The Influence of Reinforcement on Relative Creep Deformations in Shotcrete Linings

By E. Stefan Bernard

Shotcrete is now widely used for ground control in underground mining and civil tunnel construction throughout the world. It is also frequently used for ground stabilization in basements and for inclined slopes, swimming pools, and other applications involving restraint of soil or rock. In all of these applications, the shotcrete generally acts as a semi-rigid passive form of restraint and interacts with the ground to redistribute stresses and limit deformation. This action is enhanced by the occurrence of creep both before and after cracking of the concrete matrix because creep assists in the process of stress redistribution. However, a question frequently arises: What level of creep is most suitable? For thin-walled linings, creep in *flexure* is particularly important to the redistribution of load because compression and tension play relatively minor roles in the structural behavior of thin-walled linings (Fig. 1). Reinforcement is essential to effective ground control because cracks invariably occur and give rise to structural discontinuities if reinforcement is not present.

"Creep" is a term used to describe the tendency of materials to deform over time under a sustained load. Creep is manifested as an increase in strain with time relative to strains experienced in the short term. Concrete subject to a sustained stress will exhibit creep as a result of the movement of moisture within the calcium-silicate-hydrate phase of the paste. This will occur both in compression and tension and is therefore quite apparent in concrete subject to bending.[1-6] Shotcrete will generally exhibit relatively large creep deformations compared to conventional concrete because of the higher-than-normal amount of cementitious material in this type of concrete. Because high cementitious contents are routinely used in tunnel construction, it is not surprising that shotcrete tunnel linings exhibit relatively high levels of creep compared to cast concrete. This is fortuitous because most ground continues to deform for a considerable period after excavation. A rigid lining exhibiting minimal creep would be more likely to crack when used to restrain mobile ground than a relatively compliant, high-creep lining (assuming materials of equal strength). However, an excessive tendency to creep is also unsatisfactory because this can lead to large deformations and less effective ground control.

Several studies have recently been published regarding the creep of cracked fiber-reinforced shotcrete (FRS) and fiber-reinforced concrete

Fig. 1: Once the shotcrete has hardened, will its creep characteristics suit the degree of ground movement expected?

(FRC) reinforced with either steel or synthetic fibers. One such study has indicated very high rates of creep for microsynthetic fibers[7] and others have indicated comparable rates of creep for steel and high-quality macrosynthetic fibers.[8-10] Other studies have demonstrated widely varying levels of creep deformation for different types of macrosynthetic fibers.[11,12] Tests comparing Dramix hooked-end steel fibers and Synmix macrosynthetic fibers have indicated extreme levels of creep deformation for Synmix macrosynthetic fibers,[13] indicating that some types of low-performance macrosynthetic fiber are probably unsuitable for use in deformation-sensitive civil tunnel linings.

An issue that has been raised by consulting engineers in relation to several recent tunneling projects is whether the type of reinforcement used in a tunnel lining has an influence on the creep deformation of an uncracked lining. According to accepted structural engineering analysis,[14,15] steel bars do not creep and heavily reinforced concrete sections will exhibit diminished creep in flexure as the degree of steel bar reinforcement is increased. However, at the low levels of reinforcement typical of thin-walled shotcrete linings (for example, a single layer of steel mesh in a 3 in. [75 mm] thick lining), the proportion of steel mesh reinforcement included is less than 1% and is usually assumed to be located at the middepth. In this situation, according to conventional analysis,[15] the influence of the steel mesh on creep in flexure is very small.

The influence of fibers on creep deformation in an uncracked lining is difficult to assess by calculation. Fibers are discontinuous and exhibit interaction characteristics within the concrete envelope that are influenced by the properties of the concrete matrix. The performance of the fibers is also altered by changes to the physical properties of the concrete matrix—especially changes that occur with age. As a result, it is not possible to uncouple the behavior of the concrete from that of the fiber reinforcement and treat these as distinct elements of a structural system in the way that conventionally reinforced members are analyzed. Instead, the FRS composite must be treated as a composite material displaying its own bulk engineering properties, and its performance is best assessed by experimental means.

A second issue of interest is whether cracks influence the degree of creep deformation exhibited by a steel-mesh-reinforced shotcrete lining. This issue is of relevance to crack width estimation with time and the question of whether crack widths measured at a given age for a steel-mesh-reinforced shotcrete lining are likely to grow in width or not. Crack width estimation is critical to the assessment of aggressive ion ingress toward embedded steel reinforcement and the possibility of subsequent corrosion of that reinforcement (whether in bar or fiber form).

Therefore, the first part of this investigation comprised an experimental assessment of the influence of reinforcement type on creep deformation in uncracked shotcrete linings. The second part involved a comparison of creep deformation over time for cracked and uncracked steel-mesh-reinforced shotcrete. Some comparisons have also been made with macrosynthetic FRS specimens.

Experimental Investigation

FRS linings predominantly act in a flexural mode of load resistance when used for ground support; hence, the experimental component of this investigation was developed to examine the creep characteristics of FRS and steel-mesh-reinforced shotcrete in *flexure*. Beams have traditionally been used to examine flexural capacity in concrete, but the high within-batch variability that typifies this method of assessment makes reliable estimates of performance difficult to obtain.[16] This investigation has therefore been undertaken using ASTM C1550 round panels,[17] as these are regarded as a more appropriate and representative means of assessing FRS lining behavior. The experimental procedures used in this investigation are the same as those described in detail by Bernard.[9,10]

Production and Curing of Specimens

The investigation involved the production of several sets of specimens that were cast using a shotcrete mixture and subsequently cured in water for approximately 180 days before being withdrawn and cured in air for an additional 180 days before the test program commenced. This was necessary to ensure that differences in the properties of the first and last specimens tested over the 4-year course of investigation were minimized.

The uncracked specimens consisted of ASTM C1550 panels (made in accordance with the mixture design in Table 1) reinforced with either hooked-end Dramix RC65/35 steel fibers (hereafter referred to as "Dramix"), embossed Barchip Macro 1.9 in. (48 mm) macrosynthetic fibers (hereafter referred to as "Macro"), or F51 steel mesh (0.2 in. [5 mm] bars on a 4 x 4 in. [100 x 100 mm] grid, hereafter referred to as "Mesh"; refer to Table 2). The cracked specimens consisted of ASTM C1550 panels made using shotcrete reinforced with either embossed Barchip Kyodo macrosynthetic fibers (hereafter referred to as "Kyodo") or F51 steel mesh (hereafter referred to as "Mesh"; refer to Table 2). All specimens

Table 1: Reinforcement used in various sets of specimens

Mixture	Fiber type	Dosage, kg/m³ (lb/yd³)
1	Dramix RC65/35 hooked-end steel	50 (84)
2	Barchip Macro 48 mm macrosynthetic	8 (14.8)
3	F51 steel mesh (5 mm bars on 100 mm grid)	0.3% steel
4	Barchip Kyodo 48 mm macrosynthetic	7 (11.8)

Note: 1 mm = 0.039 in.

Table 2: Mixture design for shotcrete used in casting trials

Component	Quantity, kg/m³ (lb/yd³)
Coarse aggregate (10/7 mm crushed river gravel)	550 (927)
Coarse sand	580 (977)
Fine sand	520 (876)
Cement	380 (640)
Silica fume	20 (33.7)
Water reducer	0.50 (0.84)

Note: 1 mm = 0.039 in.

Fig. 2: One of the four creep rigs used for gravity-load testing of specimens

were produced by casting into round steel and plywood forms that were positioned on a flat surface. They were immediately screeded to achieve a flat surface and uniform thickness and were then left outside under plastic sheeting to harden overnight before being stripped and transferred to curing tanks. Set accelerator was not used.

Testing of Specimens

Two types of tests were undertaken in this investigation: 1) tests on specimens that were cracked prior to placement in a creep rig and subject to 3 months of gravity loading; and 2) tests on specimens that were free of cracks during the 3 months of gravity loading. The tests on the precracked specimens were identical to those described by Bernard[9,10] and involved initial cracking in a servo-controlled test rig up to a central deformation of about 0.08 to 0.12 in. (2 to 3 mm) before the load was removed and the specimen was transferred to a gravity-loaded apparatus, such as the one shown in Fig. 2. A predetermined gravity load was applied to the center of the specimen for a period of 3 months, during which the deformation at the center was recorded. In this type of test, the load ratio was determined as the ratio of the gravity load over the static capacity of the cracked panel at the maximum deflection sustained in the initial cracking test in the servo-controlled rig.[10]

The second type of test was very similar to the first, but the precracking stage in the servo-controlled rig was omitted. Instead, a gravity load was applied to each uncracked specimen throughout the 3-month creep phase of testing. The creep phase was followed by a conventional ASTM C1550 test, in which a displacement-controlled load was applied up to a central deflection of 1.6 in. (40 mm). The load ratio in this sequence of tests was taken to be the gravity load divided by the cracking load in the subsequent ASTM C1550 test. Thus, the load ratio in both types of tests was found to be the ratio of gravity load over the static capacity at the start of the creep test.

Performance during each creep test was recorded as a time-deflection relationship, such as that shown in Fig. 3. These relationships were curve-fitted using a five-element Maxwell-Kelvin viscous damping model.[18] A curve corresponding to this expression was fitted to the d-*t* data obtained for each specimen. The results (shown for five specimens in Fig. 3) indicated that a power relationship dominated behavior over the first 3 months of loading.

Results

The primary result for each specimen was a record of central deflection measured over the 3-month duration of each test. As shown in Fig. 3, the central deflection increased steadily throughout the creep tests. The results were summarized by plotting the maximum deflection sustained at 3 months as a function of the creep load imposed on the specimen (Fig. 4) and as a function of the load ratio (defined previously; refer to Fig. 5). It is apparent in both of these figures that the magnitude of the deformation measured at 3 months increased steadily with load for both the cracked and uncracked specimens. It is also apparent that the magnitude of deformation due to creep in the uncracked specimens did not vary with the type of reinforcement contained within the specimen (although there was a significant variation within these sets; the deformation data are plotted on a log scale and, thus, differences are exaggerated for the small-deformation results).

It is clear that the cracked steel-mesh-reinforced specimens exhibited greater time-dependent deformations than uncracked specimens made using the same concrete and reinforcement and that the difference increased with the magnitude of the load. Results for the cracked Kyodo macrosynthetic FRS specimens have been included for comparison with the cracked steel-mesh-reinforced specimens. At load ratios of up to 30%, there did not appear to be any significant difference between the cracked and uncracked specimens, regardless of the type of reinforcement used. The differences between the steel-mesh-reinforced panels and Kyodo-reinforced panels remained relatively minor at 50% of static capacity but became significant at load ratios of over 50 to 55% (tests have previously shown that steel FRS creeps very little at up to 70% of static capacity[10]). Given that FRS and FRC tunnel linings are unlikely to be "designed" to sustain loads greater than 50% of the short-term static capacity, it would appear that at this level of load, cracked steel-mesh-reinforced FRS will exhibit about twice the time-dependent deformation of uncracked linings, and linings reinforced with high-performance macrosynthetic fibers, such as Kyodo, will exhibit about three to four times greater time-dependent deformation. This observation is specific to this fiber, however, because previous work has demonstrated that low-performance macrosynthetic fibers can exhibit far higher levels of time-dependent deformation.[7,9,11,13]

Creep Rupture

Creep rupture occurred in several of the cracked Kyodo-reinforced specimens at load ratios of between 72 and 90% of static capacity. These failures, which occurred within 6 weeks of loading, suggest that sustained loads should not exceed 60% of static capacity for this fiber. This is consistent with the findings of Gossla and Rieder,[12] who found that loads in excess of 50 to 55% of static

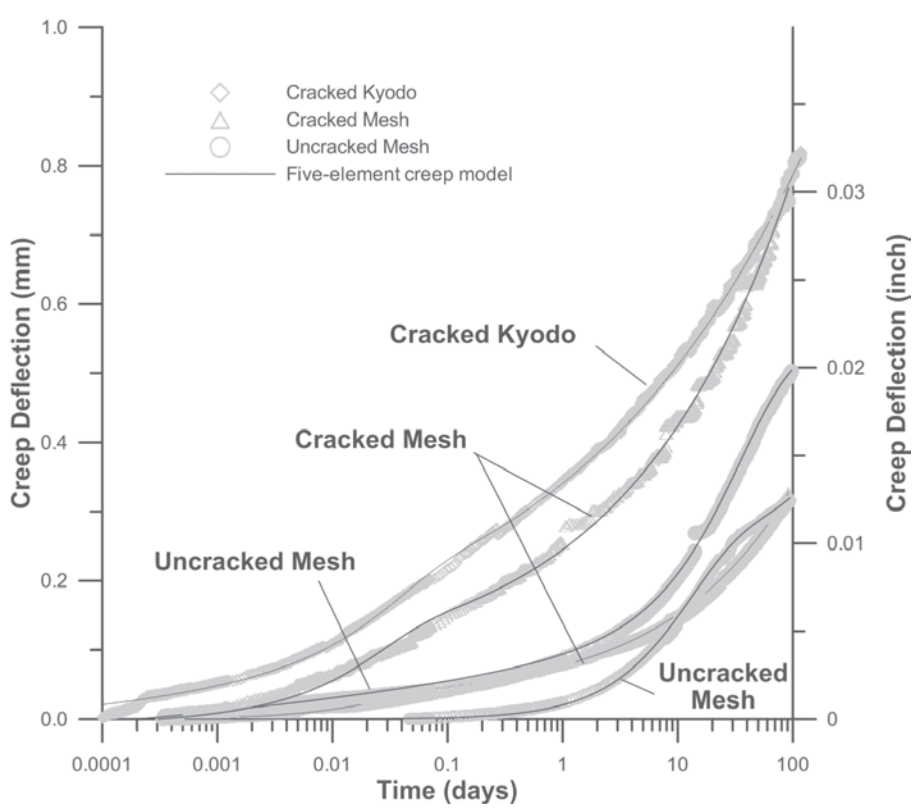

Fig. 3: Creep deflection as a function of time for cracked specimens made with steel mesh reinforcement compared with uncracked specimens. One cracked Kyodo-reinforced specimen is also included for comparison

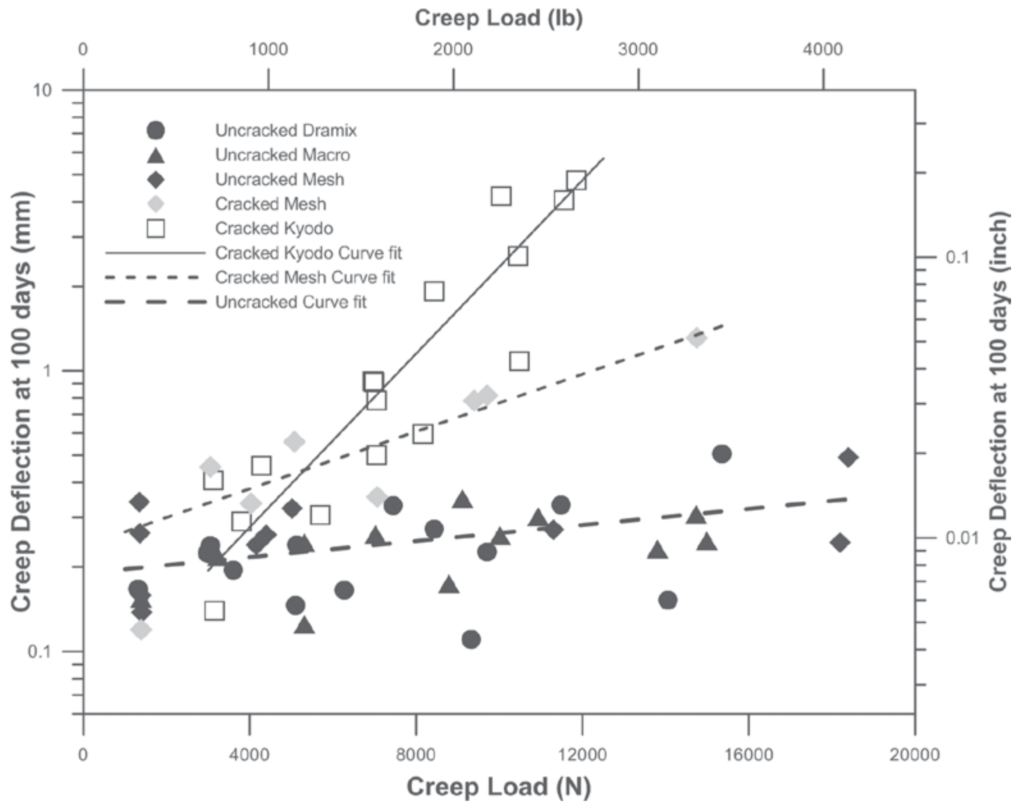

Fig. 4: Creep deflection at 100 days expressed as a function of load imposed at the center of each panel

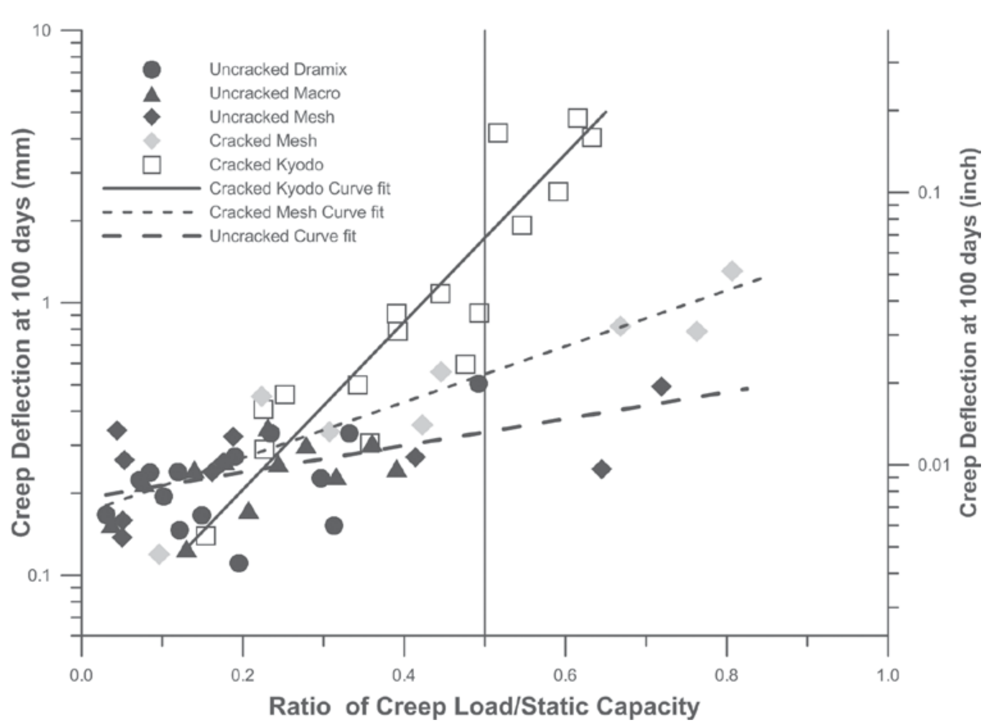

Fig. 5: Creep deflection at 100 days expressed as a function of load ratio (based on ratio of imposed gravity load over static capacity for cracked panels or imposed gravity load over cracking load in the subsequent ASTM C1550 test for uncracked panels)

capacity led to creep rupture when Strux 90/40 macrosynthetic fibers were used in concrete, and Kusterle,[11] who found that loads in excess of 60% of static capacity led to creep rupture for several macrosynthetic fibers and loads in excess of 75% of static capacity led to creep rupture in steel FRC loaded in flexure.

Conclusions

An investigation was undertaken into the time-dependent creep behavior of uncracked shotcrete ASTM C1550 panels reinforced with either steel fibers, macrosynthetic fibers, or steel mesh reinforcement, and the time-dependent creep behavior of cracked shotcrete panels reinforced with steel mesh reinforcement or macrosynthetic fibers. The investigation revealed that the time-dependent creep deformation of uncracked panels is insensitive to the type of reinforcement contained within the concrete, at least for the levels of steel mesh reinforcement and fiber dosages typical of thin-walled concrete linings used for ground support in underground and basement excavations.

The investigation also indicated that postcrack creep deflections are higher for cracked steel-mesh-reinforced shotcrete than for uncracked steel-mesh-reinforced specimens made using the same shotcrete mixture. The level of creep deformation exhibited by cracked panels reinforced with Barchip Kyodo macrosynthetic fibers is about the same as cracked panels reinforced with steel mesh at around 30% of static capacity. However, at 50% of static capacity, which is typical of design loadings in most structures, cracked panels reinforced with Barchip Kyodo fibers deform about three to four times as much as cracked steel-mesh-reinforced panels.

Acknowledgments

The author gratefully acknowledges W.R. Grace & Co. Inc., Elasto-Plastic Concrete P/L, and the Roads and Traffic Authority of NSW for their generous support of this investigation.

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