Embrittlement of Fiber-Reinforced Shotcrete

by E. Stefan Bernard

In underground construction, minimum performance levels for shotcrete with respect to compressive and flexural strength, ductility, and resistance to the environment are usually required to be maintained over the entire design life of a lining. Successful maintenance of compressive and flexural strength is normally related to the issue of durability, and many investigations assessing the durability of concrete materials under a variety of exposure conditions have been published. In contrast, the issue of ductility and the effects of aging and exposure are less well researched despite its importance to structural integrity. This paper describes some preliminary results obtained over 3 years of toughness testing for shotcrete reinforced with hooked-end steel fibers, macro-synthetic fibers, and welded wire fabric (WWF). It reveals that toughness data obtained at 28 days is not necessarily an indicator of satisfactory material performance over the life of a fiber-reinforced shotcrete (FRS) structure.

Background

In recent years there has been an increasing trend toward specification of a very long design life for most tunnels.[1] Many mine declines and workings also have an intended life extending to several decades. The issue of durability and age-dependent performance of FRS has therefore become more significant to the owners of underground infrastructure. Performance can be assessed in many ways, but the ability of FRS to rapidly achieve and then retain ductility (commonly measured as toughness) over time is generally recognized as being important to the successful use of this material. This is because ductility is critical to the redistribution of load when, for example, ground movement causes localized cracking of the concrete matrix within a shotcrete lining. If ductility diminishes with age or exposure to aggressive agents, then the ability of the structure to maintain stability may be compromised. This is why minimum levels of ductility are considered mandatory in conventional above-ground structures made of, for example, reinforced concrete.[2,3] The ability of FRS infrastructure to achieve and then maintain a high level of toughness over the life of an underground structure is a valid and relevant indicator of fitness-for-purpose and therefore constitutes an important aspect of durability.

Degradation of the concrete matrix and corrosion of reinforcement have traditionally been regarded as the principal indicators of deterioration. Previous investigations have shown that the shotcrete matrix can generally be considered durable, probably on account of its high binder content and low water-binder ratio.[4-10] Fibers also remain free of corrosion if embedded within a sound matrix.[10-12] Steel fibers, however, will corrode across cracks wider than about 0.003 in. (0.1 mm)[13-16] and toughness will thereafter fall. Macro-synthetic fibers do not corrode either at cracks or within the concrete matrix if made of a polymer compatible with cement paste.[14,17-19]

Whereas durability issues in FRS related to matrix degradation and corrosion have been relatively widely addressed, loss of ductility with age has only recently entered the consciousness of the construction industry. The ductility of FRS may be compromised either through degradation of the concrete matrix, corrosion of the fibers, or changes in the mechanism of fiber behavior after cracking of the concrete matrix. A study of the age-dependent behavior of FRS on the M5 motorway tunnel in Sydney, Australia,[20] first revealed a loss of toughness at late age (termed embrittlement) for shotcrete reinforced with some types of fiber. This was due to the development of high strength and hardness in the enveloping concrete matrix resulting in a change from the high-energy pullout mode of post-crack fiber behavior to the low-energy yielding mode of fiber failure (Fig. 1). This behavior has also been observed in single-fiber pullout tests.[21] The change in failure mode leads to a fall in post-crack performance that is unrelated to corrosion or any mechanism of deterioration in the concrete. Indeed, it is usually associated with high strength and rigidity in concrete, and thus tends to occur in shotcrete due to the high cementitious content and low water-binder ratios typical of this material.

As a result of the tests conducted as part of the M5 motorway project,[20] the Roads and Traffic Authority of New South Wales became concerned about the capacity of FRS linings in motorway tunnels to maintain ground stability in the long term. The present investigation was therefore initiated to examine the age-dependent development of toughness in FRS reinforced with steel and macro-synthetic fibers. The study was intended to quantify deterioration due to corrosion and embrittlement in cracked and uncracked FRS exposed to typical environmental conditions in a motorway tunnel over a period of 10 years. This paper presents results for the first 3 years of exposure and testing.

Experimental Program

Several sets of FRS specimens were produced by spraying and one set of specimens reinforced with WWF was produced by casting (refer to Tables 1 and 2 for reinforcement and mixture data). Each set included 105 ASTM C1550[22] round panels that, if sprayed, included a set accelerator at a dosage rate of about 4% by weight of cement. Cores were also produced and tested in parallel with the panels. The ages at testing were 1, 2, 3, 7, 14, 28, 56, 91, and 180 days, and then 1, 2, 3, 5, and 10 years. Because the specimen sets were produced in sequence over a period of 3 years, only a limited number of results are presently available for the most recently produced sets.

All the sprayed specimens were produced by manually spraying shotcrete into round steel and plywood forms that were propped at 45 degrees against a rack. The specimens were moved to a flat surface immediately after spraying and screeded to achieve a flat surface and uniform thickness. They were then left outside under plastic sheeting to harden overnight before being stripped and transferred to curing tanks for 56 days of immersed curing. About one-third of the panel specimens acted as controls and were cured continuously in water at the laboratory up until the required age of testing. The other 60 specimens within each set were precracked at 56 days and then placed in the field for exposure until the required age of testing. In this way, the influence of both corrosion and embrittlement on toughness could be distinguished.

The exposure site was intended to represent the entrance to a motorway tunnel, but because space was not available within a tunnel, the sheltered underside of a wide overpass between dual carriageways on a motorway was chosen as being equivalent to a tunnel entrance. The specimens were not exposed to direct rain but were subject to the spray generated by passing vehicles during downpours. The average daytime temperature at the site varied from 59 °F (15 °C) in winter to about 82 °F (28 °C) in summer. The area was about 12 miles (20 km) from the coast and no deicer salts were ever used on the roadway. The site could therefore be considered a benign environment with respect to corrosion of steel.

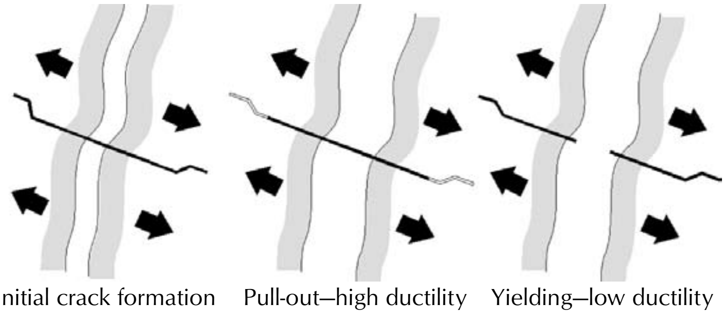

Fig. 1: Post-crack failure mechanisms for FRS reinforced with hooked-end steel fibers

Results

The results of the investigation comprised load-deflection curves obtained for each of the ASTM C1550 panel specimens and unconfined compressive strength (UCS) data obtained from the cores and cylinders. The performance of all the panel specimens has been summarized in terms of energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) cumulative central deflection.

The influence of corrosion at the cracks on the performance of the field specimens was found to be negligible over the first 3 years of the study. Despite some minor surface staining at crack intersections, the steel WWF and fibers remained free of any significant corrosion. The macro-synthetic FRS specimens appeared to be completely free of any corrosive effects. The energy absorption characteristics of the specimens therefore did not indicate any fall in capacity with increasing crack width. This is not surprising given the benign exposure conditions and limited duration of the investigation thus far.

In contrast to the marginal effect of corrosion on performance over the first 3 years of the trial, the influence of aging on energy absorption was much more pronounced. This occurred for both the uncracked control specimens kept in the laboratory and the field exposure specimens. An example set of load-deflection curves for the Dramix RC65/35 specimens produced using 7252 psi (50 MPa) shotcrete and continuously wet-cured in the laboratory is shown in Fig. 2. The change in energy absorption for each specimen set as a function of age is shown for the uncracked controls in Fig. 3 to 8. Each set of curves includes actual data points for 0.2 and 1.6 in. (5 and 40 mm) energy absorption, and curve-fits to energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) deflection.

The energy absorption data obtained to date indicate that neither of the macro-synthetic FRS

Table 1: Mixture details for shotcrete sets examined

Reinforcement	Quantity, lb/yd^3 (kg/m^3)	Nominal grade, psi (MPa)	UCS 28 days, psi (MPa)	UCS 365 days, psi (MPa)
Barchip Kyodo	16.7 (10)	4641 (32)	6902 (42)	8702 (60)
SL62 WWF	—	7252 (50)	8412 (58)	9572 (66)
Dramix RC 65/35	84 (50)	7252 (50)	8267 (57)	10,298 (71)
Dramix RC 65/35	84 (50)	5802 (40)	6527 (45)	10,733 (74)
Dramix RC 65/35	84 (50)	3626 (25)	4206 (29)	5565 (39)
Enduro 600	11.8 (7)	5802 (40)	6962 (48)	—

Table 2: Mixture design for shotcrete used in each trial

Component	Nominal grade and quantity, lb/yd^3 (kg/m^3)			
	3626 psi (25 MPa)	4641 psi (32 MPa)	5802 psi (40 MPa)	7252 psi (50 MPa)
Coarse aggregate (1/4 to 3/8 in. [7 to 10 mm CRG])	1011 (600)	1011 (600)	1030 (610)	1045 (620)
Coarse sand, 1/12 in. (2 mm)	627 (372)	627 (372)	590 (350)	555 (330)
Fine sand	1214 (720)	1146 (680)	1146 (680)	1080 (640)
Binder (Cement/fly ash/silica fume)	650 (385)	716 (425)	750 (445)	835 (495)
Water reducer, Qt/yd^3 (L/m^3)	1.5 (1.0)	1.5 (1.0)	1.6 (1.1)	1.7 (1.2)

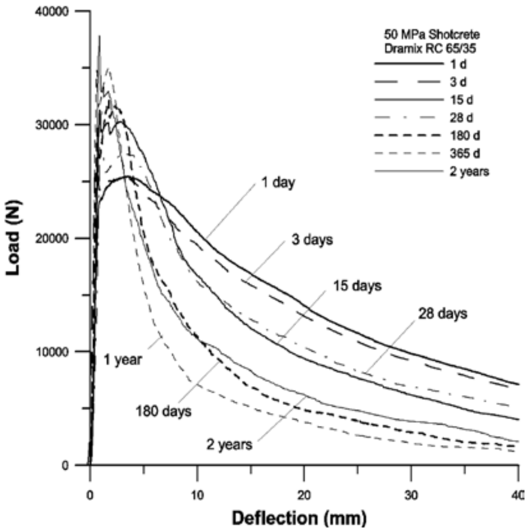

Fig. 2: Load-deflection curves for specimens reinforced with Dramix RC65/35 in 7252 psi (50 MPa) shotcrete tested at various ages after spraying showing an increase in load resistance at small deflections with aging but a fall in load resistance at large deformations

specimen sets exhibited a fall in performance with age. The SL62-reinforced specimens also demonstrated a close-to-maximum post-crack performance capacity within 1 day of casting. In contrast to the macro-synthetic fibers and WWF, the hooked-end steel fibers exhibited performance that was very sensitive to the compressive strength and age of the shotcrete, with optimum post-crack performance occurring for concrete with a medium compressive strength. The 7252 psi (50 MPa) mixture exhibited close-to-maximum performance over the first few days following spraying, after which performance at larger deflections fell markedly as the mode of fiber failure changed from pullout to yielding and rupture. For the 5802 psi (40 MPa) Dramix RC65/35 mixture, the peak in performance occurred around 28 to 56 days; and for the 3626 psi (25 MPa) Dramix RC65/35 mixture, the peak occurred around 180 days.

Note that none of the steel FRS mixtures exhibited a fall in UCS with age. Inspection of the crack surfaces after testing revealed that the loss of toughness that occurred with age was due to a change in the mechanism of post-crack fiber behavior as the concrete matrix became progressively stronger and harder. The loss of toughness was not associated with degradation of the concrete. Examination of the relation between UCS and energy at 1.6 in. (40 mm) for the steel FRS sets (Fig. 9) indicates that an optimum level of performance occurred for a UCS of about 6527 psi (45 MPa), beyond which performance diminished.

All the steel FRS mixtures exhibited an increase in energy absorption at small deformations with age while concurrently exhibiting a fall in energy absorption at large deformations. This meant that the residual load resistance at large deformations was doubly diminished with age (see Fig. 2 for typical load-deflection curves). In contrast, the macro-synthetic FRS mixtures exhibited an increase in energy absorption with age at all levels of deformation. These results suggest that macro-

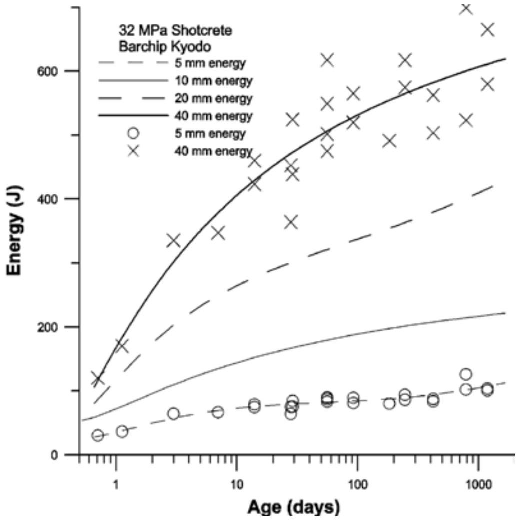

Fig. 3: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for Barchip Kyodo

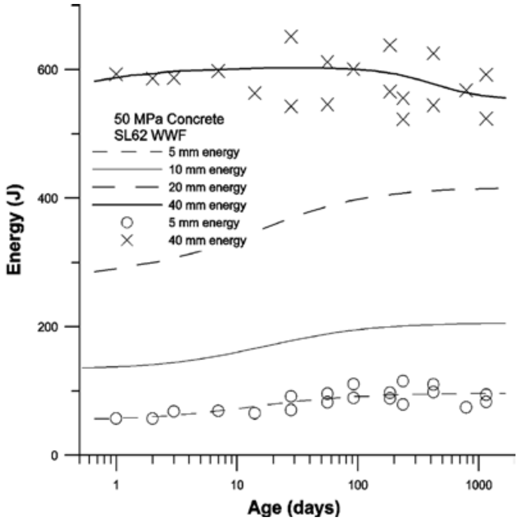

Fig. 4: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for SL62 WWF

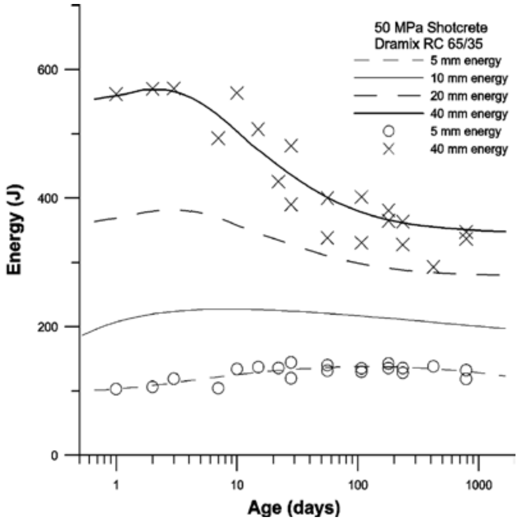

Fig. 5: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for Dramix RC65/35 in 7252 psi (50 MPa) shotcrete

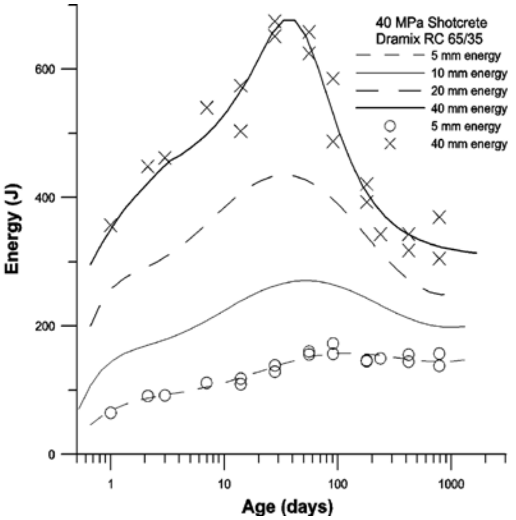

Fig. 6: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for Dramix RC65/35 in 5802 psi (40 MPa) shotcrete

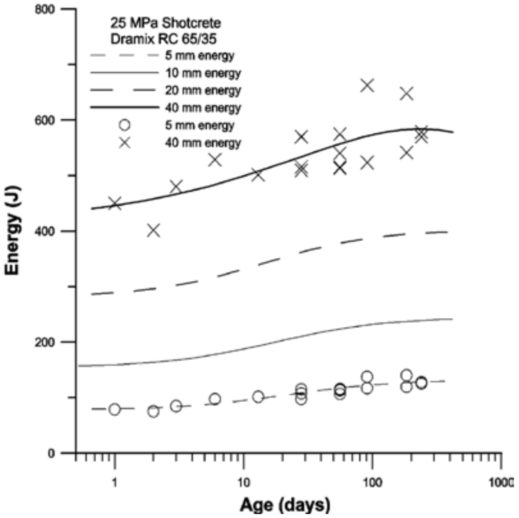

Fig. 7: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for Dramix RC65/35 in 3626 psi (25 MPa) shotcrete

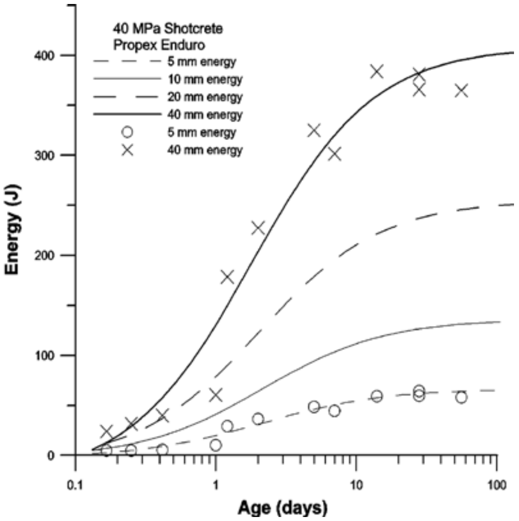

Fig. 8: Energy absorption at 0.2, 0.4, 0.8, and 1.6 in. (5, 10, 20, and 40 mm) for Enduro 600 in 3626 psi (40 MPa) shotcrete

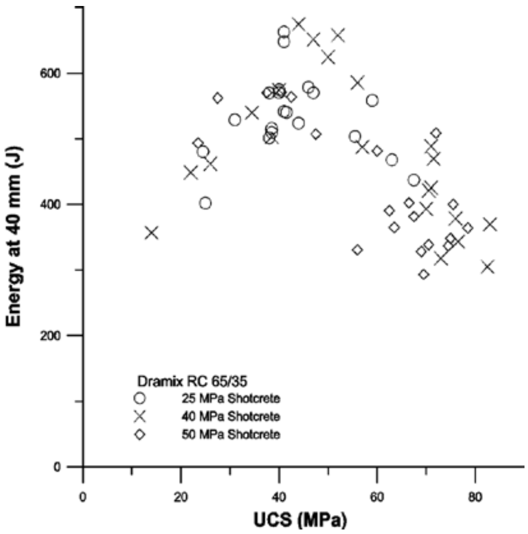

Fig. 9: Energy absorption at 1.6 in. (40 mm) for Dramix RC65/35 as a function of UCS obtained from cores

synthetic fibers and WWF both offer superior performance to that of high-performance hooked-end steel fibers at late ages and in high-strength shotcrete because they continue to exhibit a high-energy mode of failure as the shotcrete ages.

Consequences of Embrittlement

The results of this study indicate that, as far as ductility retention is concerned, the consequences of embrittlement are more significant than the consequences of corrosion for steel FRS placed in a benign environment. Ductility is as important to the maintenance of satisfactory load resistance in structures as the maximum strength of materials, hence the loss of ductility with age exhibited by the steel FRS examined in this investigation is of concern.

The data shown in Fig. 2 and 5 is particularly important in the context of recent rapid underground excavation practice. Early reentry during in-cycle shotcreting usually demands high early-age strength development, and this is most commonly achieved using a high-strength shotcrete incorporating high cement and silica fume contents. FRS mixtures intended for final linings also commonly incorporate high cementitious contents due to requirements for low permeability. The problem with this type of shotcrete is that the late-age strength can be very high (>10,153 psi [70 MPa]), leading to a change in post-crack failure mechanism from a high-energy friction-based pullout mode to a lower-energy yielding mode for some types of fiber (such as the hooked-end steel fibers presently examined). This can reduce the ability of a lining to redistribute loads should ground movement occur at late ages. Late-age ground movement may occur, for example, in the event of a nearby excavation or change in groundwater level many years after the FRS lining had been installed. Loosening of horizontal strata above an excavation with time may also give rise to loads that must, in many circumstances, be supported by the FRS lining.[23] Such events are common in mines and congested city centers subject to intensive development.

If high toughness is required throughout the life of an FRS structure, then it is necessary to look beyond the performance achieved at 28 days and consider the effects of excessive strength development and embrittlement on late age performance. The present preliminary data indicate that fibers intended for long life structures should be selected on the basis of demonstrated performance at late ages. The assumption that excellent toughness obtained in 28-day quality-control specimens will automatically translate to similar levels of performance throughout the design life of a structure could lead to overestimation of structural ductility in long-life infrastructure.

Conclusions

The most important conclusion from this investigation is that satisfactory performance with respect to quality-control toughness tests at 28 days may not guarantee satisfactory performance at later ages, at least for some types of steel FRS. Aging and associated effects such as strength gain and hardening can change the mechanism of failure for some types of fiber leading to a loss of toughness at large deformations. This may reduce the late-age capacity of FRS to redistribute loads in response to ground movement. It is therefore necessary to consider the ultimate compressive strength of a shotcrete matrix and its likely long-term effect on the failure mechanism of fibers contained in the matrix when assessing the most suitable fiber to use as reinforcement in long-life mining, tunnel linings, and underground openings in mines.

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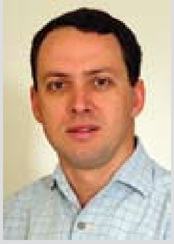

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