

Age-Dependent Flexural Properties of Fiber Reinforced Concrete Used in Thin Overlays

Min Ook Kim¹ and Amanda Bordelon²

Abstract

This paper presents measured age-dependent flexural properties of fiber-reinforced concrete (FRC) as are used in the design of thin overlay pavements. A laboratory investigation was performed to quantify the pavement design properties, particularly residual strength ratio of FRC as a function of age. Four different types of structural macro-fibers, made of steel or polypropylene, and of different lengths or aspect ratios were investigated. Also different fiber volume contents from 0%, 0.5%, and 1.0% were studied for all fiber types and ages. The results confirmed that there is a significant age-dependency to the residual strength ratio. The short steel FRC at high fiber volume content was the only mixture which showed constant residual strength ratio as a function of time. All other FRC mixtures exhibited a reduced residual strength ratio when tested at later ages.

Introduction

Many experimental studies have been carried out to investigate how fibers added to concrete will improve toughness and enhance cracking resistance (Banthia and Sheng 1996; Bayasi and Zeng 1993; Gopalaratnam et al. 1991; Jenq and Shah 1986; Mobasher et al. 2014; Song et al. 2005; Wang et al. 1990; Ward and Li 1990). There are a few standardized testing procedures to evaluate fiber-reinforced concrete (FRC) flexural performance such as ASTM C1609, JCI-SF 4, EN 14651, and RILEM TC 162-TDF. Among these, a residual strength ratio as determined from ASTM C1609 remains to be the current FRC overlay design parameter (Harrington and Fick 2014). In the design calculations for overlays, since the residual strength ratio is used as a modifier to the modulus of rupture as shown in Eq. 1 (Bordelon and Roesler 2012). For this design procedure, typically the 28 day property is measured and reported for the FRC. This 28 day strength is considered close to the material's final strength and generally accepted for the design of various concrete structures including concrete overlays.

$$MOR_{design} = MOR_{unreinforced} * (1 + R_{150}) \quad (1)$$

where MOR_{design} is the overlay design flexural strength; $MOR_{unreinforced}$ is the peak flexural strength of the plain concrete without fibers; and R_{150} is the residual strength ratio.

As the concrete matrix itself is expected to increase in strength with age, the residual strength ratio may in fact decrease with age. A reducing residual strength ratio with age would mean that the designed fiber-reinforcement provides the maximum crack

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resistance benefit only at early ages. In other words, the addition of fibers to the concrete may only be beneficial if the pavement cracks at early ages. This could be beneficial for thin overlays or lower strength mixtures since most cracking in concrete pavement sections occurs during the first thermal cycle, and often at 1 day, rather than at 28 days. Alternatively, if the post-cracking strength of the FRC correspondingly increases with age besides the flexural strength, the residual strength ratio may be the same or higher with time. Understanding the age-effect of FRC is crucial for predicting cracking or improving the design of FRC overlays.

Some laboratory experimental studies have been carried out to investigate age-dependent properties of FRC (Bernard 2014; Bernard 2015; Bordelon 2007; Chan and Li 1997; Hodicky et al. 2014). A study by Bernard which tested FRC at different ages from 7 to 365 days found that steel fiber reinforced concrete (SFRC) exhibited an increase in residual strength up to 56 days, followed by a reduction with later ages. In this same study, polymeric fiber reinforced concrete (PFRC) showed an increase in residual strength over all ages. Bordelon reported an increase in residual strengths, but that the residual strength ratio reduced for PFRC from 7 to 28 days (Bordelon 2007). On a microstructure level, the fiber-to-cement interfacial bond between 0.5 to 28 days, as determined from a pull-out test, was found to only increase within the first 2 days, but have no significant change from 7 to 28 days (Chan and Li 1997).

The purpose of this study is to estimate whether the fiber type, length, aspect ratio, or volume content are the factors which may affect the changes in flexural properties of FRC versus age. Additional age-dependent properties of FRC were tested, but are not presented herein for the sake of brevity. Standard flexural beam tests will be conducted for FRC samples of ages 3 and 90 days, which represent the service life performance of an overlay section. Earlier-age tests may be impractical to specify by agencies or municipalities for quantifying the FRC performance.

Research Significance

Applying fibers in thin concrete overlays is becoming popular since the FRC is found to have reduced cracking and improved load carrying capacity. Currently, the residual strength ratio, which may be commonly measured at 28 days age, is utilized in the design of thin concrete overlays. However, if the residual strength ratio varies significantly with age, specifications for new FRC overlay performance may need to also include a specified age for which the flexural properties should be measured. The research also provides insight into whether there is an age-dependence with different but common fiber types, lengths, aspect ratios, and volume fractions on the measured flexural properties.

Experimental Program

Mixture Design and Test Variables

Table 1 shows the concrete mixture proportions utilized in this study. All FRC specimens were cast with the same mass proportions in the concrete, but with varying volumetric dosages of fibers. All had the same dosage of polycarboxylate high range water reducer to improve workability and fiber dispersion. The fibers were selected to cover different material types of steel versus polymeric; different fiber lengths of 35 mm (1.64 in.) to 60 mm (2.4 in.), and different aspect ratios (65 versus 90). Four selected fibers were studied as listed in Table 2. All of selected fibers are commonly used in concrete overlay or thin

shell structures. All fibers were dispersed by hand and mixed for 2 minutes into a rotary drum mixer, after the plain concrete was mixed. The FRC was placed in the molds using a hand scoop and vibrated using a vibrating table. FRC specimens were demoulded after 24 hours of casting and moist cured at a temperature around 30 °C (86 °F).

Table 1 Plain Concrete and FRC Mix Proportions

Material		Plain	Short Steel	Long Steel	Long Polymeric	Slender and Long Polymeric
Water		167 kg/m ³				
Cement		292 kg/m ³				
Fly Ash		125 kg/m ³				
Coarse Aggregate		1052 kg/m ³				
Fine Aggregate		857 kg/m ³				
High Range Water Reducer		1028 mL/m ³				
Air Entraining Admixture		107 mL/m ³				
Fiber	(for 0.5% volume fraction)	0	40 kg/m ³	40 kg/m ³	4.5 kg/m ³	4.5 kg/m ³
	(for 1.0% volume fraction)	0	79 kg/m ³	79 kg/m ³	9.0 kg/m ³	9.0 kg/m ³

Table 2 Properties of Fibers

Fiber Type	Short Steel	Long Steel	Long Polymeric	Slender and Long Polymeric
Material	Hooked steel	Hooked steel	Polypropylene	Polypropylene-polyethylene
Cross section	Circular	Circular	Rectangular (bi-tapered)	Rectangular (straight)
Length	35 mm	60 mm	50 mm	40 mm
Diameter	0.55 mm	0.9 mm	-	-
Thickness	-	-	0.4 mm	0.11 mm
Width	-	-	1.2 mm	1.4 mm
Aspect ratio	65	65	75	90
Tensile strength	1345 MPa	1160 MPa	550 MPa	620 MPa
Elastic modulus	210 GPa	210 GPa	7.0 GPa	9.5 GPa
Photograph				

The flexural properties of FRC were determined from standard 150 x 150 x 533 mm (6 x 6 x 21 in.) beams, with span of 450 mm (18 in.) and a constant loading rate of 0.10 mm/min (0.004 in./min) according to the ASTM C1609. A mounted deflection frame and a calculated average deflection from two LVDTs were used to measure the midspan deflection on the flexure beams. All strengths were measured from samples at the ages of 3, 7, 14, 28, 56, and 90 days. There were three replicates of the plain unreinforced concrete mixture; two replicates of the 1% volume fraction FRC mixtures; and one beam for each 0.5% volume fraction FRC mixtures.

Data Analysis

The properties from the flexural beam test were analyzed according to ASTM C1609, JCI-SF 4, and Naaman and Reinhardt (Naaman and Reinhardt 2006). Figure 1 shows a typical load versus deflection curve of FRC. The first peak load (P_1) is defined as the first point on the load-deflection curve when the slope is zero and the concrete initially cracks. The reported modulus of rupture (MOR) is determined as the flexural strength from this first cracking. In some deflection-hardening samples, the sample continues to carry load to a higher value, in this case the ultimate load is defined as P_{max} (Kim et al. 2008; Mobasher et al. 2014; Naaman and Reinhardt 2006). Naaman and Reinhardt (2006) suggests also recording the secondary peak load for deflection-softening samples, in this case labelled P_2 . The recorded load values are summarized as follows:

1. P_1 : First-crack load; either used for MOR with deflection softening, or called the Limit of Proportionality with deflection hardening
2. P_{max} : Maximum peak load for deflection hardening
3. P_2 : Second peak load for deflection softening
4. $P_{L/150}$: the load reading for when the midspan deflection reaches 1/150 of the span

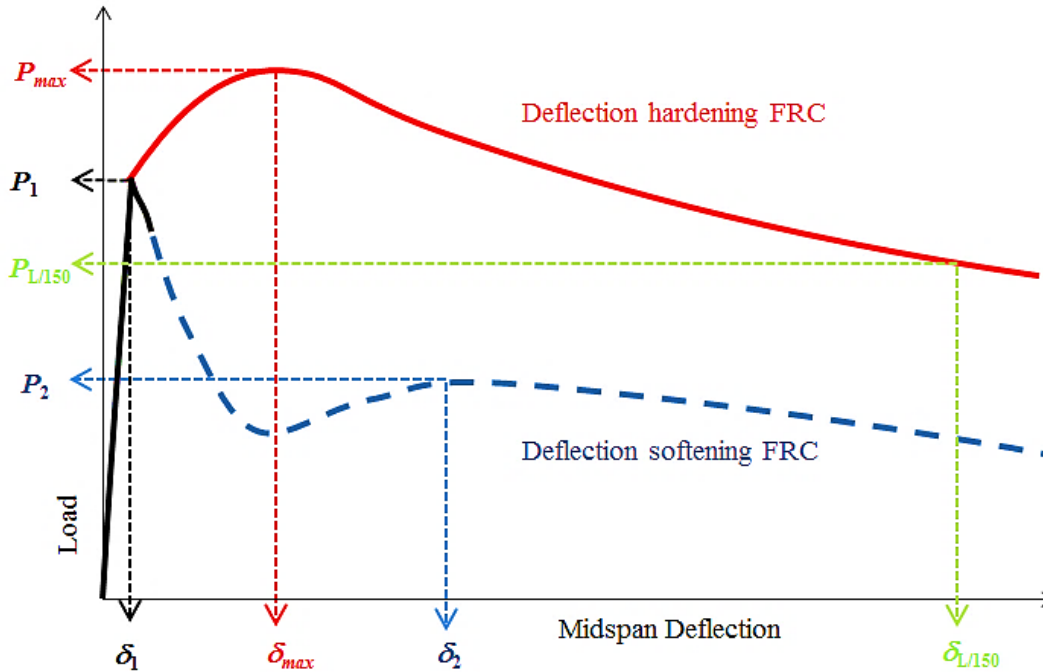


Figure 1 Typical load-deflection curves of FRC.

The stresses are then calculated at the first crack, and maximum deflection-hardening peak or deflection-softening second peak based on Eqs. (2), (3) or (4), respectively.

$$f_1 = P_1 \cdot \frac{L}{bh^2} \quad (2)$$

$$f_{max} = P_{max} \cdot \frac{L}{bh^2} \quad (3)$$

$$f_2 = P_2 \cdot \frac{L}{bh^2} \quad (4)$$

where L is the span length, b is the width of specimen, and h is the height of specimen.

Based on the ASTM C1609 standard, the residual strength, $f_{L/150}^{ASTM}$, and residual strength ratio, R_{150}^{ASTM} , can be calculated using Eqs. (5) and (6) as shown below.

$$f_{L/150}^{ASTM} = P_{L/150} \cdot \frac{L}{bh^2} \quad (5)$$

$$R_{150}^{ASTM} = \frac{f_{L/150}}{f_1} \times 100 \quad (6)$$

The JCI-SF4 standard calculates the residual strength, $f_{L/150}^{JCI}$, and residual strength ratio, R_{150}^{JCI} , both based on the toughness, or the area under load-deflection as shown in Eqs. (7), (8), and (9), respectively.

$$f_{L/150}^{JCI} = \frac{T_{L/150}}{L/150} \cdot \frac{L}{bh^2} \quad (7)$$

$$R_{150}^{JCI} = \frac{f_{L/150}}{f_1} \times 100 \quad (8)$$

$$T_{L/150} = area(P \cdot \delta)_0^{L/150} \quad (9)$$

where $T_{L/150}$ is the area under load-deflection curve between 0 and L/150 of deflection.

Experimental Results and Discussion

Flexural Strength

Figure 2 shows an example flexural load versus deflection curves of two different fiber types with several tested ages. The SFRC at 1% volume fraction undergoes a deflection hardening response, while many of the PFRC samples and 0.5% SFRC samples exhibited deflection-softening responses. As mentioned previously, stresses (f_1 , f_2 or f_{max} , and $f_{L/150}$) at different points along the load versus deflection curve were recorded. The ASTM C1609 and Naaman and Rienhardt values are shown in Tables 3, 4, and 5 for plain concrete, SFRC, and PFRC mixtures, respectively. Comparisons of the addition of fibers to the measured flexural properties are indicated in the following sections.

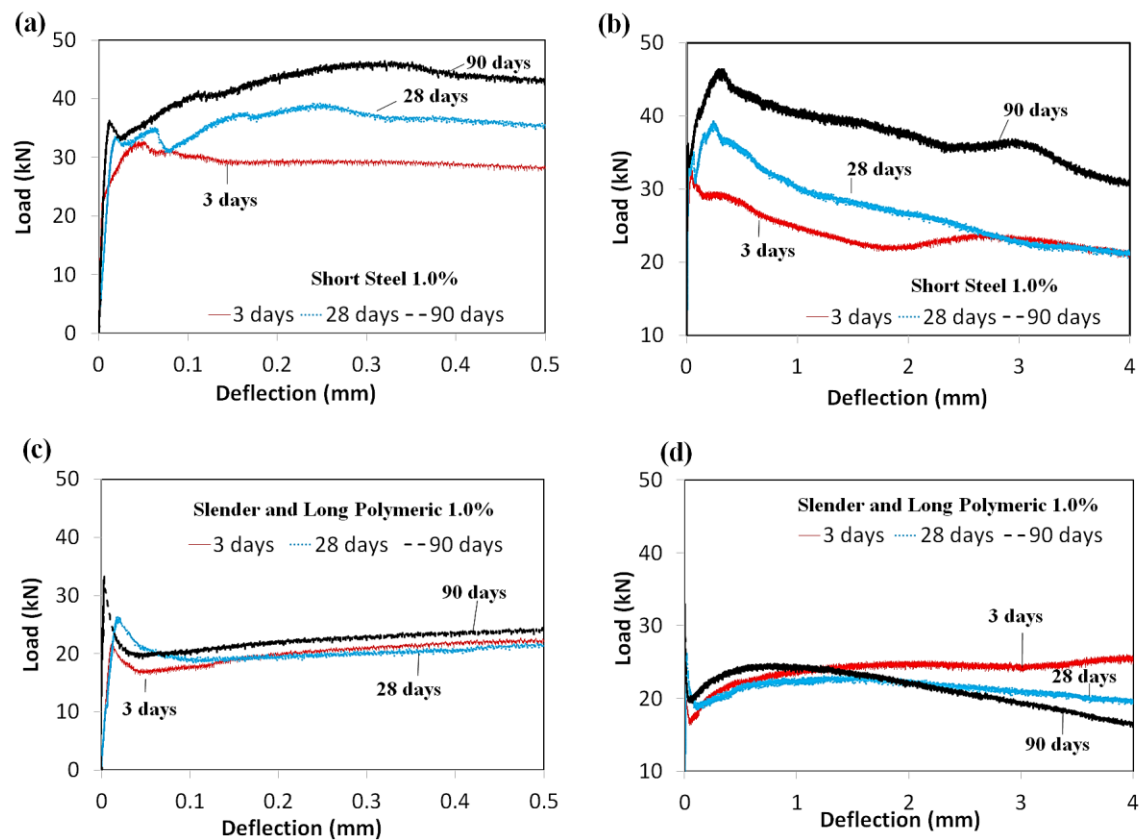


Figure 2 Typical load versus deflection of a beam containing either (a) and (b) short steel FRC or (c) and (d) slender and long polymeric FRC; each at 1.0% volume fraction. Plots show both the smaller deflection values (on left) and full deflection test range (on right).

Table 3 Average Flexure Test Results for Plain Concrete

Age (Days)	First Peak	
	f_1	δ_1
	(MPa)	(mm)
3	2.74	0.014
7	3.04	0.020
14	3.43	0.011
28	4.08	0.006
56	5.33	0.018
90	5.02	0.008

Note: average of three beam specimens per age.

Table 4 Average Flexure Test Results of Steel Fiber Reinforced Concrete

Short Steel Fiber 0.5%¹									
Age (Days)	First Peak		Second Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	f_2 (MPa)	δ_2 (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
7	3.15	0.0030	3.09	0.48	2.40	3.0	76.2	59.2	83.6
14	3.68	0.0128	3.83	0.25	2.62	3.0	57.7	67.8	66.4
28	4.21	0.0004	4.75	0.23	2.83	3.0	67.2	79.6	84.1
56	4.54	0.0353	3.53	0.45	2.61	3.0	70.9	62.7	75.7
90	4.97	0.0418	3.44	0.41	2.48	3.0	49.9	60.2	53.7
Short Steel Fiber 1.0%²									
Age (Days)	First Peak		Maximum Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	$f_{\max}$ (MPa)	$\delta_{\max}$ (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	3.16	0.0060	4.74	0.17	2.71	3.0	85.8	77.9	109.5
7	3.36	0.0039	4.92	0.26	3.08	3.0	91.7	85.2	112.6
14	3.80	0.0144	4.87	0.23	3.26	3.0	85.8	89.9	105.2
28	4.81	0.0365	5.86	0.36	3.21	3.0	66.7	91.8	84.8
56	4.87	0.0144	6.80	0.25	4.03	3.0	82.8	114.7	104.7
90	5.19	0.0163	6.88	0.25	4.53	3.0	87.9	125.1	107.2
Long Steel Fiber 0.5%¹									
Age (Days)	First Peak		Maximum Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	$f_{\max}$ (MPa)	$\delta_{\max}$ (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	3.12	0.0108	3.50	0.35	2.71	3.0	86.9	68.1	97.0
7	3.11	0.0068	3.96	0.79	2.99	3.0	96.1	78.0	111.5
14	3.87	0.0045	3.79	1.50	3.45	3.0	89.1	78.6	90.3
28	4.44	0.0031	4.85	0.48	4.18	3.0	94.1	98.3	98.4
90	6.54	0.0138	4.61	3.61	4.19	3.0	64.1	92.5	62.8
Long Steel Fiber 1.0%²									
Age (Days)	First Peak		Maximum Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	$f_{\max}$ (MPa)	$\delta_{\max}$ (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	3.24	0.0086	5.24	0.57	4.06	3.0	125.3	104.5	143.3
7	3.56	0.0012	5.56	1.80	4.60	3.0	129.2	106.5	133.0
14	3.34	0.0039	5.71	0.51	4.61	3.0	138.0	112.8	150.2
28	4.15	0.0015	6.66	0.65	6.51	3.0	156.9	136.4	146.1
56	4.88	0.0030	8.23	0.50	4.77	3.0	97.7	133.2	121.4
90	5.90	0.0144	7.51	0.29	5.26	3.0	89.0	145.5	110.1

Note: 1 MPa = 0.145 ksi; 1 mm = 0.04 in.; and 1 N·m = 8.85 lb-in.

¹ One beam tested at each age.

² Two beams tested at each age. Average shown in table.

Table 5 Average Flexure Test Results of Polymeric Fiber Reinforced Concrete

Long Polymeric Fiber 0.5%¹									
Age (Days)	First Peak		Second Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	f_2 (MPa)	δ_2 (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	2.77	0.0112	1.84	2.70	1.68	3.0	60.6	36.3	58.3
7	3.57	0.0059	2.44	3.70	2.10	3.0	58.8	38.7	48.2
14	3.38	0.0059	2.03	3.58	1.97	3.0	58.3	40.1	52.7
28	4.34	0.0066	2.40	2.40	2.29	3.0	52.8	44.9	46.0
56	4.14	0.0021	3.47	3.52	3.27	3.0	79.0	56.8	61.0
90	5.10	0.0159	2.39	2.61	2.34	3.0	45.9	51.4	44.8
Long Polymeric Fiber 1.0%²									
Age (Days)	First Peak		Second Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	f_2 (MPa)	δ_2 (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	3.25	0.0123	3.45	0.93	2.99	3.0	92.0	70.6	96.6
7	3.07	0.0101	3.31	2.62	3.00	3.0	97.7	62.3	90.2
14	3.74	0.0119	4.98	2.41	4.39	3.0	117.4	94.9	112.7
28	4.21	0.0068	4.66	2.20	4.49	3.0	106.7	89.1	94.1
56	4.39	0.0053	4.06	2.41	3.68	3.0	83.8	75.6	76.6
90	5.44	0.0064	4.88	4.11	4.26	3.0	78.3	86.0	70.3
Slender and Long Polymeric Fiber 0.5%¹									
Age (Days)	First Peak		Second Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	f_2 (MPa)	δ_2 (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	2.56	0.0064	2.27	3.00	2.22	3.0	86.7	39.5	68.5
7	3.27	0.0092	1.79	2.31	1.64	3.0	50.2	35.2	47.8
14	4.41	0.0079	2.18	0.94	1.97	3.0	44.7	47.4	47.8
28	3.87	0.0070	1.25	1.31	1.10	3.0	28.4	26.9	30.8
56	4.05	0.0040	1.86	2.68	1.79	3.0	44.2	32.9	36.1
90	4.67	0.0074	1.60	0.39	1.25	3.0	26.8	32.5	30.9
Slender and Long Polymeric Fiber 1.0%²									
Age (Days)	First Peak		Second Peak		ASTM C1609		JCI-SF4		
					L/150		R_{150}	$T_{L/150}$	R_{150}
	f_1 (MPa)	δ_1 (mm)	f_2 (MPa)	δ_2 (mm)	$f_{L/150}$ (MPa)	$\delta_{L/150}$ (mm)	(%)	(N·m)	(%)
3	2.62	0.0073	3.01	3.57	2.87	3.0	109.5	58.5	99.2
7	3.57	0.0115	3.47	2.13	3.05	3.0	85.4	67.5	84.0
14	3.94	0.0220	4.27	2.74	4.22	3.0	107.1	81.0	91.3
28	3.55	0.0103	2.90	1.51	2.73	3.0	76.9	61.4	76.8
56	4.10	0.0021	3.66	2.32	3.20	3.0	78.0	68.2	73.9
90	4.38	0.0029	3.14	0.81	2.62	3.0	59.8	65.0	65.9

Note: 1 MPa = 0.145 ksi; 1 mm = 0.04 in.; and 1 N·m = 8.85 lb-in.

¹ One beam tested at each age.

² Two beams tested at each age. Average shown in table.

The first cracking stress or MOR as used in pavement design increases with age for all of the mixtures, as expected and shown in Figure 3. If the highest stress value f_{max} were used to describe the MOR in pavement design instead of the first-cracking stress, then the deflection-hardening samples (which are most of the SFRC mixtures) clearly would have a greater MOR value. Among deflection-softening samples (which are all of the PFRC and low volume fraction short steel FRC), no clear trend was seen between age and fiber type or fiber content on the secondary peak stress f_2 .

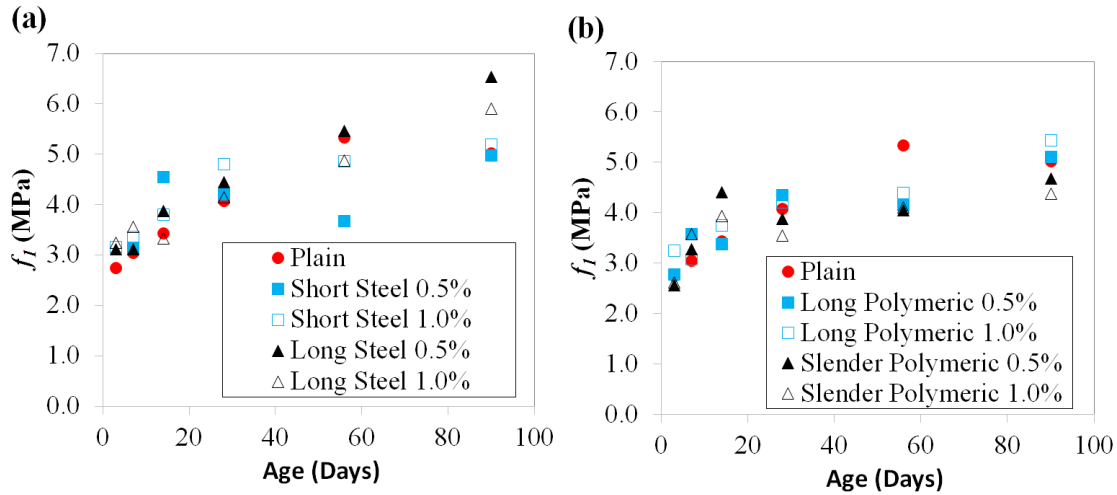


Figure 3 Effect of fibers on averaged first peak cracking stress for (a) steel FRC and (b) polymeric FRC.

Among the different types of fibers studied, the short steel FRC exhibited an increased f_{max} and $f_{L/150}$ as a function of age, while slender and long polymeric FRC did not show any trend in f_2 , and $f_{L/150}$ with age. The effects of fiber volume fraction, fiber length, and fiber aspect ratio on f_{max} or f_2 were investigated. All post-cracking stresses, either f_{max} or f_2 , for all FRC mixtures were increased as fiber volume fraction and as fiber length increased. Those results are reasonable because increased effective bonding area will improve both flexural performance and cracking resistance. As the aspect ratio increased, from 75 to 90 among the two PFRC mixtures studied, there was a decrease in the secondary peak f_2 . Although this was not explicitly studied, the micro-texture of the two polymeric fibers may have also caused this effect since the higher aspect ratio polymeric fiber also had a smooth surface, while the lower aspect ratio polymeric fiber had some mechanical friction for higher pullout resistance. Also shown in the toughness values from Tables 4 and 5, the deflection-hardening samples all had an increased $T_{L/150}$ as a function of age while deflection-softening samples exhibited no trend in $T_{L/150}$ versus age.

Residual Strength Ratio

Instead of comparing only the strength values, the residual strength ratio is useful because it is expected to reduce the age-dependency by normalizing the changing post-cracking stress values by the first peak strength. Figure 4 indicates the effect of different fiber properties on the residual strength ratio, R_{150}^{ASTM} for various ages. All FRC mixtures showed the increased R_{150}^{ASTM} as the fiber length or the fiber volume fraction increased as

illustrated in Figure 4 (a), (c), and (d). This is expected because the longer fibers or more fibers provide increased effective bonding area and as such there is improved cracking resistance. The more slender fibers, with larger aspect ratios were found to have a decreased R_{150}^{ASTM} as shown in Figure 4 (b). Thinner fibers were more likely to fail before complete pull-out resistance is reached.

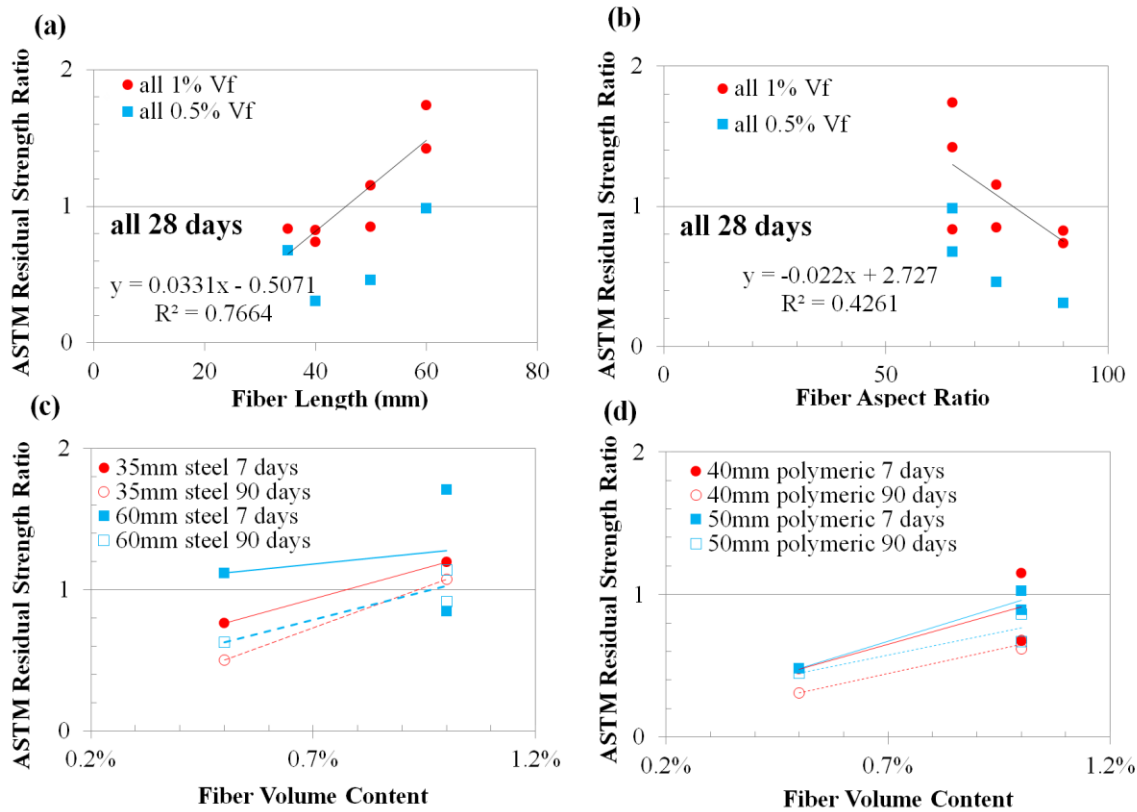


Figure 4 Effects of fiber length, aspect ratio, volume fraction and material type on ASTM residual strength ratio.

Figure 5 illustrates the change in residual strength f_{150} itself versus age for the different FRC mixtures. This is similar to the toughness calculated trend with age as well. The high variability seen in the residual strength is due to the specific fiber pull-out performance during each FRC flexural test specimen. In Figure 6, R_{150} calculated either by ASTM C1609 or JCI-SF4 both indicate trends of the different fiber types capability to carry load after failure if cracking occurs at various ages. Regardless of which standard is used to find the residual strength ratio, the R_{150} reduced or stayed the same as the age of the tested sample increased. The important finding here was that the longer or more slender fibers of both steel and polypropylene in FRC, actually decreased in R_{150} as a function of age.

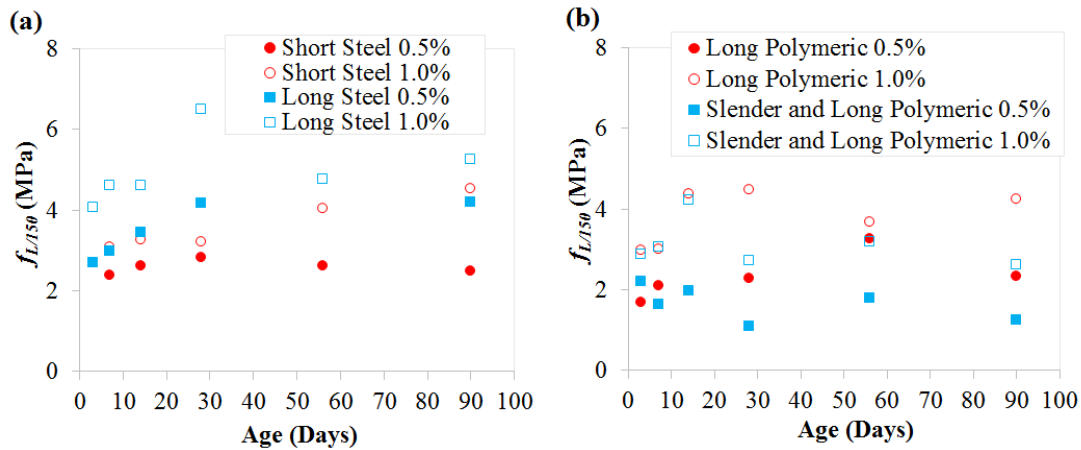


Figure 5 Effect of fibers on ASTM residual strength for a) SFRC and b) PFRC.

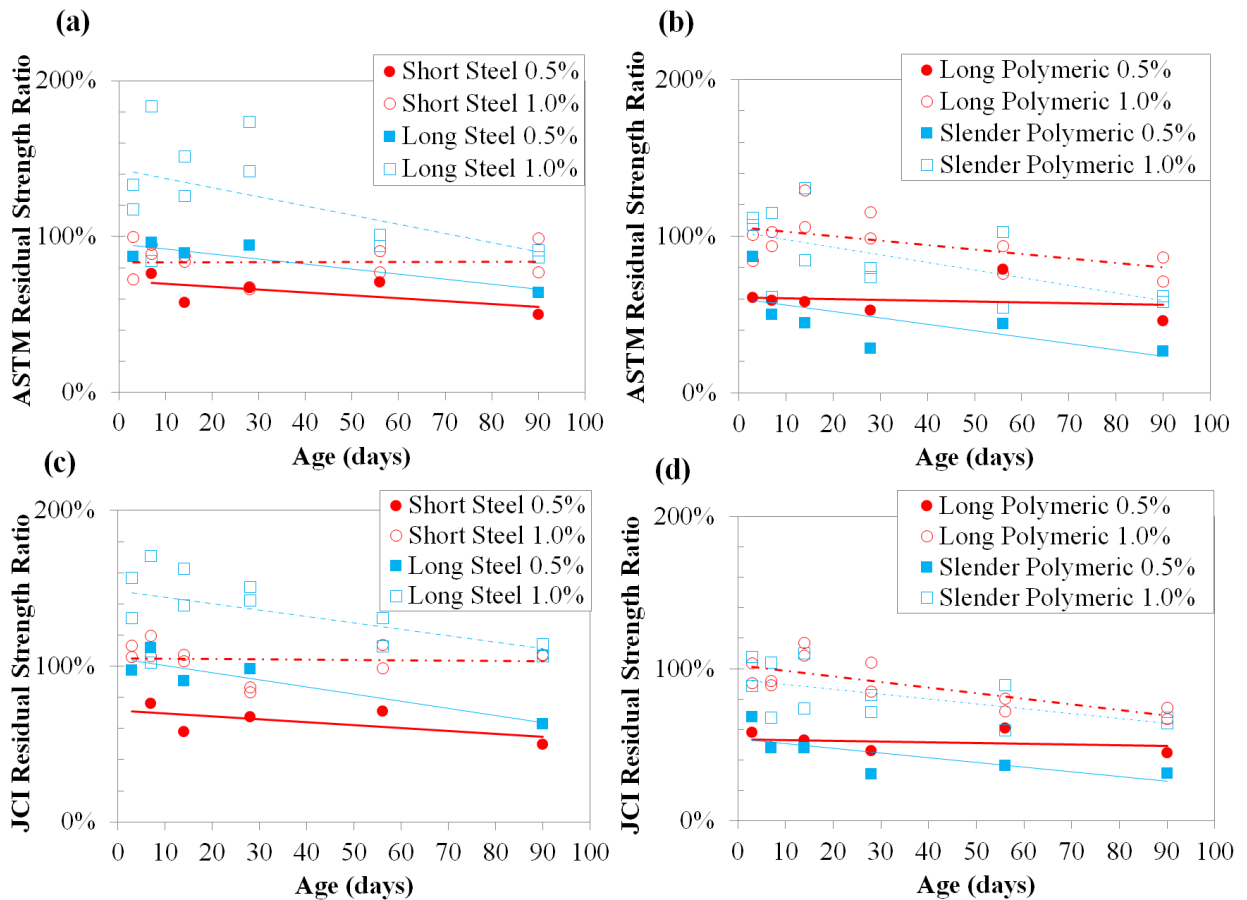


Figure 6 Effect of fibers on ASTM or JCI residual strength ratio for (a, c) SFRC and (b, d) PFRC.

Conclusions

The post-cracking residual strength or residual strength ratio are the parameters in pavement design to accommodate for the benefit of FRC. The results of this laboratory study strongly indicate that there is an age-dependency to the flexural properties of FRC. Even among different fiber types, and FRC that exhibits deflection hardening or deflection softening (as is more common with pavement overlay FRC mixtures) the normalized post-cracking response is still dependent on age of the concrete. Specific findings related to the fiber types investigated here were as follows:

- The residual strength ratio increased with longer fibers, shorter aspect ratio fibers, and higher fiber volume contents, among the same tested age of FRC.
- Mixtures with a lower fiber content of 0.5%, especially those with a short steel fiber, were found to have less effect of age on the residual strength ratio.
- For both deflection-hardening and deflection softening FRC mixtures, even though the post-cracking flexural stresses increases with age, because the concrete strength also increases, the normalized reduced residual strength ratio still was confirmed to have a reduction with age.

Acknowledgements

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