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Age-dependent changes in post-crack performance of fibre reinforced shotcrete linings

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ABSTRACT

It is commonly assumed that when a mix achieves satisfactory performance in Quality Control tests at 28 days this result will translate into satisfactory performance throughout the design life of the corresponding concrete structure. While this is generally true of the compressive strength of concrete it is not necessarily true for other parameters. The post-crack performance of fibre reinforced concrete (FRC) differs from that of conventionally reinforced concrete in that the post-crack performance of fibres is related in a complex manner to the characteristics of the concrete matrix. Age-dependent changes in the characteristics of the concrete matrix can effect changes in the post-crack behaviour of fibres. The present investigation has examined how the post-crack energy absorption of fibre reinforced shotcrete (FRS) changes with aging and has found that some types of fibre exhibit dramatically different performance characteristics at late age compared to that displayed at 28 days. This change can have significant consequences for the design of ground support based on fibre reinforced shotcrete. Tunnel linings required to resist sustained ground stresses, or which may be subject to deformation associated with seismicity or ground movement at later ages, should be designed with consideration of a possible long-term loss of ductility exhibited by some types of fibre reinforced shotcrete.

1. Introduction

In the construction of public infrastructure such as tunnels it has become common to specify a design life of 100+ years (Franzen et al., 2001). This places very high demands on shotcrete used for ground stabilisation given the concurrent requirement on this material to be pumped and sprayed without blockages, gain strength rapidly, and then remain firmly in place while resisting the effects of environmental exposure. Requirements for resistance to deterioration have generally promoted the use of high binder contents, including pozzolanic additives, and low water/binder ratios leading to low permeability and good chemical inertness. The long-term consequence of this tends to be high strength development at late ages (Malhorta, 1993). Most shotcrete used in underground applications is reinforced with fibres. Unlike conventional steel bar reinforcement, the post-crack performance of fibres is strongly influenced by the characteristics of the concrete matrix. Post-crack performance characteristics therefore change with the evolution of strength and hardness of the concrete matrix.

The ability of fibre reinforced shotcrete (FRS) to rapidly achieve and then retain ductility (commonly referred to as 'toughness') as it ages is generally recognized as being important to the successful use of this material, especially for ground stabilization. This is because ductility is critical to the re-distribution 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 a structure such as a tunnel lining to maintain stability may be compromised. This is why minimum levels of ductility are considered mandatory for moment re-distribution requirements in conventional above ground structures, made of, for example, reinforced concrete (Beletich et al., 2013; Nielsen, 1998) and is also the reason why FRS performance is specified in terms of energy absorption in widely used design approaches to ground stabilization such as the Q-system (Barton and Grimstad, 2004). The ability of FRS infrastructure to achieve and then maintain a high level of energy absorption over the life of a structure can be considered a valid and relevant indicator of fitness-for-purpose and 'durability'.

The vast majority of FRS is used to stabilize excavated ground, particularly hard rock, thus the focus of the present investigation has been the performance of FRS in this application. When FRS is first sprayed on to freshly excavated ground, the ability of the shotcrete to stabilize the ground will initially depend on the adequacy

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Table 1
Mix details for shotcrete sets examined.

Reinforcement	Quantity (kg/m^3)	Nominal grade (MPa)	UCS 28 days Cyl. (MPa)	UCS 5 years Cores (MPa)	UCS 5 years Cyl. (MPa)
Barchip Kyodo, 48 mm	10	32	42	64	59
SL62 WWF[a]	–	50	58	–	72
Dramix RC 65/35BN	50	50	57	82	77
Dramix RC 65/35BN	50	40	45	83	78
Dramix RC 65/35BN	50	25	29	50	43
Novotex 0730, 30 mm	50	40	43	61	61
Enduro 600, 50 mm	7	40	48	65	62
Enduro 600, 50 mm	7	50	53	60	61
Barchip BC54, 54 mm	7	50	55	88	85

[a] SL62 denotes 6 mm deformed steel bars welded on a 200 mm orthogonal grid placed at mid-depth.

of the bond established between the freshly sprayed shotcrete and the ground. Early-age competency does not depend on fibre reinforcement because macro-fibres (whether made of steel or polymers) are largely ineffective over the first few hours after spraying (Bernard, 2008a). Moreover, most early-age lining failures are governed by punching resistance rather than flexure and fibres contribute very little to shear resistance in young concrete (Bernard, 2011). However, as the shotcrete gains strength the pre-dominant mode of failure changes from shear to flexure and it is at this point that the performance of fibre reinforcement becomes important. Fibre reinforcement provides substantial post-crack energy absorption and load re-distribution capacity to a material that is otherwise quite brittle and ineffective in ground control (Bernard, 2002; Naaman, 1985). It thereby allows a concrete lining to accommodate a degree of ground movement without loss of structural competency. Maintenance of this property is important to the long-term functionality of FRS linings should later-age ground movement occur.

It is generally recognized that the more unstable the ground, the greater is the requirement for energy absorption capacity in a FRS lining. The relationship between ground stability and minimum energy absorption requirement has been expressed in several widely used design guidelines for shotcrete linings such as the Q-system (Barton and Grimstad, 2004), the Australian *Recommended Practice for Shotcrete* (Shotcreting in Australia: Recommended Practice, 2010), and the Norwegian Concrete Association *Publication Number 7* (Concrete for Rock Support, 2011). In each of these documents the minimum energy absorption requirement for FRS is related to the expected degree of ground movement. In Australian and North American practice (Bernard, 2013; Decker et al., 2012), energy absorption is specified on the basis of FRS performance using ASTM C1550 round panels (ASTM, 2012). ASTM C1550 panels have therefore been used to assess FRS performance throughout this investigation. As an indication of performance requirements for underground applications, a minimum energy absorption of 400 J at 40 mm central deflection in the ASTM C1550 panel test has been found to be adequate for the majority of tunnelling and mining projects (Papworth, 2002).

Aging of concrete in underground environments normally gives rise to concerns about durability. The ability of fibres within uncracked FRS to resist corrosion under conditions of normal atmospheric exposure has been demonstrated through several long-term exposure trials (Schupack, 1985; Hara et al., 1992; Mangat and Gurusamy, 1985). While carbonation may promote corrosion and loss of structural performance, including ductility, for near-surface steel fibres (Schupack, 1985), any fibres that corrode due to proximity to a concrete surface have been shown to exert insufficient expansive pressure to disrupt the enveloping concrete (Hoff, 1987; Lankard and Walker, 1978). Localized surface corrosion therefore does not develop into structurally-threatening

Table 2
Mix design for shotcrete used in each trial.

Component	Nominal grade and quantity (kg/m^3)			
	25 MPa	32 MPa	40 MPa	50 MPa
Coarse aggregate (10/7 mm CRG)	600	600	610	620
Coarse sand (2 mm)	372	372	350	330
Fine sand	720	680	680	640
Binder (Cement/fly ash/silica)	385	425	445	495
Water reducer (L/m^3)	1.0	1.0	1.1	1.2

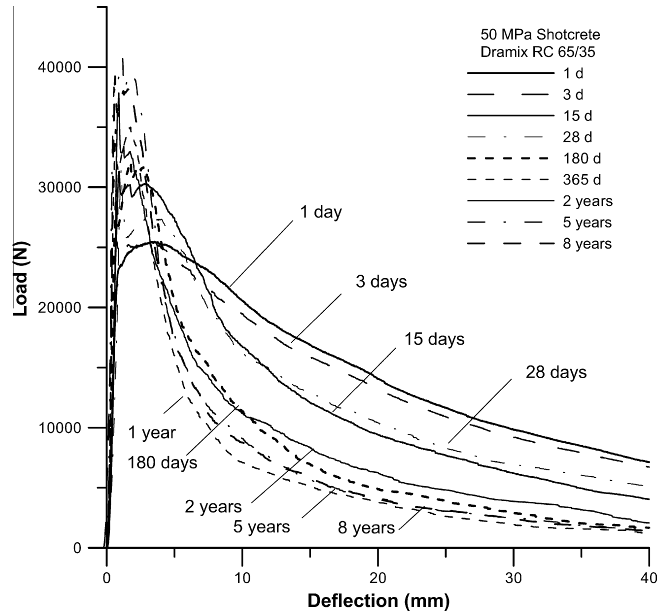

Fig. 1. ASTM C1550 Load–deflection curves for specimens reinforced with Dramix RC65/35BN in 50 MPa shotcrete tested at various ages after spraying showing an increase in load resistance at small deflections with aging but a fall in resistance at large deformations.

Fig. 2. Pulled-out Dramix RC65/35BN fibres on crack face of 3 day old shotcrete of 50 MPa nominal grade.