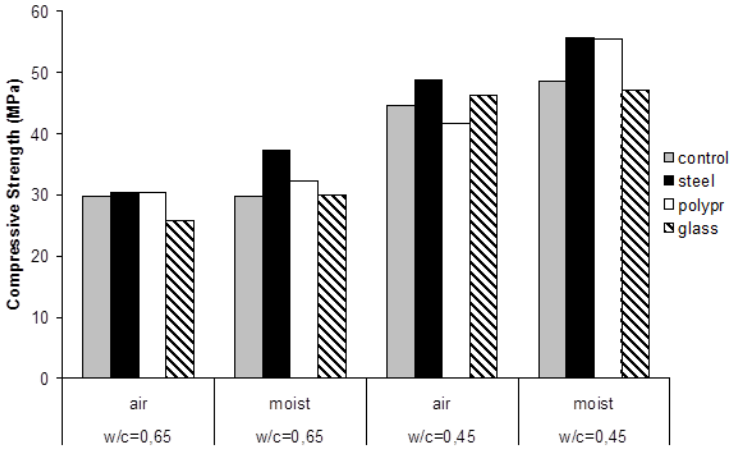

Figure 1. Compressive strength test results of the concrete mixes

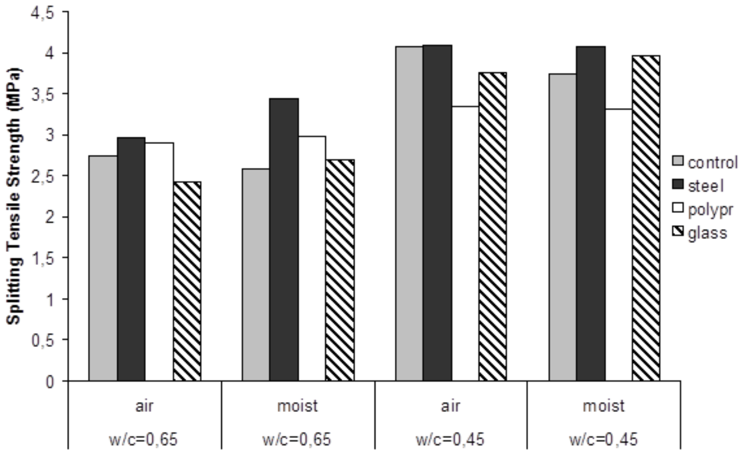

Figure 2. Splitting tensile strength test results of the concrete mixes

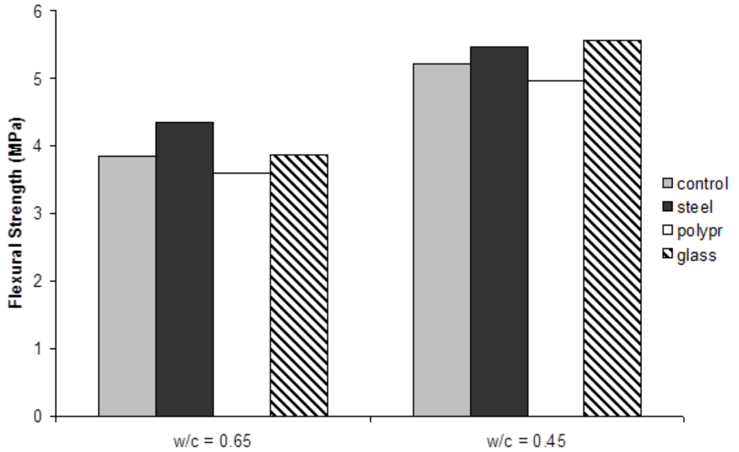

Figure 3. Flexural strengths of different concrete mixes

Previous study on the effect of curing is scarce. In a previous research study, curing was found to be more effective in strength increase for fiber reinforced concrete compared to control concrete (Aruntaş et al., 2008).

Flexural strength test was carried out only in moist cured specimens. SFRC had the highest f_{fl} at 0.65-w/c. The f_{fl} of the SFRC was 13% and 5% higher than that of the control at 0.65-w/c and 0.45-w/c, respectively. PFRC had the lowest f_{fl} at both 0.65 and 0.45 w/c, showing 6% and 5% lower values than the control concrete, respectively. The f_{fl} for GFRC was the same with control at 0.65-w/c and the highest at 0.45-w/c which was 7% higher than that of the control mix. The results of flexural strength tests are shown in Fig. 3.

Table 5. Percent change in strength by steel and polypropylene fiber addition

Ref	fiber	L_f/d_f	V_f (%)	f_c (MPa)	Δf_c (%)	Δf_{sp} (%)	Δf_{fl} (%)
P*	steel	35/0.55 = 64	0.5	30	25	33	13
				45	15	9	5
3		30/0.55 = 55	0.5	35	2	11	15
				65	2	12	11
				85	2	13	15
			1	35	5	24	31
				65	3	25	28
				85	3	25	30
			1.5	35	8	38	46
				65	6	41	39
				85	6	49	40
4		35/0.55 = 55	0.65	35	13	54	105
5		35/0.55 = 64	0.5	85	7	19	28
			1		12	50	58
			1.5		15	86	92
			2		13	98	127
6		30/0.5 = 60	0.5	55	6	27	16

7		40/0.615 = 65	0.5	30	3	8	4
			1		15	32	17
		60/0.75 = 80	0.5		5	6	7
			1		19	90	77
8		35/0.55 = 64	0.25	75	3		-6
			0.5		1		-6
			1		4		5
			1.5		5		30
9		60/0.8 = 75	0.5	40	8		25
				50	8		-4
				80	6		0
10		30/0.62 = 48	0.5	50	4	11	3
			1		9	16	6
			1.5		17	40	30
		60/0.90 = 67	0.5		9	11	5
			1		19	17	36
			1.5		15	54	57
		60/0.75 = 80	0.5		14	13	8
			1		19	28	64
			1.5		6	45	81
P*	polypropylene	591	0.1	30	8	11	-6
				45	14	-11	-5
11		-	0.07	25	3	4	3
12		152	0.75	75	-22	12	-3
4		460	0.08	35	1	30	100
		333	0.05		-3	22	5

* The results of the current study for moist cured specimens

Aspect ratio, fiber content and compressive strength data from the literature for steel and polypropylene fiber reinforced concretes and the changes reported for compressive, splitting tensile and flexural strengths due to the use of fibers are presented in Table 5 together with the data for the moist cured specimens of this study. The findings in literature are generally indicating that the contribution of steel fibers is more significant for flexural strength and splitting tensile strength and this contribution increases as a function of the fiber addition rate and aspect ratio.

Previous research on GFRC is very limited. In a research study by Sekhar & Rao (2008), glass fiber addition of 0.03% by concrete volume caused approximately 5% increase in compressive, splitting tensile and flexural strengths of concrete with a compressive strength of 30 MPa. Sivakumar & Santhanam (2007) recorded 3%, 5% and 14% increases in compressive, splitting tensile and flexural strengths, respectively, by 0.5% glass fiber addition in concrete with 55 MPa compressive strength.

According to the literature listed above, polypropylene and glass fiber addition lead to an increase in splitting tensile strength and flexural strength. Increases in compressive strength look lower compared to steel fiber reinforced concrete and some studies even indicate reductions in compressive strength.

Rebound numbers and pulse velocities were measured for all and air cured specimens, respectively (Table 4). In air curing, control specimens had the highest rebound number. The difference is more significant at 0.45-w/c. SFRC had the closer results to the control concrete at both w/c. In moist curing, rebound number results were lower than those in air curing. On the other hand, fiber reinforced concrete mixes in moist curing had higher results with respect to the control mix at 0.65-w/c. The same fact was true at 0.45-w/c except PFRC, which had the lowest results in both curing conditions. Pulse velocities for GFRC had the same results with the control at both w/c. SFRC had the lowest pulse velocity at both w/c and the PFRC had the highest. Slight decrease in the pulse velocity was recorded in SFRC by Yazıcı et al. (2007).

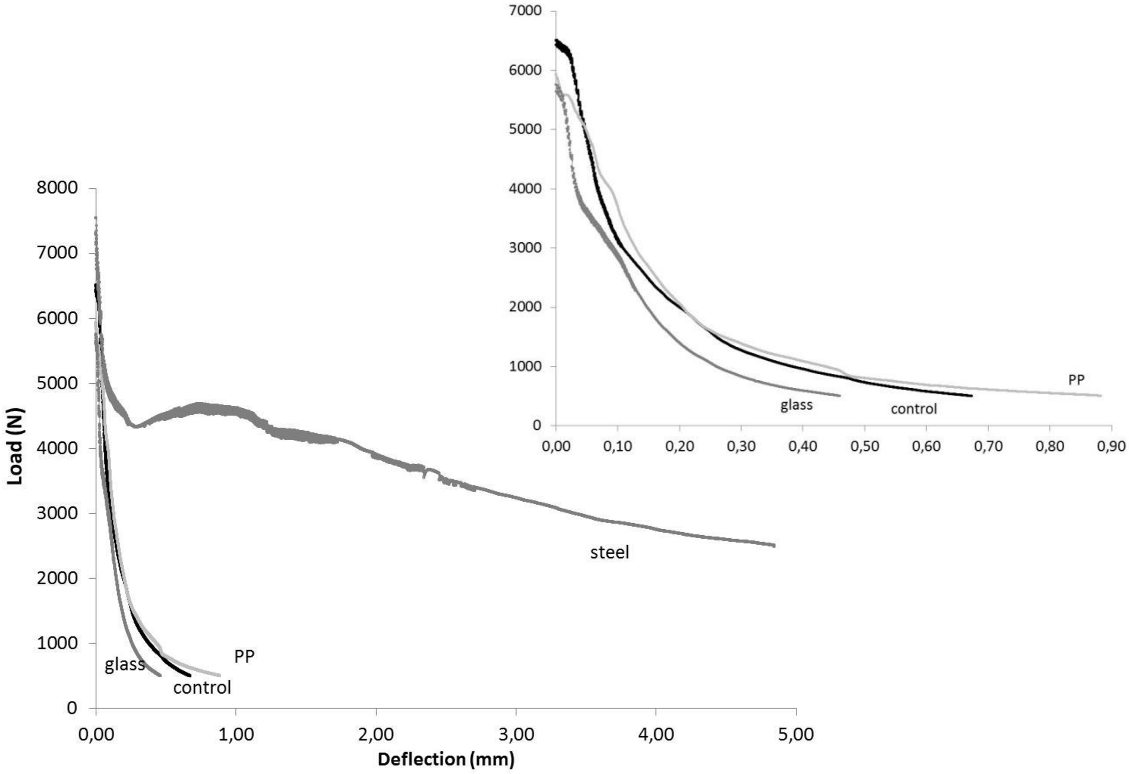

Figure 4. Load – deflection curves after ultimate load for 0.65-w/c ratio concretes

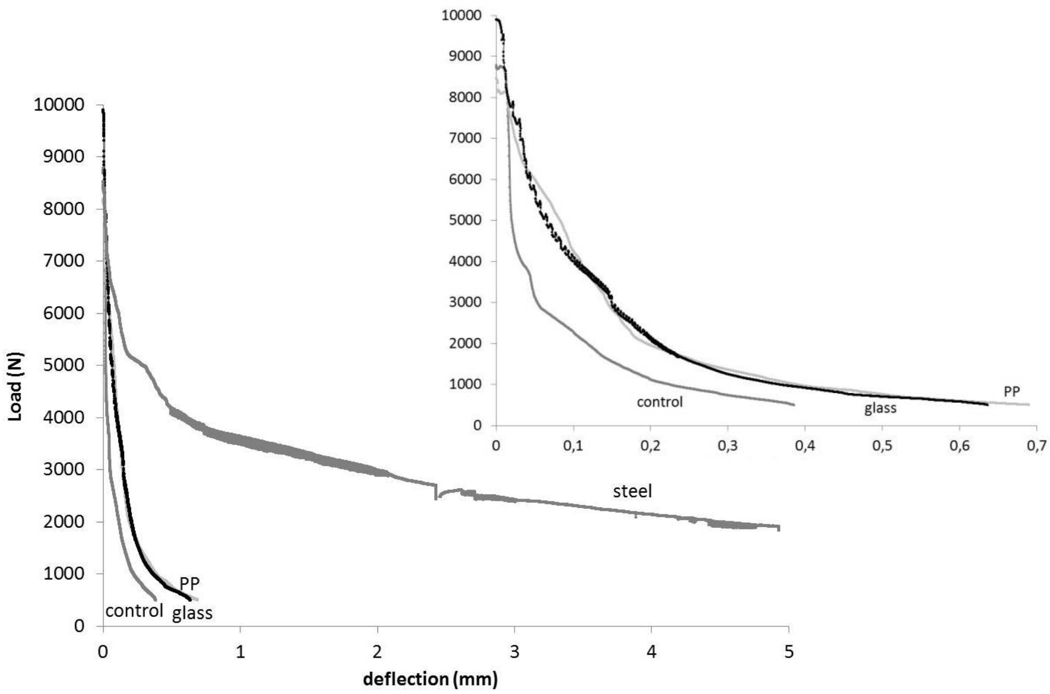

Figure 5. Load – deflection curves after ultimate load for 0.45-w/c ratio concretes

The G_f of SFRC was higher nearly by one order of magnitude than the other specimens (Table 6). At 0.65-w/c, the G_f results were very close for the other three mixes, where PFRC was slightly higher (by 3%). At 0.45-w/c, on the other hand, PFRC and GFRC also were higher than the control (17% and 50% respectively). The improvement in toughness by steel fiber addition is well-known. However, the data on polypropylene and glass fibers are limited. Sivakumar & Santhanam (2007) measured 1128%, 355% and 259% higher toughness compared to samples without fiber in steel, mono-filament polypropylene and glass fiber reinforced concretes, respectively, by 0.5% volume addition for each type of fiber in a concrete with compressive strength of 55 MPa. Sun & Xu (2009) recorded 115%, 152% and 140% increases in toughness by 0.05%, 0.1% and 0.15% of mono-filament polypropylene fiber addition in 50 MPa compressive strength concrete. According to a study by Mu et al. (2001), toughness indices of concrete reinforced by polypropylene (0.5%) and glass (0.38%) fibers were approximately 50% higher than those of the unreinforced specimens. Load-deflection curves of selected specimens for 0.65 and 0.45 water-cement ratio concretes are given in Figs. 4 and 5.

Table 6. Modulus of elasticity and fracture energy of concrete mixes

	w/c = 0.65				w/c = 0.45			
	control	steel	polypr.	glass	control	steel	polypr.	glass
E (GPa)					27.6	31.1	29.3	27.8
Gf (N/m)	152.0	1485.0	156.6	151.5	147.3	1778.2	172.3	219.2

The modulus of elasticity of SFRC and PFRC are higher by 12.7% and 6.2% respectively (Table 6). GFRC had only 0.7% higher modulus than the control. In the literature data, it is possible to find increases (Thomas & Ramaswamy, 2007; Sivakumar & Santhanam, 2007; Atiş & Karahan, 2009; Trottier & Banthia, 1994) as well as decreases (Köksal et al., 2008; Atiş & Karahan, 2009; Trottier & Banthia, 1994; Kayali, 2004) by steel fiber addition, decrease (Kayali, 2004) and increase (Sivakumar & Santhanam, 2007) by polypropylene fiber addition and increase (Sivakumar & Santhanam, 2007) by glass fiber addition. However, the variations are generally insignificant.

4 CONCLUSIONS

1) Mechanical properties of concrete mixes tested in the present study were affected by fiber addition, fiber type, water-cement ratio and curing conditions.
2) Steel fiber addition caused an increase in compressive strength and splitting tensile strength of concrete. The improvement with respect to the concrete without fiber was more significant in moist cured specimens and higher water-cement ratio. The concrete mixes with polypropylene fibers had the same behavior. However, the improvements were less significant and in some conditions, there were decreases in strength. Strength of glass fiber caused generally decreases with respect to the control specimen in air curing and slight increases in moist curing.
3) Steel fiber reinforced concrete had the highest flexural strength at both water-cement ratios and polypropylene fiber reinforced concrete had the lowest. The fracture toughness results calculated from flexural testing were higher by one order of magnitude for the SFRC. For the

other mixes, the results were closer at 0.65-w/c but there were also significant improvements for the PFRC and GFRC at w/c-0.45.

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