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Postcrack creep of polymeric fiber-reinforced concrete in flexure

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Abstract

Results of an experimental investigation of the creep-time behavior of polypropylene and nylon fiber-reinforced concrete (FRC) are presented. Gravity loads were applied in flexure to precracked low volume fraction (0.1%) polypropylene and nylon FRC beams. Beams were tested at a range of stress levels to produce three outcomes: load sustained indefinitely (low stress), creep failure (intermediate stress), and rapid failure (high stress). Emphasis was placed on determining the maximum flexural stress that is sustainable indefinitely. The results indicate that polypropylene FRC has higher initial strength but nylon FRC can sustain a higher stress level. For both groups the sustainable stress is much lower than the postcrack strength.

Keywords: Fiber reinforcement; Polymers; Creep; Mechanical Properties; Sustained loading

1. Introduction

Low-modulus fibers such as polypropylene and nylon have been shown to be effective in reducing cracking during plastic shrinkage even at low volume fractions (~0.1%). Their effectiveness in reducing cracking during plastic shrinkage is well documented and widely accepted [1,2]. Because of their effectiveness during plastic shrinkage and low additional cost, polymeric fibers are now routinely added to concrete. It was reported in 1997 that 10% of all ready-mixed concrete in the United States contained polypropylene fibers [3].

In addition to plastic shrinkage crack reduction, polymeric fibers are also reported to improve the mechanical properties of concrete [4–9]. Research has shown that low-volume fractions (~0.1%) of polypropylene fibers bring about statistically significant improvements in flexural toughness, impact resistance, and fatigue performance. Alhozaimy et al. [4] found a 44% increase in flexural toughness and a 48% increase in impact resistance with the addition of 0.1% polypropylene fibers. Tawfiq et al. [7] reported that 0.1% polypropylene fibers were sufficient to delay the initiation of crack formation during cyclic fatigue by 67%. At much larger volume fractions (~1%) it has been reported that shear strengths can be improved by the addition of fibers [3].

Engineering practice has not made use of the fact that polymeric fibers enhance the mechanical properties of concrete. These mechanical benefits cannot be used in design until all of their properties are fully understood. Research has been presented on toughness, impact resistance, and fatigue resistance. Additional benefits of polymeric fiber-reinforced concrete (FRC) have been found with respect to improved environmental durability [10,11]. New applications for polymeric FRC are also being studied [12,13]. To date, no research has been conducted on the long-term behavior of polymeric FRC under sustained loads. Since polymeric fiber behavior is viscoelastic, the cracks that occur can be expected to widen considerably under sustained loads. Hence, an investigation was initiated to study the creep-time behavior of cracked beams under sustained loading.

2. Experimental program

The experimental program was designed to evaluate the time-dependent performance of concrete containing two polymeric fibers: polypropylene and nylon 6. Both fibers were 19 mm long (0.75 inches). The polypropylene fibers were fibrillated, whereas the nylon fibers were made of a single filament. The fibers were added at a dosage of 0.9 kg/m^3 (1.5 lb/$yard^3$) to represent the typical usage in the field, a volume fraction of 0.10% and 0.08% for polypropylene and nylon, respectively. The load levels were chosen to produce rapid, creep, or no failure.

The time-dependent properties of the fibers can be estimated by considering the typical properties of polypropylene and nylon 6 [14]. The tensile elastic moduli of polypropylene and nylon are estimated to be 1,800 and 2,000 MPa,

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Table 1
Mix proportions

Component	Proportion (kg/m^3)
Portland cement (ASTM Type I)	340
Natural sand	804
Crushed stone (9.5 mm maximum size)	1,033
Potable water	130
Air entraining admixture	0.13
High range water reducing admixture	10.77
Fibers	0.9

respectively. The tensile creep moduli at 1,000 h are estimated to be 1,350 and 350 MPa, respectively. From this data, it is expected that polypropylene fibers will creep at a higher rate than nylon fibers.

2.1. Materials and methods

The mix proportion for concrete was the same for both groups and is presented in Table 1. The constituent materials were ASTM Type I cement, concrete sand, coarse aggregate with a maximum size of 19 mm, tap water, admixtures, and fibers. The concrete was mixed in the laboratory using a 9 ft^3 (0.25 m^2) capacity rotating drum mixer. Both groups had a 25-mm (1 inch) slump and 5% air, measured by the volumetric method.

2.2. Specimens

Twelve beams (100 × 100 × 350 mm; 4 × 4 × 14 inches) were cast for each fiber type, along with five cylinders (150 × 300 mm; 6 × 12 inches) cylinders. The cylinders were used for compressive strength tests and the beams were tested for postcrack load-deflection behavior and time-dependent postcrack load-deflection behavior.

After 24 h, the specimens were removed from the molds and cured for 27 days in a room maintained at 70°F and 100% humidity.

2.3. ASTM C 1399

The new ASTM standard C 1399 *Test Method for Obtaining Average Residual-Strength of Fiber Reinforced Concrete* was introduced in 1998 [15]. This new flexural test specifies the best method of obtaining the postcrack reloading curve and the residual strength of the FRC beam. Residual strength refers to postcrack flexural strength of the test beam. It is not a true stress, but an engineering stress that is computed by using the flexural formula for linear elastic materials. It is a parameter that may be used to evaluate the effectiveness of different fiber types, mix designs, and fiber contents. This new test is similar in design and use to the older C 1018 *Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete* [16]. The major difference between the tests is that in the old test the beam is loaded continuously to failure, whereas in the new test load is applied in two stages. The first stage is a cracking stage and is intended to gently crack the beam while controlling the rate of postcrack deflection and thereby minimizing fracture damage. This is accomplished by loading the beams while supported by a steel plate (Fig. 1). No measurements are made during this first stage. The second stage consists of reloading the cracked beam while recording loads and deflections in a manner similar to C 1018.

After precracking, two beams from each group were re-

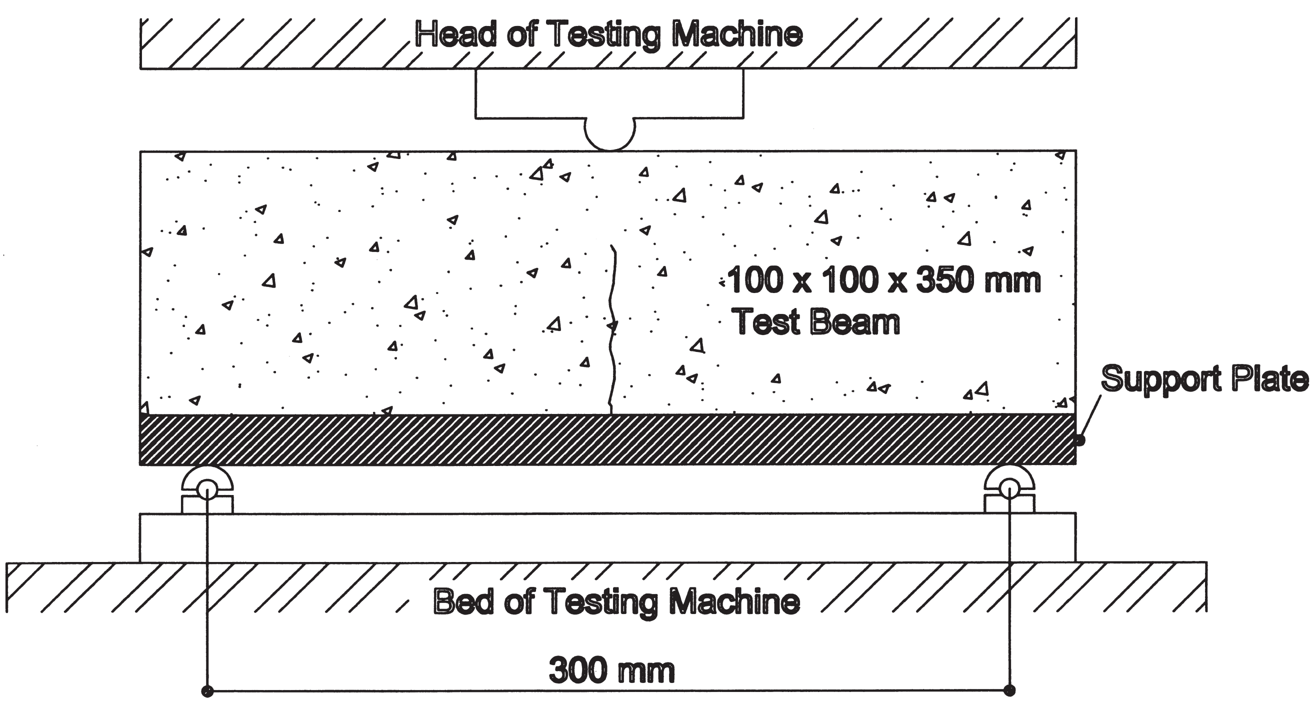

Fig. 1. ASTM C 1399 precracking setup.

loaded in four-point flexure. Midspan deflections were measured with a mechanical dial gage having a resolution of 0.0025 mm. The dial gage was mounted to a support yoke, a rigid frame fastened to the test beam at the supports. Because the support yoke is fastened to the beam at a point over its supports, displacements caused by seating or twisting of the specimen are minimized. Loads were measured using a proving ring with a capacity of 2,224 N and a resolution of 0.4 N. Two beams reloaded in bending were tested until failure, with load and deflection readings taken every 0.127 mm. Following ASTM C 1399, the loads P_A, P_B, P_C, and P_D at deflections of 0.50, 0.75, 1.00, and 1.25 mm are used to compute the average residual strength using Eq. (1):

$$\mathrm{ARS} = \frac{(P_A + P_B + P_C + P_D)}{4} \times k \tag{1}$$

Where:

$k = L/bd^2$, mm^{-2}
ARS = average residual strength, MPa
$P_A + P_B + P_C + P_D$ = sum of recorded loads at specified deflections, N
L = span length, mm
b = average width of beam, mm, and
d = average depth of beam, mm

2.4. Creep tests

The creep tests were performed on precracked beams that were further loaded to a deflection of 0.75 mm. All the creep tests were performed at a temperature of 20° C and relative humidity of about 50% [17]. The creep test setup shown in Fig. 2 consisted of a clamped support at one end and gravity loads at the other end. The load was applied using a cantilever mechanism with a 7:1 mechanical advantage [18]. The weights were carefully applied over a period of about 10 s to reduce sudden impact. The applied weight was different for each beam and ranged from 22% to 88% of the average residual strength (ARS).

The upward deflection of the cantilever test beam was measured by a mechanical dial gage with resolution of 0.00254 mm. Readings were taken at 1-min intervals for the first hour, followed by every hour for 24 h, and every 4 to 8 h for the remaining test duration in most cases. In cases of creep failure, reading frequency was increased prior to failure to intervals as short as 1 min.

Creep deformations are presented in terms of rotation instead of deflections because rotation is independent of size and scale. The distance a between the load point and crack was measured for each specimen (Fig. 2) to express creep deformation in terms of its rotation, as seen in Eq. (2):

$$\theta = \frac{\delta}{a} \tag{2}$$

Where

θ = creep rotation, in radians
δ = creep deformation, measured at the load point, in mm
a = distance from load point to the crack, in mm

3. Results and discussion

3.1. Compressive strength

Five cylinders were sulfur-capped and tested in compression according to ASTM C 39. The average compressive

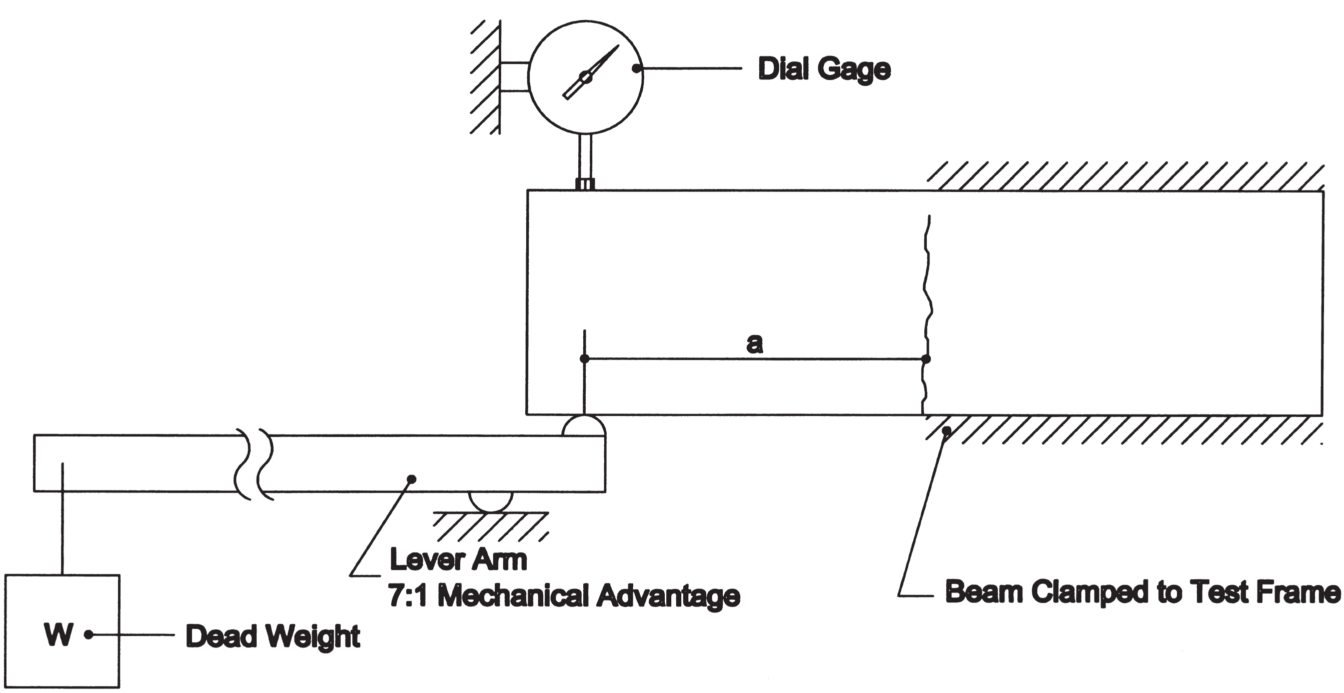

Fig. 2. Creep test setup.

Table 2
Polypropylene FRC test summary

Beam #	Long-term applied stress (kPa)	Fraction of average residual stress (%)	Test outcome
1	–	–	ASTM C1399
2	–	–	ARS = 275 kPA
3	61.4	22.3	Load sustained
4	64.6	23.5	Load sustained
5	68.5	24.9	Load sustained
6	69.8	25.4	Creep failure: 34,920 min
7	90.5	32.9	Creep failure: ~2 min
8	134.5	48.9	Creep failure: <1 min
9	182.9	66.5	Rapid failure
10	190.0	69.1	Rapid failure
11	237.2	86.3	Rapid failure

strength of the polypropylene group was 61 MPa with a standard deviation of 2.25 MPa. The average compressive strength of the nylon group was 64 MPa with a standard deviation of 1.59 MPa. The differences in compressive strength are not considered important because it is not a critical variable in this experiment.

3.2. Residual flexural strength

The average residual strengths for the two polypropylene samples were 247 and 302 kPa, respectively, and the average residual strengths for the two nylon samples were 169 and 223 kPa, respectively. The average ARS and range of 275 and 55 kPa for the polypropylene group and 196 and 54 kPa for the nylon group are consistent with the precision statements found in C 1399, which indicate an acceptable range of two results to be 280 kPa when the ARS is 500 kPa.

3.3. Creep study

A summary of the creep study can be found in Tables 2 and 3. The test outcomes are divided into three groups: rapid failure, creep failure, and load sustained (no failure). Load sustained refers to samples that reached a condition of zero or negligible rate of creep and remained in this state indefinitely, without failure.

Table 3
Nylon FRC test summary

Beam #	Long-term applied stress (kPa)	Fraction of average residual stress (%)	Test outcome
1	–	–	ASTM C1399
2	–	–	ARS = 196k Pa
3	69.2	35.3	Load sustained
4	74.3	37.9	Load sustained
5	75.0	38.3	Load sustained
6	76.9	39.2	Creep failure: 162 min
7	76.9	39.2	Creep failture: ~2 min
8	84.0	42.9	Creep failure: 7,605 min
9	104.7	53.4	Rapid failure
10	127.3	64.9	Rapid failure
11	144.8	73.9	Rapid failure
12	173.2	88.4	Rapid failure

3.3.1. Samples that failed under sustained loading (rapid failure and creep failure)

Rapid failure occurred when the fraction of creep load was high as shown in Tables 2 and 3. Failures were time-dependent and occurred at loads lower than needed to produce monotonic failure. Failures occurred within several seconds of load application. Because the gravity load was applied very slowly, the difference between start and failure time was insignificant. The time to failure was unquantifiable and it is on this basis that the distinction is made between rapid failures and creep failures.

Creep failures occurred at lower loads than rapid failures. These time-dependent failures proceeded slowly enough so that the time to failure was quantifiable. Six failures of this type occurred with equal number from each fiber group. Failures occurred in as little time as 1 min and as much time as 25 days.

Three creep failures proceeded slowly enough to provide meaningful creep-time data, two from the nylon group and one from the polypropylene group. The behavior of these specimens can be described in terms of conventional creep-time curve shown in Fig. 3. The conventional creep curve comprises three stages: primary, secondary, and tertiary. Such curves commonly describe the high temperature behavior of metals. In different functional forms, the general shape of these curves also describes the viscoelastic behavior of polymeric materials. The three stages are described as:

A. Primary: a period of decreasing creep rate.
B. Secondary: a period of nearly constant creep rate. In tests that do not end in failure, this is the final stage.

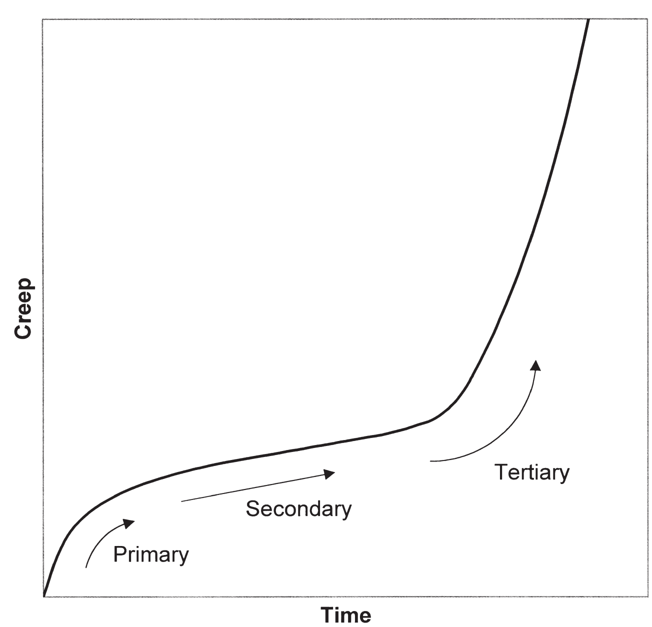

Fig. 3. A typical creep-time curve.

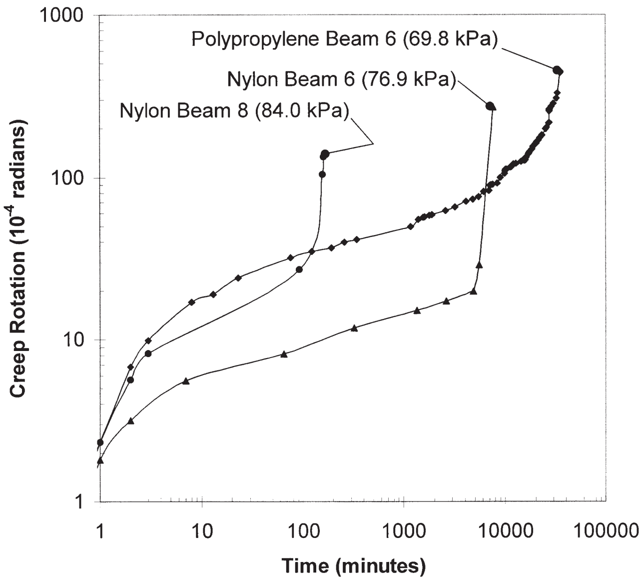

Fig. 4. Creep-time response of beams that failed in creep failure.

C. Tertiary: a period of increasing creep rate, prior to failure.

The creep-time responses of three creep failure specimens are presented in Fig. 4. All of the beams have the familiar creep stages: primary, secondary, and tertiary. The polypropylene and nylon fibers provide similar curves. The creep rates during each creep stage appear to be comparable for each test. The only noticeable difference between the polypropylene and nylon groups is that the nylon tests exhibit a sharp and sudden transition from secondary to tertiary stages, while this transition is smooth for beams with polypropylene fibers.

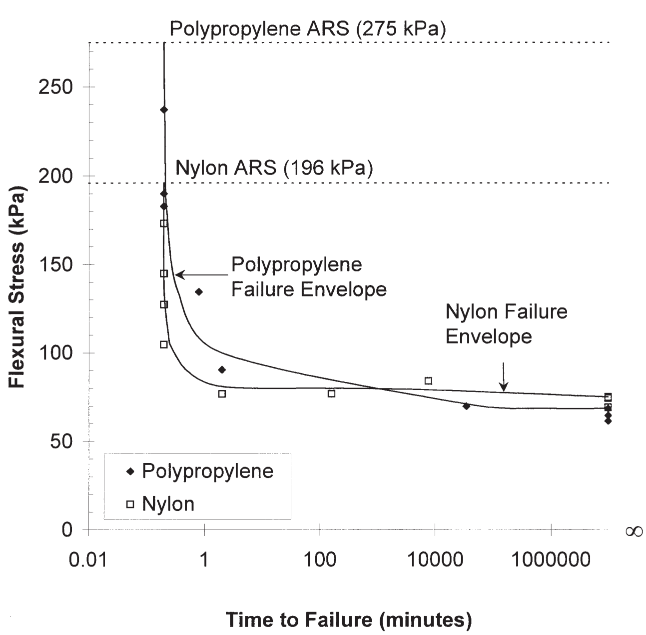

Fig. 5. Time-dependent failure envelopes for polypropylene and nylon FRC.

Time-dependent failure envelopes can be constructed by plotting time to failure vs. the applied flexural stress as shown in Fig. 5. The failure envelope represents the best estimate of failure stress for a given time of exposure. Stresses that fall above the envelope result in failure and stresses that fall below the envelope are sustainable. The left side of Fig. 5 indicates the monotonic strength limits of each group, delineated by the ARS of the fiber group. In the short term, the best estimate of failure for the polypropylene group is the ARS, 275 kPa. The best estimate of short-term failure of the nylon group is its ARS, 196 kPa.

The right side of the graph indicates the long-term strength limits, the maximum stress that is sustainable indefinitely. For the polypropylene group the maximum sustainable stress is estimated to be 68.5 kPa and for the nylon group this stress limit is estimated to be 75.0 kPa.

3.3.2. Sustainable creep

Sustainable creep occurred in beams 3, 4, and 5 of both fiber groups (Table 4). All of these beams exhibited substantial creep deformation prior to the creep rate diminishing to zero. For the polypropylene group, the highest stress for which the load was sustained indefinitely was 68.5 kPa. For the nylon group, the highest stress sustained was 75.0 kPa.

Fig. 6 shows the creep-time response of nylon FRC beams that did not fail. These creep-time curves can be compared with the traditional curve of Fig. 3 for the first two stages. All three generally exhibit primary creep for between 103 and 1,242 min. The transition from primary to secondary creep is very distinct in the samples containing nylon fibers, characterized by an almost instantaneous drop in creep rate to zero or a negligible level. Though the nylon curves closely resemble the conventional creep curves, close examination of Figs. 6a and 6c shows that the primary portion of the curve is bilinear, with the change in slope occurring at a rotation of 10×10^{-4} radians.

Fig. 7 shows the creep-time response for the polypropy-

Table 4
Sustainable creep summary

Beam #	Total creep time[a] (min)	Total creep rotation[b] (10^{-4} radians)	Average creep rate[c] (10^{-6} radians/min)
(a) Polypropylene FRC beams that sustained load indefinitely			
3	9,959	10.12	0.10
4	6,977	9.41	0.13
5	26,378	38.88	0.15
(b) Nylon FRC beams that sustained load indefinitely			
3	1,242	28.85	2.32
4	103	7.67	7.45
5	530	36.60	6.91

[a] Time required to reach a negligible creep rate.
[b] Creep rotation at the time negligible creep rate is reached.
[c] Total creep rotation/total creep time.

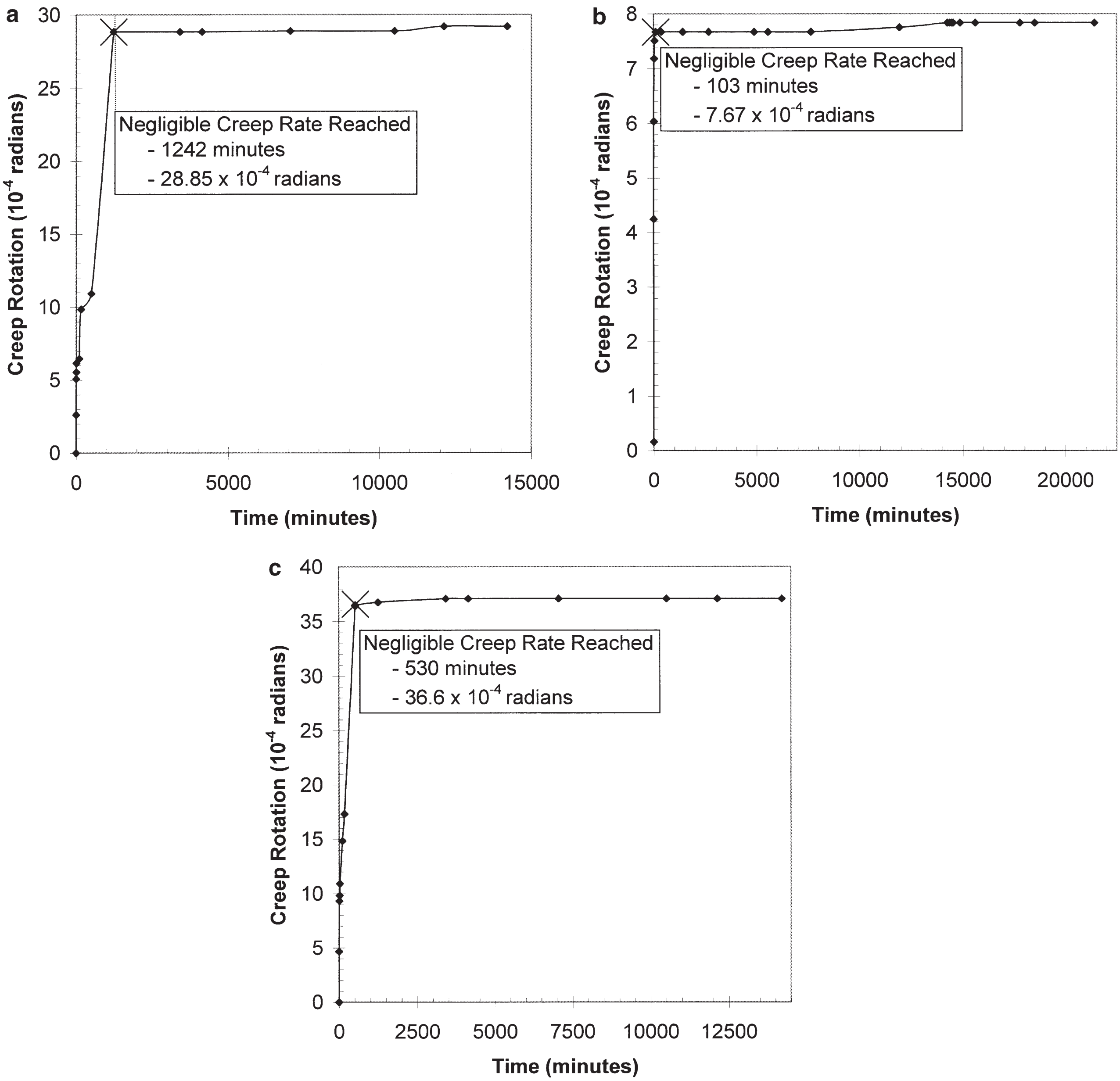

Fig. 6. Creep-time responses for: (a) nylon FRC beam 3 (69.3 kPa flexural stress); (b) nylon FRC beam 4 (74.3 kPa flexural stress); and (c) nylon FRC beam 5 (75.0 kPa flexural stress).

lene group. In contrast to the nylon group, these curves do not resemble the traditional creep-time curve. In the primary creep stage there are discontinuities that are best explained by the fibrillation of the polypropylene fibers. Fibrillation facilitates better bonding and its behavior is characterized by the ability to sustain slip without complete loss of bond. These characteristics best explain the modified primary creep stages found in Fig. 7 that appear to comprise several substages. It is observed that substages with increasing creep rates are often followed by the sudden drop rate, suggesting the creep rupture of some fibers, followed by the initial stressing of other, well-bonded fibers.

From the beams that sustained loads indefinitely, there is another substantial difference between the fiber types (Table 3). The time required to reach a negligible or zero rate of creep is considerably higher for polypropylene beams compared to nylon beams. The nylon beams, however, creep at a substantially higher average rate than the polypropylene beams. In summary, the nylon group creeps faster, but for less time.

These results suggest that pullout creep is a greater factor in the creep of nylon FRC than in polypropylene FRC. Whereas polypropylene fibers are expected to creep more than nylon fibers, a higher net creep rate in nylon FRC suggests that its creep rate in fiber pullout is higher. Finally, the result that the nylon FRC creeps for less time suggests that the magnitude of pullout creep diminishes over time, relative to fiber creep.

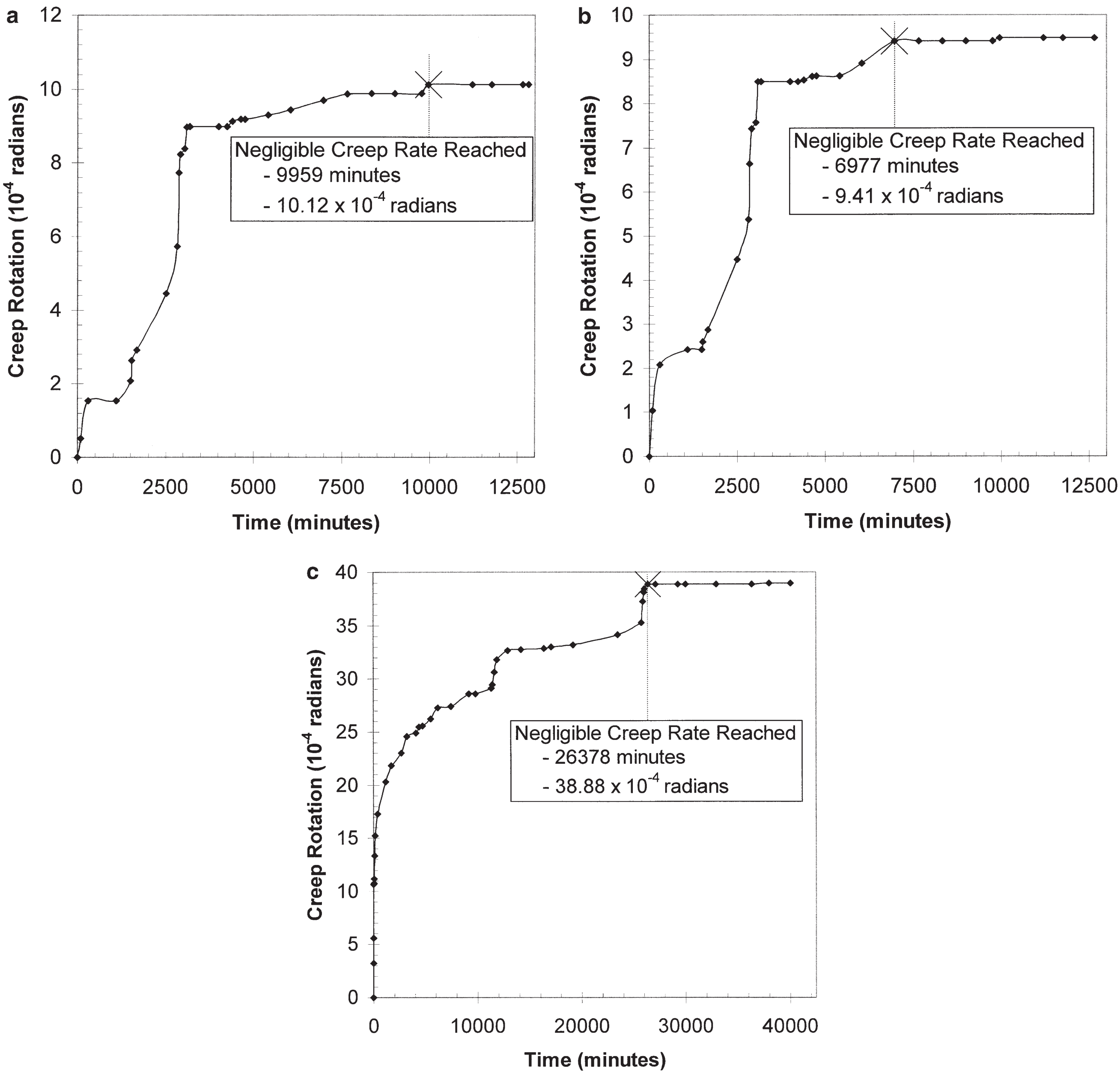

Fig. 7. Creep-time responses for: (a) polypropylene FRC beam 3 (61.6 kPa); (b) polypropylene FRC beam 4 (64.6 kPa); and (c) polypropylene FRC beam 5 (68.5 kPa).

4. Conclusions

Based on the results presented in this paper and observations made during the testing, the following conclusions can be drawn:

- As in typical creep cases, creep failure occurs when the stress level is higher than a certain percentage of failure load under monotonic load testing.
- In some cases creep deformations follow the classical three stages: primary, secondary, and tertiary.
- Even low levels of load that do not produce creep failure produce substantial creep deformations.
- Both polypropylene and nylon FRC can sustain only a small percentage of the postcrack strength. The maximum sustainable stress for the polypropylene represents only 24.9% of the ARS. For nylon this percentage is 38.3%.
- Nylon FRC was found to creep considerably faster than the polypropylene but for much less time. The net level of creep deformation was not substantially different between the two groups.

Acknowledgments

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