Toughness of Glass Fiber Reinforced Concrete Panels Subjected to Accelerated Aging

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Glass fiber reinforced concrete (GFRC) is a cement based composite product which is reinforced with glass fibers. GFRC cladding panels are increasingly being used in the United States and other countries. These panels are generally produced by simultaneously spraying a portland cement mortar slurry and alkali resistant (AR) chopped glass fibers onto molds. The size of properly designed panels with appropriate configuration can be as large as 8 x 30 ft (2.4 x 9.1 m) with only ½ in. (1.27 cm) skin thicknesses. GFRC panels are relatively light in weight facilitating their handling, transporting and erection. GFRC cladding panels are produced as wall units, window units, spandrels, mullions, and column covers. In 1985, more than 5.5 million sq ft (511,600 m^2) of cladding panels were produced in the United States at an approximate total cost of $100 million.

The expanding use of GFRC panels should be supported with sufficient information on short-term and long-term mechanical properties. The mechanical properties of GFRC depend on the type, length, and volume of glass fibers, matrix composition, fabrication method, curing regime, and storage conditions. It has been established that after prolonged exposure to wet climates, the strength of a GFRC composite may be reduced to nearly that of the unreinforced matrix. To account for this eventual potential strength loss, the Recommended Practice for GFRC Panels, developed by the PCI Committee on GFRC Panels,[1] assumes that the aged flexural strength of GFRC is equal to its 28-day proportional elastic limit value (which is essentially equal to the 28-day strength of the unreinforced matrix).

In addition to the reduction in strength, GFRC composites also exhibit a dramatic reduction in ductility (fracture toughness, strain capacity) when aged in wet conditions. Although considerable information on long-term strength of GFRC products exists, relatively little data on long-term ductility are available. The ability of the panel to withstand forces and deformations may depend not only on its strength but also on its ductility.

Improvements are being sought to increase the long-term durability of GFRC.[2] These include modifying the portland cement mortar with a polymer latex, modifying the portland cement matrix with pozzolanic additions, modifying glass composition, coating the glass fibers, and development of a lime-free cement.[2] The results of these improvements should be quantified through a better understanding of toughness of the GFRC composite. This may require the development of new and more appropriate definitions for toughness.

Tests were conducted at the Construction Technology Laboratories (CTL) to evaluate long-term properties of three different GFRC composites.[3,4] The results of these tests were reviewed and evaluated with an emphasis on quantifying toughness. The results and analyses are described in this paper.

Synopsis

Glass fiber reinforced concrete (GFRC) is a cement based composite product which is reinforced with glass fibers. GFRC cladding panels are increasingly being used in the United States and other countries. The expanding use of GFRC panels should be supported with sufficient information on long-term properties. Although information on long-term strength is available, relatively little data on long-term ductility are available. The ability of the panel to withstand forces and deformations may depend on its strength but also on its ductility.

Tests were conducted to evaluate long-term properties of three different GFRC composites. The results of these tests are evaluated with an emphasis on quantifying toughness. The results of these tests and analyses are described in this paper. Two toughness indices: TI (aging) and TI (improvement) are proposed as methods to quantify the ductility of GFRC panels. Both of these indices can be evaluated from flexural tests currently being performed for quality control of GFRC.

EXPERIMENTAL INVESTIGATION

Three types of GFRC compositions were tested. They consisted of panels made with alkali resistant glass fibers (AR-GFRC) and panels made with E-glass fibers (borosilicate glass fibers) in which the matrix was modified with two different amounts of polymer latex (E-PGFRC-1 and E-PGFRC-2). AR-GFRC and companion unreinforced specimens were tested in flexure, while E-PGFRC specimens were tested in flexure and tension.

Table 1. Mix design of AR-GFRC.

Specific gravity	Ingredients*	Weight, (lb)	Percent by weight	Volume (cu ft)	Percent by volume
3.15	Cement	94.0	51.3	0.478	35.5
2.64	Sand	47.0	25.7	0.285	21.2
1.00	Water	33.0	18.0	0.529	39.3
2.78	Glass	9.2	5.0	0.053	3.9
Totals		183.2	100.0	1.345	100.0

*Also, 1.3 ml/lb of cement of water reducer was added. This equaled 122 ml (4 fl oz) of water reducer.

Characteristics:
Cement/sand ratio = 2/1 by weight.
Water/cement ratio = 0.35 by weight.

Table 2. E-PGFRC Composition 1.

Specific gravity	Ingredients‡	Weight, (lb)	Percent by weight	Volume (cu ft)	Percent by volume
3.15	Cement	94.0	60.6	0.478	41.2
2.65	Sand	18.8	12.1	0.114	9.8
1.00	Water*	20.9	13.5	0.335	28.9
1.12	Polymer solids†	12.2	7.9	0.174	15.0
2.55	E-glass	9.2	5.9	0.058	5.0
Totals		155.1	100.0	1.159	100.0

*Total water = Batch water plus water contained in polymer latex compound.
†Polymer solids = 48 percent by weight of the polymer latex compound.
‡Also, 1.3 ml/lb of cement of water reducer was added. This equaled 122 ml (4 fl oz) of water reducer.

Characteristics:
Cement/sand ratio = 5/1 by weight.
Water/cement ratio = 0.22 by weight.
Percent polymer solids = 15 percent by volume of total mix.
= 13 percent by weight of cement.
Percent E-glass = 5 percent by volume of total mix.

Mix Design

Mix properties for AR-GFRC panels are given in Table 1. Mix properties for E-PGFRC-1 and E-PGFRC-2 panels are given in Tables 2 and 3, respectively.

Materials

The following materials were used:

(a) Owens Corning AR-glass fiber (minimum of 16 percent zirconia and manufactured under license to Cem-FIL*) and PPG* E-glass fiber; both fiber types were chopped to about 1.5 in. (3.81 cm) in length.

(b) Type I portland cement.

(c) Washed silica sand with a maximum particle size of 0.02 in. (0.05 mm).

(d) Pozzolith 322-N* water reducing agent for AR-GFRC and unreinforced panels. Melment L-10A* superplasticizer for E-PGFRC panels.

(e) Forton* polymer latex (48 percent solids) used for E-PGFRC compositions.

Table 3. E-PGFRC Composition 2.

Specific gravity	Ingre-dients‡	Weight, (lb)	Percent by weight	Volume (cu ft)	Percent by volume
3.15	Cement	94.0	51.6	0.478	36.3
2.65	Sand	47.0	25.8	0.284	21.6
1.00	Water*	22.8	12.5	0.365	27.7
1.12	Polymer solids†	9.2	5.1	0.132	10.0
2.55	E-glass	9.1	5.0	0.057	4.3
Totals		182.1	100.0	1.316	100.0

*Total water = Batch water plus water contained in polymer latex compound.
†Polymer solids = 48 percent by weight of the polymer latex compound.
‡Also, 1.3 ml/lb of cement of water reducer was added. This equaled 122 ml (4 fl oz) of water reducer.
Characteristics:
Cement/sand ratio = 2/1 by weight.
Water/cement ratio = 0.24 by weight.
Percent polymer solids = 10 percent by volume of total mix.
= 9.8 percent by weight of cement.
Percent E-glass = 5 percent by volume of total mix.

Fabrication

Fabrication of GFRC composites was performed by the hand-sprayed, non-dewatered method. A thin "mist coat" of slurry was first sprayed onto the mold surface followed by a thin glass fiber layer applied over the mist coat. This was then rolled to ensure that the fibers were as close to the outer surface as possible. Layers of fresh GFRC were then deposited by simultaneously spraying slurry and chopped glass fibers. Approximately three layers were required to build a ⅜ in. thick specimen. The composite was rolled between layers. The board size was 36 x 48 x ⅜ in. (91 x 122 x 1 cm).

Curing

For AR-GFRC and the unreinforced companion specimens, the curing regime was divided into three periods:

1. After spray-up, the composites were covered with a plastic sheet and stored overnight at 73°F (23°C).

2. The next day, the composites were demolded and placed in a moist room at 73°F (23°C) and 100 percent relative humidity for 6 days.

3. After moist curing, the specimens were stored at 50 percent relative humidity and 73°F (23°C) for 20 days.

For E-PGFRC and the corresponding unreinforced matrix, the curing regime was divided into two periods:

1. After spray-up, composites were left uncovered overnight at 50 percent relative humidity and 73°F (23°C).

2. The next day, composites were demolded and stored at 50 percent relative humidity and 73°F (23°C) for 26 days.

Note that a dry environment is helpful for the polymer latex modified mortar compositions.[5] Polymer particles form films during drying. These polymer films reinforce the matrix as well as provide possible protection for the glass fiber strands.

After the 27-day curing period, speci-

* Use of trade names does not constitute an endorsement of the product.

mens were saw-cut. The dimensions for flexural specimens were 12 x 2 x ⅜ in. (30.5 x 5.0 x 1 cm) while those for tensile specimens were 12 x 1 x ⅜ in. (30.5 x 2.5 x 1 cm). The cut specimens were kept immersed in water at 73°F (23°C) until the 28th day.

Accelerated Aging

On the 28th day after spray-up, specimens were either tested (0-week aging) or placed into an accelerated aging environment. Accelerated aging was accomplished by immersing specimens in lime-saturated water at 122°F (50°C). Specimens were tested after storing in the accelerated environment for time periods ranging from 0 to 52 weeks. The complete test program is shown in Table 4.

Note that it has been reported that accelerated aging can simulate a natural weathering exposure.[6,7] For example, Litherland, et al.[6] have shown that a one-day immersion in water at 122°F (50°C) is equivalent to 101 days of natural weathering exposure in the United Kingdom (mean annual temperature 50.7°F (10.4°C).

The concept behind the accelerated aging test is based on many assumptions and has been established based on correlation with strength results from specimens exposed to actual long-term aging in an outdoor environment. It is possible that loss in strength involves different mechanisms than those for reduction in ductility. As a result, the time-temperature equivalence quoted earlier may not be applicable to toughness estimations.[8]

Test Procedure

For each age of storage, six flexural specimens were subjected to a third-point bending test (Fig. 1a). A constant crosshead speed was maintained at a rate of 0.9 in./min (2.3 mm/min) using a closed-loop servo-controlled hydraulic testing machine. The average deflection

Table 4. Test program.

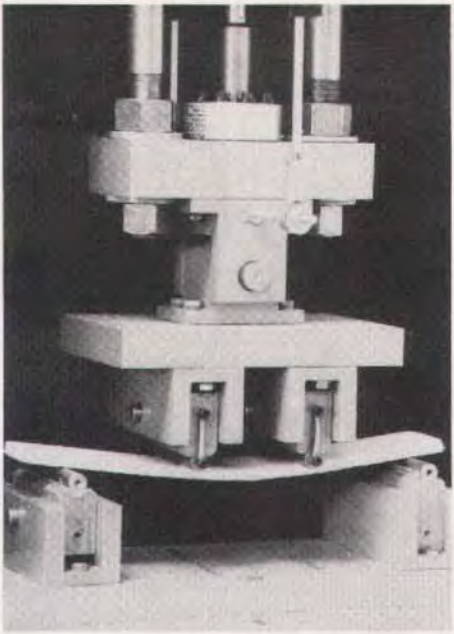
Glass type	Mix design*	Curing type†	Accelerated aging at 50°C									Type of test	No. of specimens
			0	1	4	8	12	17	26	39	52		
AR	C	A	X	X	X	X	X	X	X	X	X	F‡	54
None	C	A	X						X			F	12
E	CP1	B	X	X	X			X	X		X	F	36
None	CP1	B	X									F	6
E	CP2	B	X	X	X			X	X		X	F	36
None	CP2	B	X									F	6
E	CP1	B	X		X			X	X		X	T	30
E	CP2	B	X		X			X	X		X	T	30

*Mix design C is shown in Table 1.
Mix design CP1 is shown in Table 2.
Mix design CP2 is shown in Table 3.

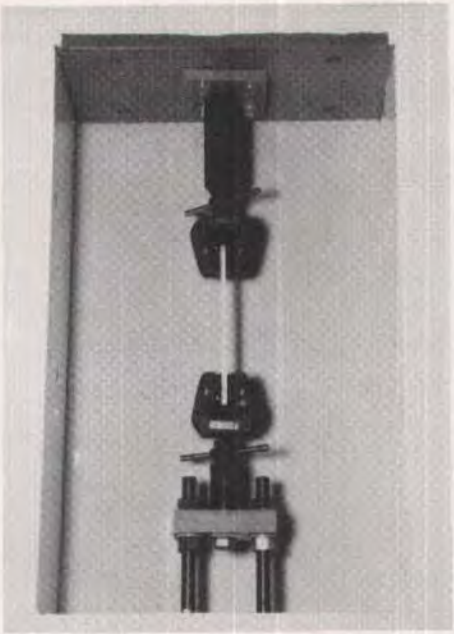
†Curing type A: 1 day covered by plastic.
6 days moist curing at 100 percent RH, 73°F.
20 days air stored at 50 percent RH, 73°F.
1 day soaked in water at 73°F.

Curing type B: 1 day left uncovered at 50 percent RH, 73°F.
26 days stored at 50 percent RH, 73°F.
1 day soaked in water at 73°F.

‡Six specimens were tested for each test type, three with smooth surface up and three with smooth surface down.



(a) Flexural test



(b) Tensile test

Fig. 1. Flexural test set-up (left) and uniaxial tensile test set up (right).

under loading points was recorded using a linear potentiometer.

Tensile tests were conducted at a constant elongation rate of 0.5 percent minimum, using a closed-loop servo-controlled hydraulic testing machine (Fig. 1b). Elongation was measured between the grips. The gage length was 8 in. (20.3 cm).

TEST RESULTS

A summary of the test results are given in Tables 5 through 9. A set of load vs. load-point deflection curves for AR-GFRC specimens stored under accelerated aging conditions for different time periods are shown in Fig. 2. Flexural stress at the extreme tensile fiber (for the section between the load points) was calculated, assuming elastic beam theory, for the load where the curve deviated from linearity (Proportional Elastic Limit — PEL also referred to as Flexural Yield, FY,[1] and for the maximum load (Modulus of Rupture — MOR also referred to as Flexural Ultimate, FU).

The calculation of MOR based on elastic beam theory is questionable for specimens tested at early ages. The average values of MOR and PEL for all three compositions are reported in Tables 5 through 7. The corresponding values of deflections are labeled the first crack deflection and peak deflection and are reported in Tables 5 through 7.

The value of deflection when the specimen finally fractures into two halves (that is, the deflection when the load becomes zero in the post-peak regime) is termed total deflection. These values are also shown in Tables 5 through 7. From the initial slope of the load-deflection curves, the modulus of elasticity was calculated and is reported in Tables 5 through 7.

A set of tensile load-elongation curves for E-PGFRC-1 is shown in Fig. 3. When the modulus of elasticity was calculated

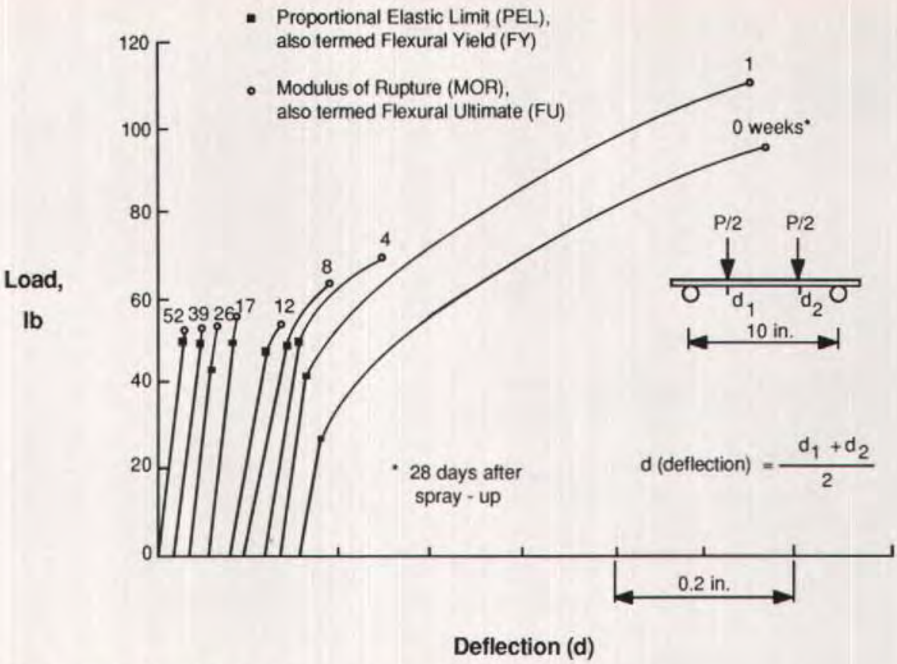


Fig. 2. Typical load-deflection curves for AR-GFRC in bending.

from the measured load-elongation curves, it was found to be substantially lower than the modulus of elasticity calculated for the corresponding specimens from the flexural test. It is likely that measured grip-to-grip elongation included not only the specimen deformation but also some slip between the specimen and the grips.

The plots shown in Fig. 3 were obtained by modifying the measured curves so that the modulus of elasticity values were identical to those observed for flexure. From the adjusted curves various quantities of interest were calculated (analogous to those mentioned for the bending test) and are reported in Tables 8 and 9.

Discussion of Strength Results

The relationship between the Proportional Elastic Limit (PEL) and the Modulus of Rupture (MOR) versus duration of accelerated aging is shown in Figs. 4 and 5 for AR-GFRC and E-PGFRC-1 compositions. For the sake of brevity only the plots for E-PGFRC-1 are shown; the results for E-PGFRC-2 showed a similar trend and are plotted in detail in Ref. 9.

It can be seen from Figs. 4 and 5 that, for both AR-GFRC and E-PGFRC compositions, values of MOR decreased with aging and approached that of the PEL. The PEL is approximately equal to the unreinforced matrix strength. This indicates that the strength contribution of fibers, which becomes effective only after matrix cracking (PEL), diminishes with aging.[2]

Various values of deflection for AR-GFRC and E-PGFRC-1 composites are shown in Figs. 6 and 7. It can be seen that the peak deflection decreased dramatically (the peak deflection for AR-GFRC specimens after 52 weeks of accelerated aging was only about 1/17th of the 28-day value) with aging for both types of composites. However, values of

Table 5. Summary of experimental results for AR-GFRC in bending.

Property	Accelerated aging period (weeks)								
	0	1	4	8	12	17	26	39	52
Proportional elastic limit (PEL), psi	1040	1405	1660	1730	1700	1640	1640	1735	1690
Relative value of PEL, percent	100.0	135.1	159.6	166.3	163.5	157.7	157.7	166.8	162.5
Modulus of rupture (MOR), psi	3500	3760	2330	2390	2060	1865	1945	1900	1840
Relative value of MOR, percent	100.0	107.4	66.6	68.3	58.9	53.3	55.6	54.3	52.6
Modulus of elasticity, ksi	2800	2700	2230	2340	2910	3400	3940	3420	3180
Toughness/cross-sectional area, lb/in.	63.04	44.14	10.93	6.57	3.49	1.07	1.37	1.65	1.15
First crack deflection, in.	0.019	0.025	0.036	0.037	0.031	0.021	0.021	0.025	0.026
Peak deflection, in.	0.505	0.347	0.129	0.091	0.055	0.026	0.026	0.028	0.029
Total deflection, in.	1.038	0.669	0.276	0.205	0.129	0.086	0.031	0.038	0.033
Relative value of total deflection, percent	100.0	64.53	26.68	19.75	12.43	8.29	3.02	3.69	3.22

Table 6. Summary of experimental results for E-PGFRC Composition 1 in bending.

Property	Accelerated aging period (weeks)					
	0	1	4	17	26	52
Proportional elastic limit (PEL), psi	1900	1765	1960	2140	1975	1770
Relative value of PEL, percent	100.0	92.9	103.1	112.6	103.8	93.1
Modulus of rupture (MOR), psi	4115	2950	2600	2845	2995	2625
Relative value of MOR, percent	100.0	71.7	63.2	69.1	72.8	63.7
Modulus of elasticity, ksi	1365	1645	1865	2225	2300	2560
Toughness/cross-sectional area, lb/in.	53.49	11.75	4.66	4.86	5.42	3.71
First crack deflection, in.	0.071	0.054	0.054	0.048	0.042	0.034
Peak deflection, in.	0.461	0.140	0.082	0.069	0.072	0.057
Total deflection, in.	0.531	0.149	0.082	0.078	0.078	0.062
Relative value of total deflection, percent	100.00	28.11	15.46	14.67	14.61	11.80

Table 7. Summary of experimental results for E-PGFRC Composition 2 in bending.

Property	Accelerated aging period (weeks)					
	0	1	4	17	26	52
Proportional elastic limit (PEL), psi	1700	1700	1660	2025	1725	1910
Relative value of PEL, percent	100.0	100.3	97.8	119.2	101.5	112.4
Modulus of rupture (MOR), psi	3680	2495	2365	2540	2560	2540
Relative value of MOR, percent	100.0	67.8	64.3	69.1	69.6	69.0
Modulus of elasticity, ksi	1820	1975	2090	2530	2720	3420
Toughness/cross-sectional area, lb/in.	47.87	7.96	4.21	3.64	3.39	2.75
First crack deflection, in.	0.050	0.043	0.405	0.044	0.032	0.029
Peak deflection, in.	0.432	0.102	0.067	0.061	0.056	0.043
Total deflection, in.	0.532	0.112	0.083	0.071	0.060	0.049
Relative value of total deflection, percent	100.00	20.99	15.69	13.34	11.25	9.29

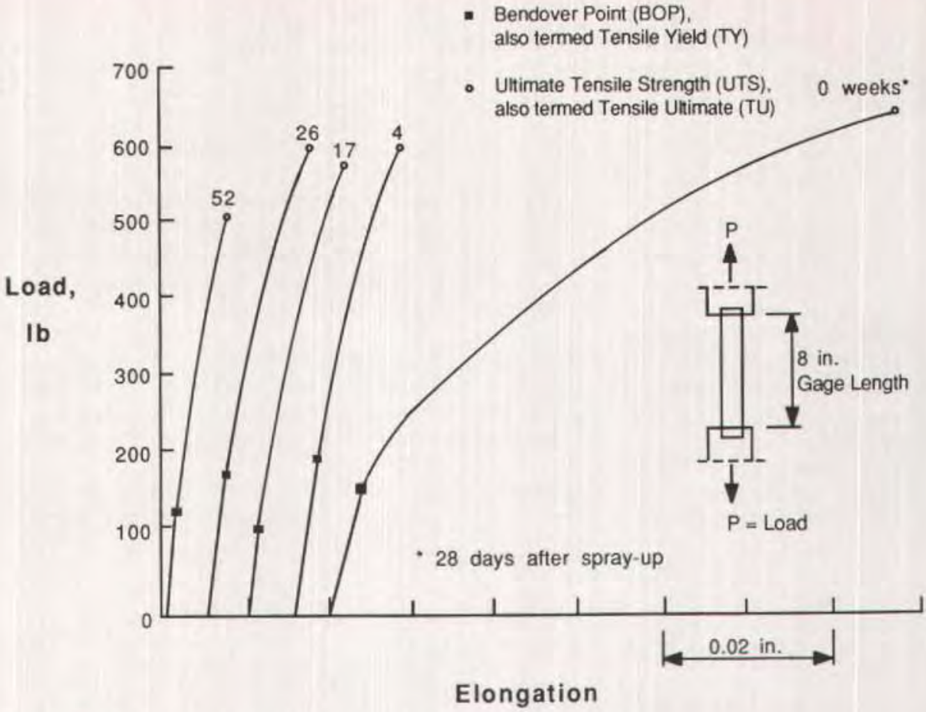


Fig. 3. Typical load-elongation curves for E-PGFRC-1 tension.

MOR as well as peak deflection for aged specimens for E-PGFRC composites are somewhat higher than those for AR-GFRC specimens (see also Tables 5 through 7).

Tensile strength results for the E-PGFRC compositions are plotted in Fig. 8. Both the ultimate tensile strength (UTS or tensile ultimate-TU) and values of stress at the proportional elastic limit (referred to as the Bend Over Point—BOP, or tensile yield—TY) are shown for the specimens subjected to various accelerated aging periods. It appears from this figure that neither the UTS nor the BOP is significantly altered by ac-

Table 8. Summary of experimental results for E-PGFRC Composition 1 in tension.

Property	Accelerated aging period (weeks)				
	0	4	17	26	52
Bend over point (BOP), psi	445	560	315	510	335
Relative value of BOP, percent	100.0	125.6	70.2	114.4	75.3
Ultimate tensile strength (UTS), psi	1740	1650	1510	1640	1355
Relative value of (UTS), percent	100.0	94.7	86.9	94.1	78.0
Modulus of elasticity, ksi	1365	1865	2225	2300	2560
First crack elongation, in.	0.003	0.002	0.001	0.002	0.001
Peak elongation, in.	0.066	0.013	0.011	0.012	0.007
Total elongation, in.	0.068	0.013	0.012	0.011	0.007
Relative value of total elongation, percent	100.00	18.92	18.04	16.28	9.68

Table 9. Summary of experimental results for E-PGFRC Composition 2 in tension.

Property	Accelerated aging period (weeks)				
	0	4	17	26	52
Bend over point (BOP), psi	485	530	515	330	360
Relative value of BOP, percent	100.0	109.3	106.2	68.1	73.9
Ultimate tensile strength (UTS), psi	1080	1050	1270	1335	1430
Relative value of (UTS), percent	100.0	97.0	117.4	123.5	132.2
Modulus of elasticity, ksi	1820	2090	2530	2720	3420
First crack elongation, in.	0.002	0.002	0.002	0.001	0.001
Peak elongation, in.	0.033	0.008	0.008	0.007	0.006
Total elongation, in.	0.032	0.014	0.010	0.008	0.007
Relative value of total elongation, percent	100.00	42.63	29.47	26.02	20.69

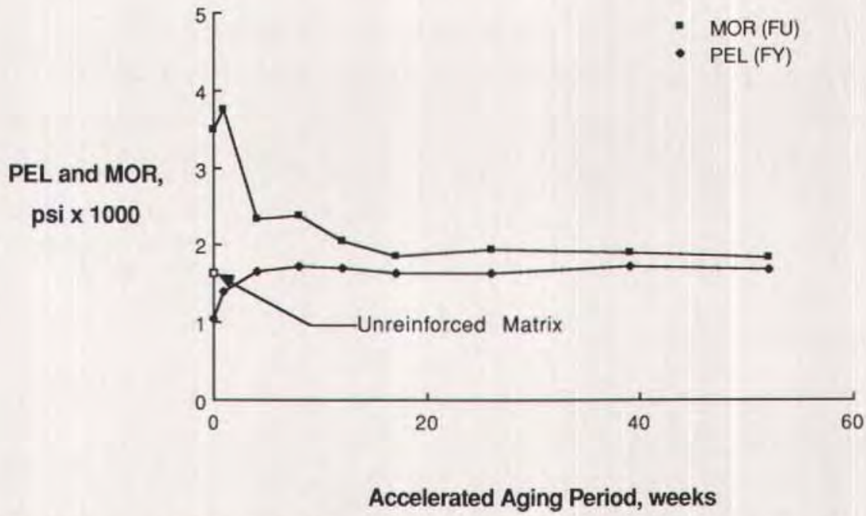


Fig. 4. PEL and MOR of AR-GFRC versus accelerated aging period at 122°F (50°C).

celerated aging. This is in contrast with the flexural response where there is a significant reduction in values of the MOR with aging (see Fig. 5).

This apparent contradiction can be understood by observing that although the peak tensile stress is not substantially reduced with aging, the peak tensile strain is reduced with aging (see Figs. 3 and 9). The MOR depends on not only the tensile strength but also on the tensile stress-strain curve. Therefore, the effect of a reduction in tensile strain capacity is a direct reduction in MOR.

To confirm this conclusion, theoretical MOR values were calculated from the observed tensile response. The observed tensile stress-strain curves (see Fig. 3) were approximated by two straight lines (from zero stress to BOP and from BOP to UTS). (The post-peak response was not included in the analysis for simplicity.) It was assumed that during bending, plane sections remain plane and that the compressive stress-strain curve is linear with the same modulus of elasticity as in tension. A comparison between the theoretically

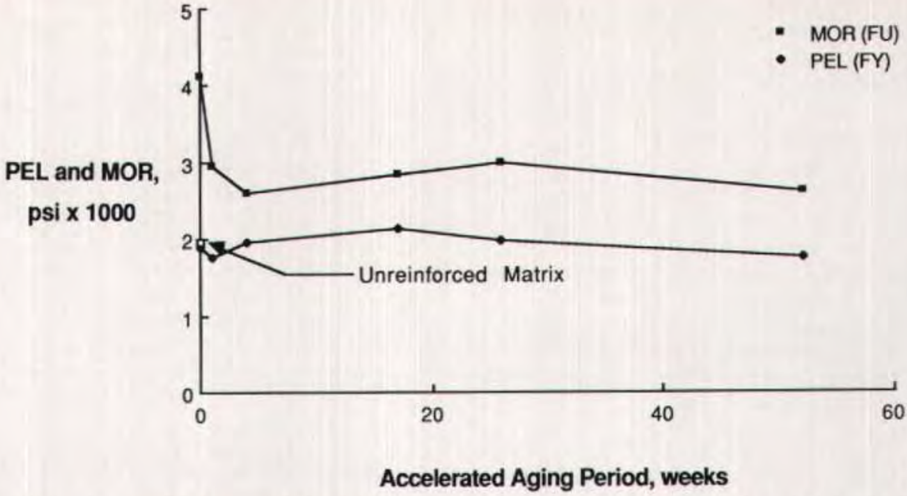


Fig. 5. PEL and MOR of E-PGFRC-1 versus accelerated aging period at 122°F (50°C).

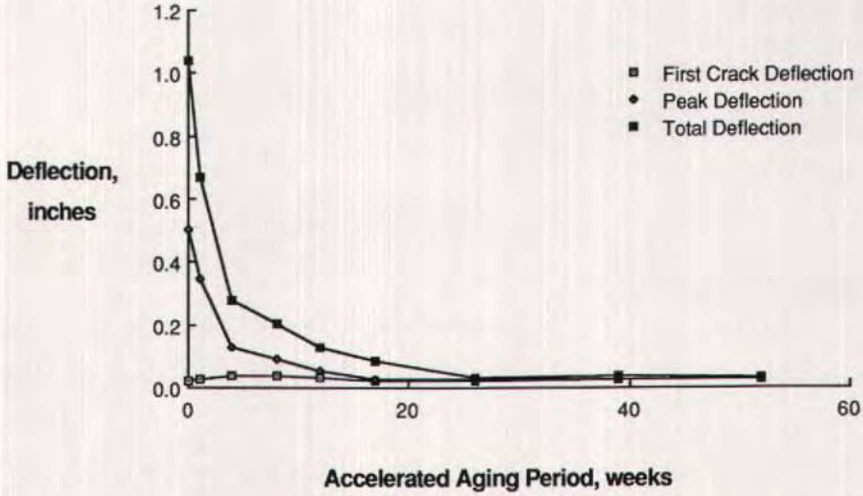


Fig. 6. Deflection of AR-GFRC in bending versus accelerated aging time at 122°F (50°C).

predicted maximum flexural load and the experimentally measured ones are shown in Fig. 10.

It can be seen that the theoretical values correlate quite well with the measured data. It should be noted that the assumption that only small deflections occur becomes less accurate at early ages, especially for unaged specimens which can exhibit quite large deflections. In addition, the assumption that, during a tensile test, strain is uniformly distributed over the 8 in. (20 cm) gage length is also questionable.[10] However, the principal point that the MOR values depend on both the tensile strength as well as the corresponding tensile strain is certainly valid.

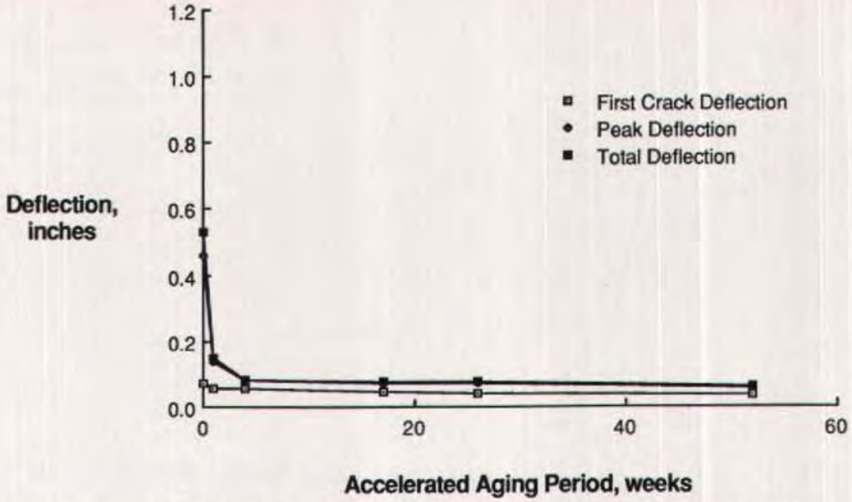


Fig. 7. Deflection of E-PGFRC-1 in bending versus accelerated aging period at 122°F (50°C).

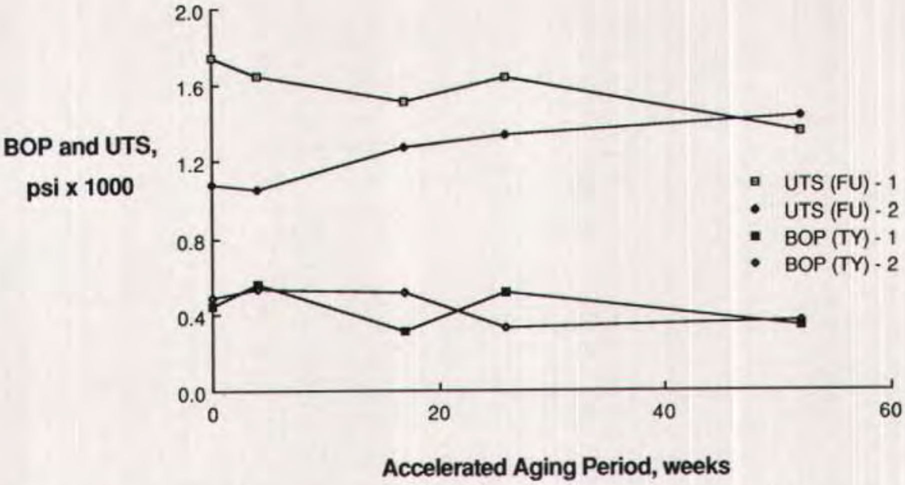


Fig. 8. BOP and UTS of E-PGFRC-1 and E-PGFRC-2 versus accelerated aging period at 122°F (50°C).

FLEXURAL TOUGHNESS INDICES

The preceding presentation has pointed out that to evaluate the effect of aging, one must consider not only strength but also ductility. Aging of GFRC panels in a moist environment causes them to become less ductile.

One common method to assess ductility (or brittleness) is evaluation of toughness. Flexural toughness is generally defined as area under the load-deflection curve observed during a bending test. The area under the load-deflection curve from the initial zero load to the final zero load (that is, up to the total deflection value) represents the

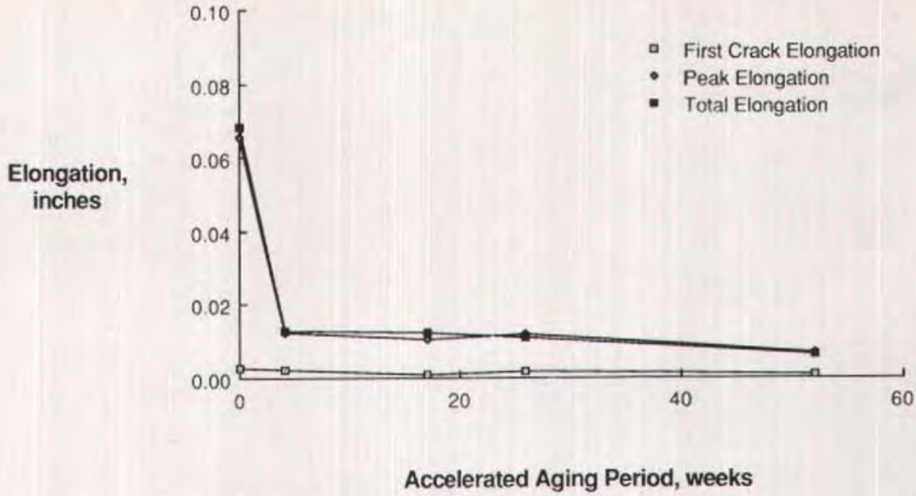
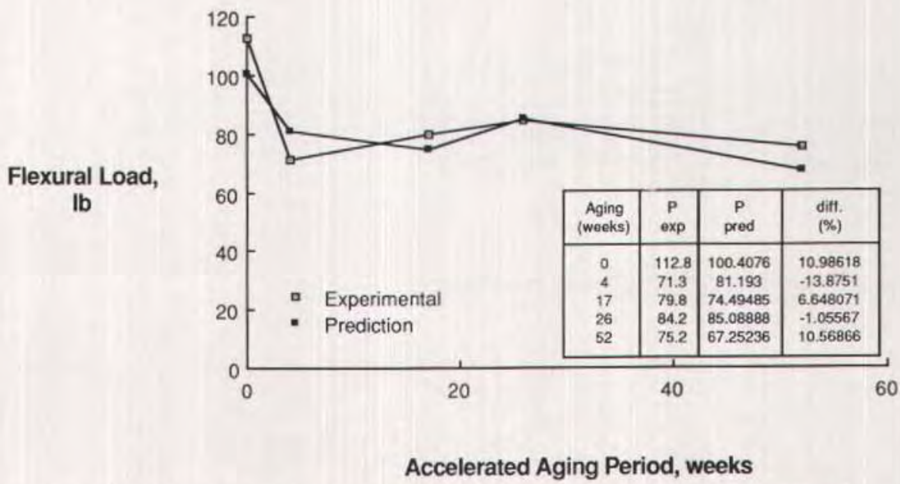


Fig. 9. Elongation of E-PGFRC-1 in tension versus accelerated aging period at 122°F (50°C).



Aging (weeks)	P exp	P pred	diff. (%)
0	112.8	100.4076	10.98618
4	71.3	81.193	-13.8751
17	79.8	74.49485	6.648071
26	84.2	85.08888	-1.05567
52	75.2	67.25236	10.56866

Fig. 10. Flexural load prediction (using tensile data) and experimentally measured flexural load for E-PGFRC-1 at different aging periods at 122°F (50°C).

external work done. This total area divided by the cross-sectional area of the beam is a measure (assuming a single fracture plane) of fracture toughness of the material.

Values of flexural toughness are reported in Tables 5 through 7 for the flexural specimens. Since the bending test is recommended for quality control of GFRC panels,[1] only flexural toughness is discussed here.

The relationships between toughness and aging for AR-GFRC composites, companion unreinforced matrix, and E-PGFRC composites are plotted in Fig. 11. It can be seen that the tough-

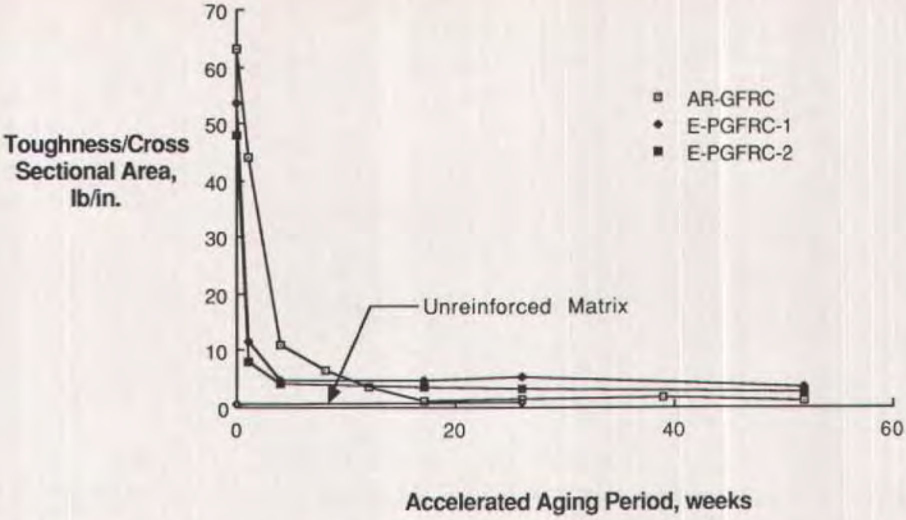


Fig. 11. Toughness/cross-sectional area of AR-GFRC and companion unreinforced matrix, E-PGFRC-1, and E-PGFRC-2 versus accelerated aging period at 122°F (50°C).

ness of AR-GFRC composites after 28 days of curing (before accelerated aging) is about 65 times that of unreinforced matrix. In contrast, after 52 weeks of aging the toughness drops to a value equal to nearly that of unreinforced matrix. It is clear that this dramatic (about 1/60th of the unaged value) drop in toughness is at least as important an indicator of aging as the reduction in strength (about one-half the unaged value).

ASTM Toughness Indices for Steel Fiber Reinforced Concrete

The flexural toughness value determined as defined above may be dependent on the type of test (center-point vs. third-point bending test), type and dimensions of specimen, and type of testing system. Thus, it is desirable to normalize the toughness value. Based on needs for steel fiber reinforced concrete, ASTM Designation: C1018-85 has adopted a set of toughness indices based on work by Johnston.[11] The ASTM definition of toughness index can be illustrated by considering toughness index I_5 which is defined as follows (see Fig. 12):

$$I_5 = \frac{\text{load-deflection area up to three times the deflection at first cracking}}{\text{area up to deflection at first cracking}}$$

If the load-deflection curve were elastic-perfectly plastic, then $I_5 = 5$, as shown in Fig. 12. Similarly, I_{10} and I_{30} are calculated using the area up to 5.5 times and 15.5 times the first crack deflection, respectively, in the numerator. For the ASTM adopted toughness index, the toughness is normalized with respect to the toughness value approximately corresponding to that of the plain matrix (area up to the first crack deflection). Therefore, the effects of specimen type and dimensions are minimized.

These three toughness indices are plotted for AR-GFRC tested after various aging periods in Fig. 13. It can be seen that toughness indices I_5 and I_{10} are not as meaningful as I_{30} in showing the extent of property degradation due to accelerated aging. A toughness index based on a higher deflection value such as I_{50} would have been better than I_{30}, since, for the unaged AR-GFRC speci-

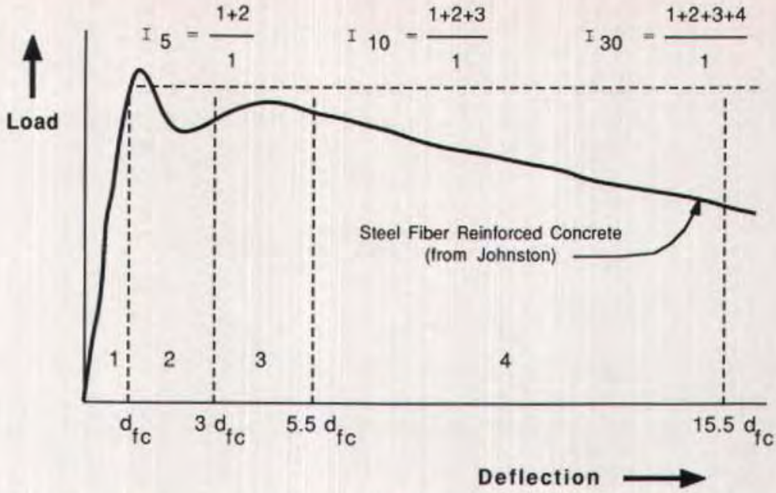


Fig. 12. Toughness indices according to ASTM Designation: C1018-85 adopted from Johnston (base unity system).

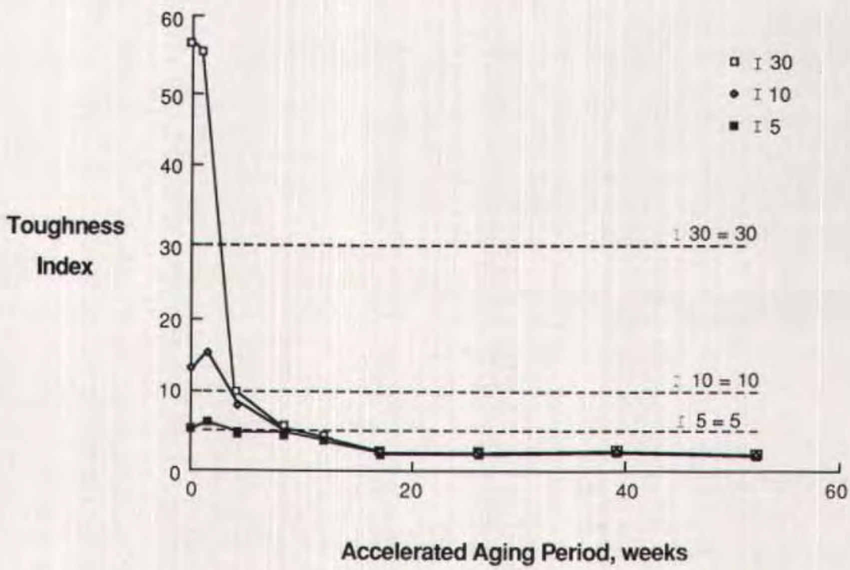


Fig. 13. I_5, I_{10}, and I_{30} for AR-GFRC in bending versus accelerated aging period at 122°F (50°C).

mens, the peak deflection was approximately 25 times the first crack deflection (see Table 5).

It should be noted that the ASTM toughness indices I_5, I_{10}, and I_{30} were developed for cases where the area beyond the peak load provides the major contribution to the toughness value (see Fig. 12). For the unaged GFRC composites, in contrast, the area prior to the peak load provides the greatest contribution.

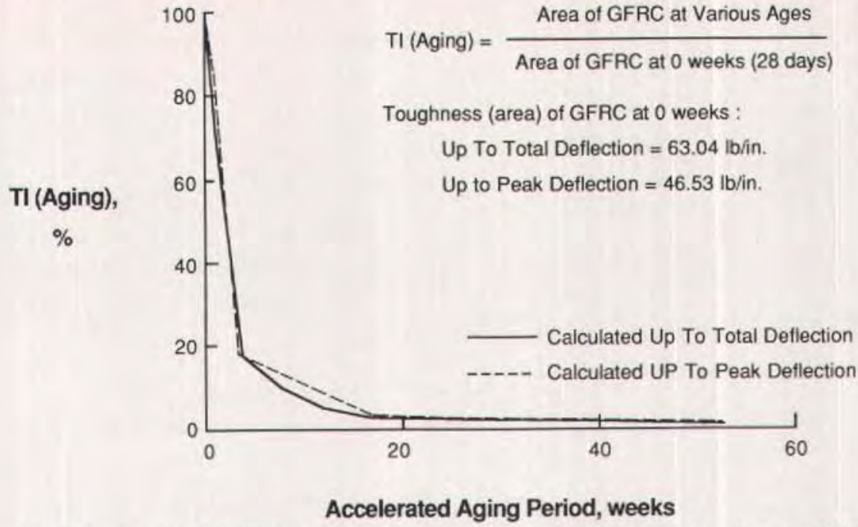


Fig. 14. TI (aging) for AR-GFRC in bending versus accelerated aging period at 122°F (50°C).

Two Proposed Toughness Indices for GFRC

Two toughness indices which seem more appropriate for GFRC are proposed. They are TI (aging) and TI (improvement).

The value for TI (aging) is defined as the area under the complete load deflection curve for GFRC at a given accelerated aging period divided by the complete area for the unaged (28 days after spraying) GFRC specimen. Values of TI (aging) at various accelerated aging periods for AR-GFRC and E-PGFRC-1 are plotted as a solid line in Figs. 14 and 15, respectively. The plot indicates that TI (aging) decreased from 100 percent to as low as 2 percent as a result of accelerated aging.

Note that since the denominator is constant for a given composition, if that value is reported, then the absolute value of the toughness can be easily calculated from the proposed toughness index values. For GFRC composites (especially at early ages) the area up to the peak deflection offers the major contribution to the toughness value. Therefore, this area can be used in calculating the proposed toughness index rather than the total area. Values of TI (aging), calculated using the area up to the peak deflection (for both numerator and denominator), are plotted as a dashed line in Figs. 14 and 15. The two plots (solid lines and dashed lines) compare very closely.

The value for TI (improvement) is defined as the area under the complete load-deflection curve of GFRC at a given accelerated aging period divided by the area under the complete load-deflection curve of the unreinforced matrix at zero accelerated aging (that is, 28 days after spraying). Values of TI (improvement) are shown in Fig. 16 for AR-GFRC and E-PGFRC-1.

Note that TI (improvement) represents the relative toughness improvement for GFRC over that for the unreinforced matrix.

If the value for the unreinforced matrix is unavailable, then one could substitute the area up to the first cracking deflection obtained from the load-deflection curve of the unaged GFRC composite.

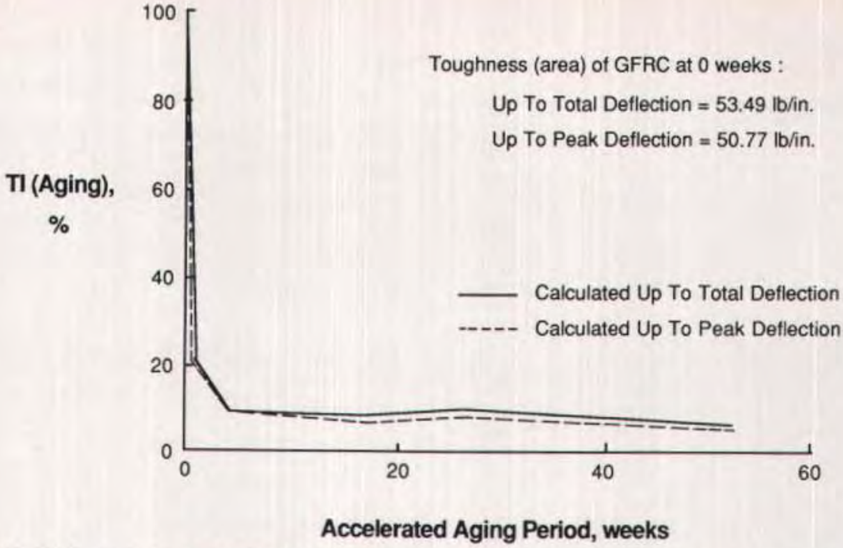


Fig. 15. TI (aging) for E-PGFRC-1 in bending versus accelerated aging period at 122°F (50°C).

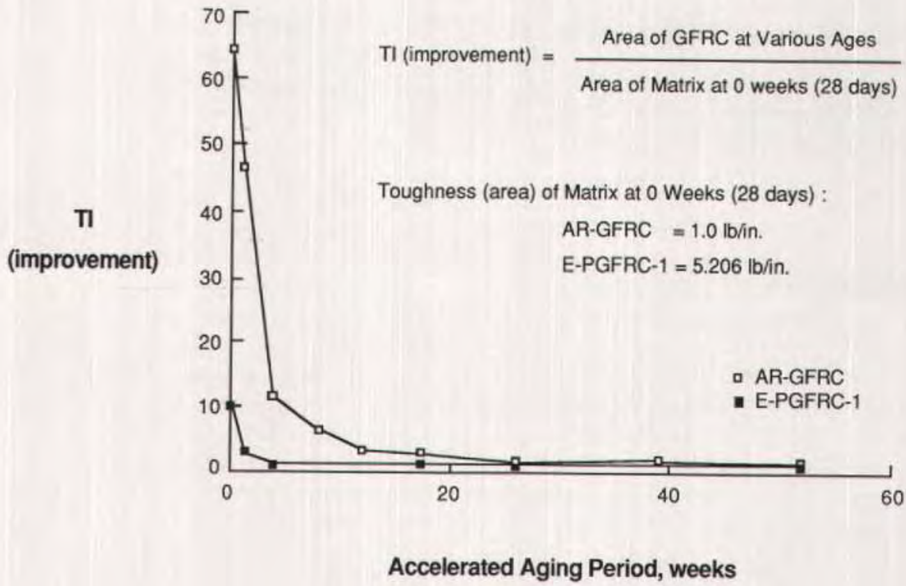


Fig. 16. TI (improvement) for AR-GFRC and E-PGFRC-1 in bending versus accelerated aging period at 122°F (50°C).

CONCLUSIONS

1. GFRC composites fabricated with commonly used alkali resistant glass fibers and composites fabricated with E-glass fibers in combination with a polymer latex modified matrix show a reduction in flexural strength and toughness when exposed to an accelerated aging environment.

2. Modulus of rupture for GFRC composites after 52 weeks of accelerated aging (fully aged) is about one-half of the corresponding value for unaged composites. The toughness value for the fully aged composite is as small as 1/60th of that for the unaged composite. This indicates that any possible improvement in long-term performance of GFRC should be based on both strength and toughness measurements of composites subjected to an accelerated aging environment.

3. To properly and rationally evaluate the toughness (that is, ductility or brittleness) of GFRC, two toughness indices are proposed. TI (aging) is a toughness index representing the toughness of an aged composite relative to an unaged composite. TI (improvement) is a toughness index representing the toughness improvement provided by the fibers after a specified aging period.

4. Both of these toughness indices can be easily evaluated from flexural tests currently being performed for quality control of GFRC panels.

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REFERENCES

1. PCI Committee on Glass Fiber Reinforced Concrete Panels, "Recommended Practice for Glass Fiber Reinforced Concrete Panels," PCI JOURNAL, V. 26, No. 1, January-February 1981, pp. 25-93.
2. *Proceedings — Durability of Glass Fiber Reinforced Concrete Symposium*, Edited by Sidney Diamond, Prestressed Concrete Institute, Chicago, Illinois, November 1985.
3. Daniel, J. I., "Long-Term Strength Durability of Forton Polymer Modified Glass Fiber Reinforced Concete," Report to Forton, Inc., Submitted by Construction Technology Laboratories, A Division of the Portland Cement Association, Skokie, Illinois, May 1984.
4. Daniel, J. I., and Schultz, D. M., "Durability of Glass Fiber Reinforced Concrete System," *Proceedings — Durability of Glass Fiber Reinforced Concete Symposium*, Prestressed Concrete Institute, Chicago, Illinois, November 1985, pp. 174-198.
5. Yannas, S., and Shah, S. P., "Polymer Latex Modified Mortar," *ACI Journal*, V. 69, No. 1, January 1972, pp. 61-65.
6. Litherland, K. L. Oakley, D. R., and Proctor, B. A., "The Use of Accelerated Aging Procedures to Predict the Long-Term Strength of GRC Composites," *Journal Cement and Concrete Research*, V. 11, 1981, pp. 455-466.
7. Proctor, B. A., Oakley, D. R., and Litherland, K. L., "Development in the Assessment and Performance of GRC over 10 Years," *Journal of Composites*, April 1982, pp. 173-179.
8. Litherland, K. L., "Test Methods of Evaluating Long Term Behavior of GFRC," *Proceedings — Durability of Glass Fiber Reinforced Concrete Symposium*, Edited by Sidney Diamond, Prestressed Concrete Institute, Chicago, Illinois, November 1985.
9. Ludirdja, D., "Durability and Fiber Orientation Effect of Glass Fiber Reinforced Concrete," MS Thesis, Northwestern University, Evanston, Illinois, 1986 (under the supervision of Prof. S. P. Shah).
10. Gopalaratnam, V. S., and Shah, S. P., "Tensile Failure of Steel Fiber Reinforced Mortar," to be published in *Journal of Engineering Mechanics Division*, ASCE.
11. Johnston, C. D., "Definition and Measurement of Flexural Toughness Parameter for Steel Fiber Reinforced Concrete" *Cement, Concrete, and Aggregates*, CCAGDP, V. 4, No. 2, Winter 1982, pp. 53-60.