Shrinkage Cracking in Slender Shotcrete Tunnel Linings

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ABSTRACT: Drying shrinkage cracks in shotcrete linings are widely assumed to be benign and are often dismissed as inconsequential to the performance of shotcrete linings. However, recent experience in Australian tunnels constructed with slender shotcrete linings indicates that this type of cracking presents a significant maintenance issue due to the frequent leakage of groundwater into the tunnel space through these cracks. This paper examines the formation and consequences of drying shrinkage cracks in slender shotcrete tunnel linings and discusses measures developed to treat the durability and maintenance problems that arise as a result of water leakage though shrinkage cracks.

1 INTRODUCTION

In recent years there has been a move toward more slender shotcrete linings in tunnel excavations, particularly in hard ground that is relatively stable and amenable to support based primarily on bolting. This trend was originally driven by economic considerations but has more recently been supplemented by 'carbon minimisation' concerns. The result has been slender final linings constructed using shotcrete of only 50-125 mm thickness, often with no primary lining. For example, the Eastern Distributor (Pells, 2002), Norfolk tunnels (Clarke et al, 2014), Lane Cove Tunnel (Maconachie et al, 2005), M5 East tunnel (Adams et al, 2001; Hanke et al, 2001), Cross City Tunnel (Asche and Bernard, 2004), and WestConnex tunnels (Aitchison et al, 2018; Barry et al, 2021) all included slender shotcrete linings in at least a portion of their length. These linings usually form part of a 'drained canopy' approach to management of water ingress in which numerous drainage elements are placed on the rock (or 50 mm initial lining) surface before spraying the final layer, thereby facilitating transfer of groundwater to drains at the sides of the tunnel space. While these slender linings may satisfy structural requirements for support of self-weight and occasional loose ground, they have tended to experience a significant amount of cracking due to drying shrinkage, as well as other problems (Kost et al, 2021).

1.1 *Background*

The extent of drying shrinkage cracking experienced by recently completed shotcrete linings has varied both within and between projects. Many linings have zones within them in which drying shrinkage cracks are infrequent, but the same linings have suffered severely from shrinkage cracking in nearby areas. The incidence of cracking does not appear to be related locally to thickness, but thin linings (<75 mm) have generally been observed to suffer more widespread drying shrinkage cracking than thicker linings (>150 mm).

Assessments of cracks in recently constructed tunnel linings have indicated that the majority of cracks have been caused by drying shrinkage (as opposed to ground movement) and the majority of these cracks pass all the way through the lining rather than being blind cracks. This has resulted in frequent uncontrolled seepage of groundwater through the linings, although this varies with the availability of groundwater which changes both spatially and temporally. It also indicates that no net compressive action exists in these linings. Very few of the cracks exhibit continuous ingress of running groundwater; the majority exhibit slow and intermittent seepage leading to evaporation of moisture on the drying surface of the lining leaving salts such as halite (NaCl), mirabilite ($Na_2SO_4 \cdot 10H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), and copiapite ($Fe^{2+}Fe^{3+}_4(SO_4)_6(OH)_2 \cdot 20H_2O$) to accumulate in and around the crack. While the concentrations of these minerals in the nearby groundwater are seldom of concern (Hunter, 2025), their steady accumulation by evaporation in and around drying shrinkage cracks can lead to elevated concentrations that potentially pose a threat to both the steel fibres and concrete matrix that comprise most shotcrete tunnel linings.

The spacing between observed drying shrinkage cracks appears to be related to the thickness. For shotcrete sprayed onto rock of relatively even geometry, the ratio of spacing/thickness has typically been observed to range from 10-20, although occasionally it is as low as 6. For shotcrete sprayed onto waterproof membranes, the ratio of spacing/thickness has been observed to range from 20-40. Drying shrinkage cracks have often been observed to coincide with discontinuities in the underlying rock strata, particularly joints and steps in rock strata, and with covered drainage features such as strip drains. This may have some bearing on why the observed range of crack spacing appears to be so broad. Nevertheless, observations of typical drying shrinkage crack spacings in shotcrete linings are much greater than the characteristic spacing between flexural cracks, which is commonly approximated as equal to the thickness of a member (DBV, 2002; *fib*, 2022). Taking the drying shrinkage spacing to be equal to the thickness of the lining will result in a gross under-estimate of crack width, since width is calculated on the basis of the factored accumulation of shrinkage strain between cracks.

Drying shrinkage cracks are typically difficult to find on a gun-finish shotcrete surface unless they are revealed by seepage of moisture and/or accumulation of calcite and salts. This suggests a bias is likely in observed distribution because their occurrence will appear to be more frequent in areas with ample groundwater. Since most shotcrete linings in Australia are drained structures, in which the lining forms a canopy that is part of a drainage system incorporating strip drains and mats immediately behind or within the lining, it is not surprising that groundwater will find its way through cracks in the lining. Indeed, it appears irrational to assume that a lining which is known to suffer shrinkage cracking is capable of fully diverting groundwater to the sides of a tunnel space without leaking.

According to industry specifications such as B82 Shotcrete Work (TfNSW, 2022), the maximum permissible unrestrained drying shrinkage strain for shotcrete at 56 days is 800 $\mu\varepsilon$ (based on AS1012.13). Taking the exposed perimeter of the lining into account (in accordance with AS5100.5) to calculate the hypothetical drying thickness (equal to twice the actual thickness), a realistic design drying shrinkage strain lies somewhere between 480 and 800 $\mu\varepsilon$ for a 75 mm thick lining depending on the relative humidity. For an elastic modulus of 15-25 GPa (depending on the age of the shotcrete), this implies a shrinkage-induced tensile stress far in excess of the typical tensile strength of shotcrete. In the opinion of the author, it is inevitable that a lining made of such a material will suffer drying shrinkage cracking. Indeed, the design for many recently constructed tunnel linings anticipated that drying shrinkage cracks would occur in the shotcrete lining and limits were therefore set on maximum allowable crack widths. The problem for the operators of the tunnels has been the very large number of drying shrinkage cracks that occur, and the ongoing challenge of managing the impacts associated with these cracks.

Tunnels are usually required to be at least free of dripping water. For transport tunnels, drips are not permitted onto trafficable surfaces such as roadways due to concerns about vehicle slippage. Moreover, drips are not permitted on equipment such as catenary in rail tunnels or M&E due to corrosion concerns. As described above, it is difficult to produce an entirely ‘waterproof’ lining so measures need to be taken to prevent or intercept the dripping groundwater. One approach is to include a water-proofing membrane within the lining, but this approach may not be entirely effective. A second approach is to intercept drips using strip drains and drainage mats that are usually installed when and where dripping is observed. However, this has also been found to be only partially effective. A third approach is to drill weep holes into the surrounding rock, intercepting geological features such as bedding planes to provide alternative routes for the groundwater to drain before it contacts the shotcrete lining. Each of these methods has its own advantages and disadvantages, but all have been developed in response to the fact that drying shrinkage cracks are ubiquitous in slender shotcrete linings and lead to leaks and seeps.

2 EFFECT OF SHRINKAGE CRACKS ON LINING DURABILITY

The design exposure environment prevailing for shotcrete linings in tunnels within Australia is usually taken to be governed by the requirements of AS5100.5. Unfortunately, this document was never intended to be applied to tunnel linings and remains inadequate to the task as it does not take into account the unique micro-environments prevailing in most tunnels. Tunnels are dynamic environments through which groundwater and air move at a much more rapid rate than other underground structures such as piles and foundations. Exposure classifications based on stationary contact with non-flowing groundwater are inappropriate to the assessment of the potential deterioration mechanisms unique to tunnel linings. Moreover, evaporation of groundwater at drying surfaces (particularly around cracks, Figure 1) has been observed to be significant in Australian tunnels: this process increases the ionic strength of contaminants in the groundwater that remains at points of evaporation on the lining surface leading to a more aggressive exposure condition than is suggested by the concentration of contaminants in groundwater within the surrounding rock.

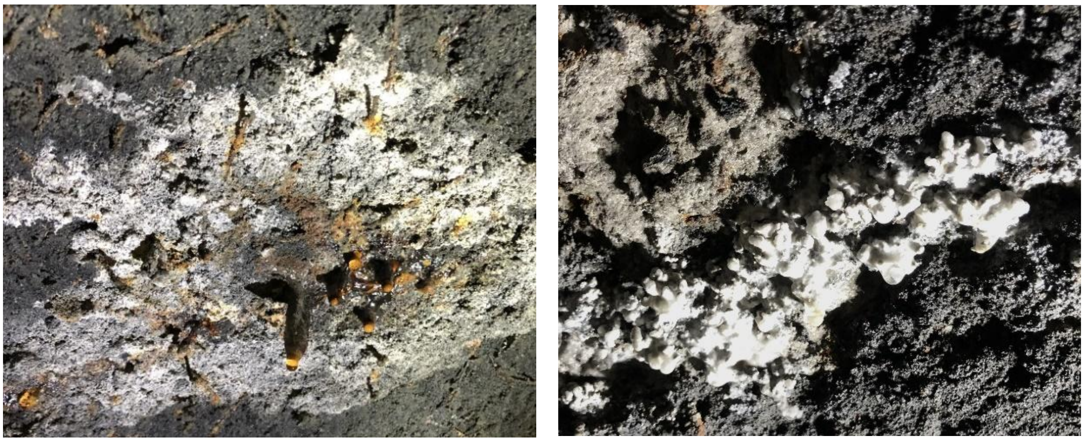

Figure 1. Examples of calcite precipitation in the form of a crust at a drying surface adjacent to slowly leaking cracks in a shotcrete lining.

Conventional thinking posits that calcite, generated by reactions between calcium hydroxide in the shotcrete and carbonic acid in percolating groundwater, will precipitate within and seal cracks that occur in a shotcrete lining. However, the presence of metallic ions in groundwater, such as magnesium and ferrous ions, increases the solubility of calcite thereby preventing precipitation of calcite in cracks (Katz et al, 1993; Nielsen et al, 2013). This process will often preclude autogenous sealing of cracks that occur through concrete linings in underground environments due to the ubiquitous occurrence of metallic ions in groundwater (Edvardsen, 2022). The failure of calcite precipitation to seal cracks is evidenced by the clear absence of calcite in through-thickness cracks observed in cores drilled through some tunnel linings. Instead, when the groundwater (ladened with dissolved calcite) emerges from a crack into the tunnel space and contacts air, the ferrous ions are precipitated out as iron oxide which then allows the calcite to precipitate as a crust at the mouth of cracks (Figure 1). The absence of precipitated calcite within the cracks means that steel fibres bridging the cracks are not protected from corrosion.

Evaporation of groundwater at drying surfaces in and around cracks leads to an accumulation of salts such as sodium chloride and magnesium sulphate which subsequently precipitate within the crust at the mouth of the crack (Figure 2). Given that the solubility of sodium chloride is 386 g/L, and that of magnesium sulphate is 186 g/L (at 20°C), the concentration of these salts must reach extreme levels in water within the crack for precipitation to occur. Relatively high concentrations of solid chloride- and sulphate-rich salts within the calcite-dominated efflorescence at the crack mouth act as a buffer to maintain elevated concentrations of these ions in the water within the crack during periods of near zero flow. Moreover, during periods of drying the surface meniscus of the water within a crack will steadily recede into the crack: this process will draw salt-rich water from the crack mouth deep into the crack thereby further promoting corrosion of the steel fibres (Figure 2).

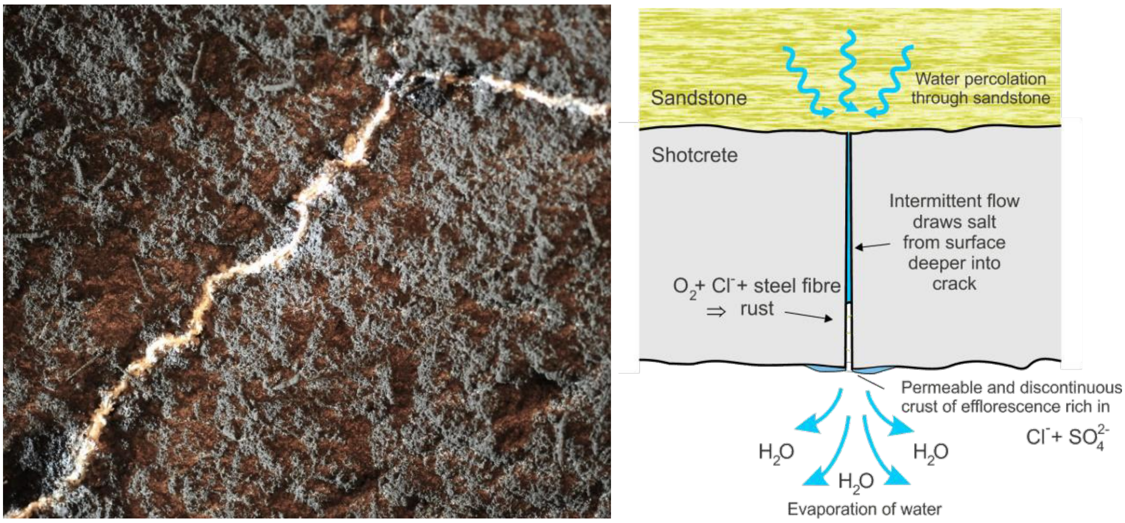

Figure 2. Percolation of groundwater through shrinkage cracks in a shotcrete lining lead to accumulation of calcite and salt at the drying surface.

Since cycles of wetting and drying occur regularly within most tunnels this process will result in a steady penetration of elevated concentrations of chloride and sulphate ions into cracks, despite the fact that gravity usually acts to drive water in the opposite direction (out of the crack) during periods of higher groundwater flow. The nett outcome is that chloride ions become concentrated in the small amount of water remaining within and around the crack, leading to rapid corrosion of steel fibres (Marcos-Meson et al, 2018) and sulphate ions become concentrated to levels at which they are more likely to attack the concrete (Romer, 2003; Hagelia, 2011, 2018; see Figure 3). Use of macro-synthetic fibres eliminates the problem of corrosion (Chernov et al, 2006) but will not prevent sulphate attack of the concrete matrix.

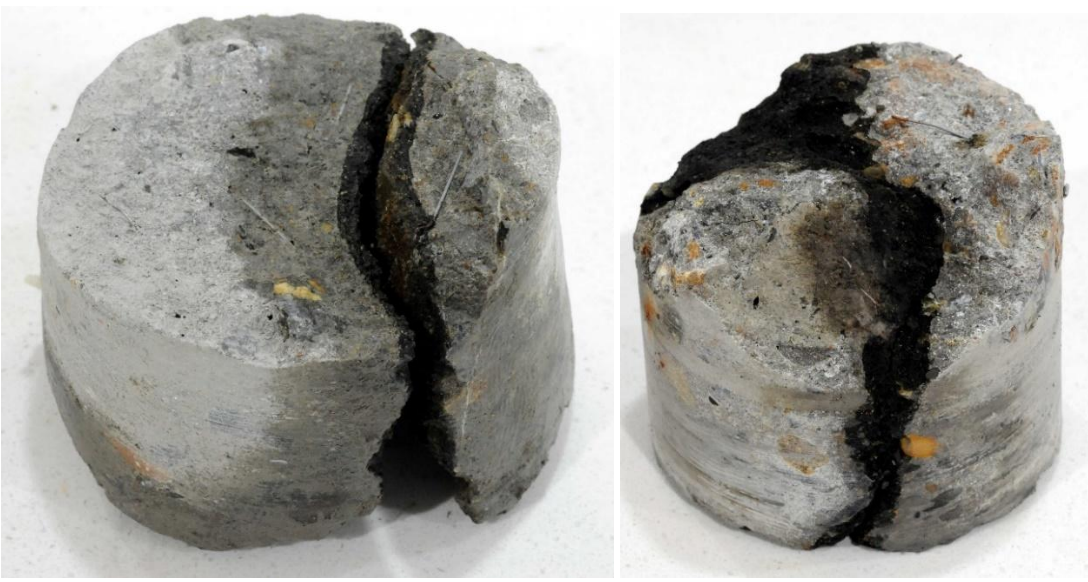
Figure 3. Examples of sulphate attack in shrinkage cracks through a shotcrete lining in a tunnel due to accumulation of sulphate ions through evaporation. Soft dark zone is depleted of calcium and enriched in magnesium and ferrous iron compared to adjacent un-altered shotcrete. The dark colour is caused by accumulation of ferrous oxide in degraded shotcrete.

The rate of corrosion of steel fibres is also governed by availability of oxygen, thus corrosion is more active near the atmospheric end of each through-crack and is relatively limited in the deeper recesses. Observations of corroded steel fibres in shrinkage cracks through shotcrete linings indicate that the 'oxidation depth' is about 50 mm for cracks 0.15 mm or greater in width. For this reason, shrinkage cracks through thin linings (< 150 mm) are likely to suffer more complete corrosion of steel fibres than would occur in shrinkage cracks (of equal width) through thick linings (> 150 mm).

3 EFFECT OF SHRINKAGE CRACKS ON STRUCTURAL CAPACITY

The most common method of designing slender shotcrete linings on hard rock is the method by Barrett and McCreath (1995). This method posits that the two main modes of lining failure are flexural and shear-based (see Figure 4). If the bond to the ground is poor or non-existent, a flexural mode of failure will govern the local load resistance of most linings. If the lining is well bonded to the ground the flexural resistance of the lining/rock composite (which tends to act like a beam) will most likely exceed the shear resistance of the lining so shear tends to govern capacity. The flexural and shear resistance of a lining are therefore estimated and compared to the load actions developed as a result of ground instability.

The presence of shrinkage cracks through a shotcrete lining can reduce the structural resistance of the lining for both flexural and shear modes of failure. Corrosion of steel reinforcement and fibres bridging a crack can locally eliminate both the tensile and flexural resistance. This is more likely to occur as the width of shrinkage cracks increases. If wider than about 0.3 mm, shrinkage cracks will also largely eliminate shear resistance. Thus, the existence of shrinkage cracks (especially wider than 0.3 mm) can locally diminish, or eliminate, the two principal mechanisms of load resistance described by Barrett and McCreath (1995). However, the extent to which this occurs will also depend on the thickness of the lining and density of local cracking.

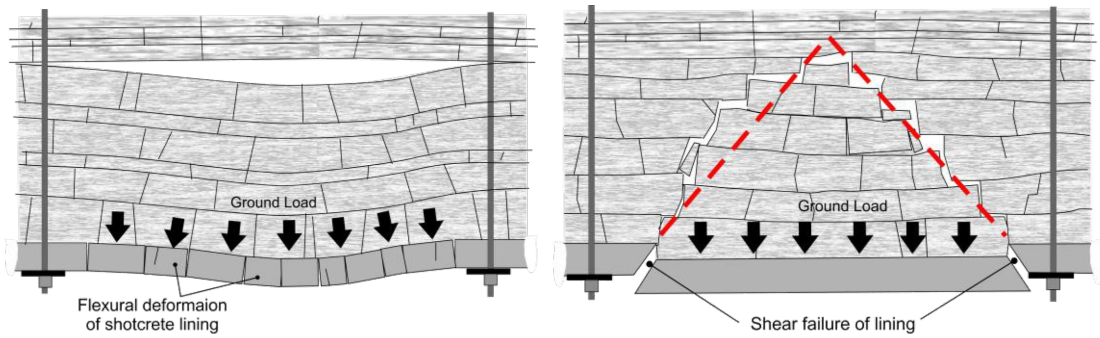

Figure 4. a) Flexural, and b) shear failure modes for slender shotcrete linings (based on Barrett and McCreath, 1995).

Many linings exhibit much greater load resistance than is suggested by pure flexural or shear action alone, largely due to Compressive Membrane Action (CMA, Reid and Bernard, 2024). This mechanism of load resistance is strongly dependent on the degree of in-plane restraint available within a shotcrete membrane, which, in turn, is diminished by the presence of shrinkage cracks. The presence of a discontinuity such as a through-thickness shrinkage crack reduces the in-plane stiffness of a lining and increases the magnitude of deformation in the flexural failure zone required before CMA is achieved (Figure 5). For example, through-thickness cracks of about 0.3-0.4 mm width can largely eliminate the potential for CMA in a slender lining of 50 mm thickness (when assessed using the method by Reid and Bernard, 2024). This is particularly significant for de-bonded regions of lining between widely spaced points of support. Elimination of CMA will reduce the load resistance of a slender lining to a level based on pure bending or shear, but as mentioned earlier, shrinkage cracking and corrosion of steel fibres can also diminish or eliminate load resistance associated with these simpler modes of resistance.

Given the significant effect that shrinkage cracking and deterioration within these cracks can have on water ingress and load resistance, it is prudent to examine what can be done to prevent the high incidence of shrinkage cracking observed in many tunnels or repair the cracks that already exist. Strategies for managing shrinkage cracks are described in the following pages.

Figure 5. Drying shrinkage cracks through the thickness of shotcrete linings. These cracks diminish in-plane stiffness and, as a result, reduce the effectiveness of CMA.

4 SEALING OF CRACKS

Surveys of cracks in shotcrete linings in Australia have identified that the majority arise as a result of drying shrinkage rather than thermal shrinkage or ground movement. This is particularly true of areas exhibiting extensive inter-connected cracking in which polygonal ‘plates’ form between the cracks (Figure 6a). In other areas, the shrinkage-based nature of cracking has been confirmed by surveys which have demonstrated an absence of convergence or localised ground movement.

Figure 6. a) Polygonal drying shrinkage cracks in a shotcrete lining, and b) secondary cracking of an epoxy repair membrane caused by on-going shrinkage of the lining.

In the absence of groundwater, shrinkage cracks are seldom noticed. However, groundwater often finds and leaks through these cracks leading to dripping and durability problems. When this happens, tunnel operators are usually required to ‘manage’ the leak in a manner that conforms with operational requirements to limit water ingress onto road surfaces, rail infra-structure, and mechanical equipment.

One solution often proposed to the problem of ‘managing’ drying shrinkage cracks that drip groundwater is to seal them with resin or grout as they occur. There are several problems with this approach:

1. Sealing a crack does not reduce shrinkage strains in the surrounding lining and therefore does not diminish the incidence of these cracks,
2. Sealing merely prevents water leakage and does not reinstate the structural performance of a lining,

3. Sealing of a crack in the lining diverts the groundwater and very likely promotes leakage somewhere else,
4. Drying shrinkage clearly occurs over an extended period of time (evidenced both by measurements in the lab and survey evidence of steady crack width increase over time in tunnels). Sealing them when they first appear therefore leads to the necessity to re-seal them as they suffer secondary cracking due to continued drying shrinkage (Figure 6b). If they are left to progressively widen until they reach a stable long-term width (which can take several years), leakage of groundwater and accumulation of aggressive ions at the drying surface can damage the lining and reinforcement in the vicinity of the crack before sealing is implemented,
5. Drying shrinkage cracks often induce curling and de-bonding of a lining on each side of the crack (Malmgren et al, 2005). The pressure required to inject grout into a crack to effect proper filling may therefore 'jack' the lining off the substrate which can lead to more serious long-term problems than dripping (Figure 7).

Further to the curling issue listed above, the problem of lining curl on either side of cracks has been extensively examined by Malmgren et al (2005), Carlswärd (2009), and Sjölander and Ansell (2017) who all concluded that de-bonding of a lining in the vicinity of a crack is inevitable because the tensile stress generated at the substrate boundary far exceeds the tensile strength of concrete (Silfwerbrand, 1997). Once initiated, the de-bonding extends to a width equal to about three times the thickness on either side of a crack (Figure 7a). Injecting grout or resin under pressure into a crack with de-bonded edges could therefore induce peeling at the adjacent boundary between lining and ground (Figure 7b). Peeling can result in a very low effective bond strength between lining and ground, as evidenced in tests conducted by Fernandez-Delgrado et al (1975), leading to the enlargement of de-bonded regions around a crack. Peeling action was described as 'adhesive failure' by Barrett and McCreath (1995) and was recognised as a significant mode of lining failure by Hahn and Holmgren (1979).

The potential for effective crack sealing is better for narrow cracks compared to wide cracks, thus any measure that reduces crack widths will improve the likelihood of successful sealing. Reinforcement may provide some control on the width of drying shrinkage cracks once they occur (Granju, 1997), but the beneficial influence of fibres is relatively limited at the dosage rates typically used in shotcrete linings. Post-crack creep through pull-out of both steel and macro-synthetic fibres, especially at early ages (Larive et al, 2016; Boshoff and Nieuwoudt, 2017; Babafemi et al, 2018), can limit the effectiveness of fibres in controlling drying shrinkage crack widths. Corrosion of steel fibres will also diminish or eliminate the likelihood that this type of fibre will restrain the widening of shrinkage cracks. All the shotcrete linings observed by the author to suffer drying shrinkage cracks (with average widths of 0.3-0.4 mm) were reinforced with between 30 and 45 kg/m^3 of hooked-end steel fibres, thus the presence of steel fibre reinforcement clearly failed to prevent the development of unacceptably wide shrinkage cracks in linings constructed to date.

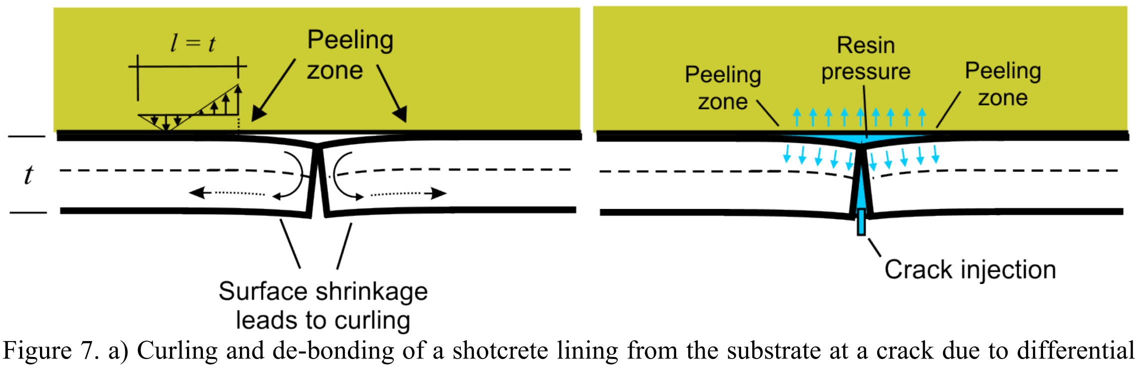

Figure 7. a) Curling and de-bonding of a shotcrete lining from the substrate at a crack due to differential shrinkage strains between exterior and interior regions of the lining (Reid and Bernard, 2019), and b) enlargement of de-bonded zone by resin injection.

The widespread incidence of drying shrinkage cracks in shotcrete linings observed both in Australia and internationally indicates that the common analytical approach of modelling shrinkage strains using 'thermal equivalence' does not result in a realistic estimate of lining behaviour. Instead, drying shrinkage causes a slender lining to break into plates bounded by cracks that, as a result of corrosion, creep, and other processes, lack sufficient tensile capacity across the cracks to induce a uniform tensile stress field throughout a lining. The presence of cracks disrupts the distribution of stress thereby undermining the models used to assess long-term behaviour (Bodner, 2022). An improved means of modelling drying shrinkage in shotcrete linings that takes account of the presence of cracks is clearly needed.

5 THE EFFECTS OF WIND, HUMIDITY, AND TEMPERATURE

Shotcrete tunnel linings tend to be quite thick in most countries, and shotcrete-based final linings are still relatively rare. Australia has been a pioneer in the use of slender single-pass shotcrete linings, but they are also used in Scandinavia and to a lesser degree in Chile. It is therefore instructive to examine the in-service performance of shotcrete linings in these countries in relation to drying shrinkage cracking.

The Norwegian practice for construction of shotcrete linings in road tunnels has been to apply a minimum thickness of 50 mm in stable hard-rock conditions, which was increased to 80 mm in 2020 (Holter et al, 2021). Further increases in thickness can be introduced to allow for degraded stability (NTS, 2010). Examination of these linings after 15-20 years of service has revealed a relatively low incidence of drying shrinkage cracking in some areas (Manquehual et al, 2022), but a high incidence in others (Holter, 2015). The incidence of cracking appears to be related to the average relative humidity in Norwegian tunnels, with some very humid coastal tunnels experiencing low levels of cracking.

Temperature variations can have a significant influence on existing crack widths. Mapping of cracks and measurement of crack widths in a shotcrete lining in Norway by Holter (2015) over a period of a year indicated that the width of cracks varied seasonally. For a 110 mm thick lining sprayed over a spray-on waterproof membrane base (which itself covered a primary lining sprayed onto a drill and blast rock surface) the mean spacing between drying shrinkage cracks was 700-1000 mm. The width of the drying shrinkage cracks varied by about 0.2 mm between winter and summer, with maximum crack widths occurring in winter and minimums in summer (for a mean seasonal temperature change in the lining of 6°C). This implies that injection sealing should be done in winter but also suggests that sealing is unlikely to be completely effective due to the combined effects of creep and seasonal thermal straining.

Low temperatures can also have a direct effect on drying shrinkage cracking of young shotcrete by limiting the development of tensile strength during the first few days of hydration. In cool and dry conditions, the likelihood of shrinkage cracking is increased because the development of tensile stress in the young lining as a result of drying shrinkage may exceed the rate of tensile strength increase. Warm humid conditions with minimal air flow represent the ideal environment for curing young shotcrete.

Investigations of drying shrinkage cracks over drain mats in Swedish tunnels (Ansell and Bryne, 2015) have indicated crack widths can average as much as 1.2 mm when shotcrete is sprayed onto a substrate providing low restraint. Since most fibre reinforced shotcrete is strain softening in direct tension, only one crack tends to form over a drain and all the accumulated drying shrinkage in the adjacent lining tends to manifest as widening of the initial crack. This was observed to occur even when curing conditions were good.

Australian tunnels generally suffer from low ambient humidity made worse by forced ventilation. Of particular concern is the Relative Humidity of air forced into tunnels during nights, especially in winter. Cool external air moving into a warm tunnel space tends to warm up upon contact with tunnel surfaces. Given that the total moisture content of the air remains relatively constant, this leads to a fall in Relative Humidity. For example, using the method of RH estimation described by Korotcenkov (2018), external air at 10°C and 60% RH entering a tunnel and rising in temperature to 20°C will experience a fall in RH to 45%. Heating of air in the tunnel also occurs due to vehicle operation, further exacerbating the problem. These processes cause the tunnel environment to be more arid than the nearby external environment. A more arid environment will lead to increased drying shrinkage.

The effect of a reduction in humidity on shrinkage strains can be assessed as follows. Using Figure 6.1.7.2 of AS5100.5 one can estimate that the long-term drying shrinkage strain will increase by 30% if the exposure environment changes from ‘temperate’ to ‘arid’. Alternatively, Model Code 2010 considers of the effect of Relative Humidity on drying shrinkage via Eqn. 5.1-

77, which includes a relative humidity factor β_{RH} (in which RH is expressed in percent) applied to the total design drying shrinkage:

$$\beta_{RH} = 1.55\left[1 - \left(\frac{RH}{100}\right)^3\right] \tag{1}$$

This equation implies that drying shrinkage in hardened concrete will increase by 16% with a fall in RH from 60 to 45%. This function also appears in ACI 209.2R, but an alternative factor equal to $\beta_{RH} = (1 - (RH/100)^4)$ is available within this guideline that implies a change of only 10% in drying shrinkage.

Another factor to consider is that an increase in ambient humidity may cause concrete to absorb moisture from the air and swell (Neville, 1996). The magnitude of this swelling will depend on the Relative Humidity, temperature, and age of the concrete, but can be as great as 300 $\mu\varepsilon$. Successive cycles of wetting and drying may cause a shotcrete lining to experience cyclic changes in surface strain and crack widths similar to the effects induced by thermal changes.

The effect of wind (including ventilation) over the surface of a young shotcrete lining draws moisture out of the surface of the lining and increases drying shrinkage. It has been known for a long time that effective curing measures such as ponding or application of curing compounds are required to prevent loss of moisture from the surface of young concrete (Hover, 2006). However, neither ponding nor curing compounds are practical in tunnel construction where shotcrete layers tend to be built up in multiple layers. Relative Humidity, temperature, and wind speed relative to the surface of the concrete all contribute to moisture loss which adversely affects hydration and especially shrinkage strains. The absence of bleed and the roughness of most shotcrete linings exacerbates the problem for tunnel linings. Zhang et al (2020) demonstrated that wind speeds of 0.5-1.5 m/s over the surface of young cement paste can substantially increase drying shrinkage strains (by up to 100%) over the first few days of hydration, compared to samples in still air. The necessity of ventilating tunnels during construction increases the amount of drying shrinkage the lining is likely to experience compared to the 'temperate' conditions assumed in AS5100.5, with the worst shrinkage likely to occur in the most heavily ventilated areas such as near the excavation face.

The damaging effect of wind is another reason why thin shotcrete linings tend to suffer worse drying shrinkage cracking than thicker linings: the outer layer of shotcrete suffers the most severe dehydration but also protects the underlying shotcrete from water loss. As thickness is increased, a larger proportion of the total shotcrete thickness is protected from moisture loss by the outermost layer.

5.1 *Effect of Set Accelerators on Drying Shrinkage*

Like all accelerators, Aluminium Sulphate-based set accelerators are known to increase drying shrinkage (Goodier et al, 2007; Lagerblad et al, 2010; Yang et al, 2022). They do this by changing the chemistry of the hydration reactions in sprayed shotcrete compared to shotcrete lacking an accelerator. The magnitude of the effect varies with the type of accelerator and dosage rate used. Due to the difficulty of producing unrestrained shrinkage specimens using set accelerated shotcrete, the typical magnitude of unrestrained drying shrinkage strain likely to occur in Australian shotcrete mixtures has seldom been examined.

To address this shortcoming, two trials were undertaken in which the dosage rate of SA160 set accelerator was varied from 0 to 4% by weight of cement (bwc). One mix included 30 kg/m^3 of Dramix RC35/65 3D fibres, while the other had 6 kg/m^3 of Barchip BC48 macro-synthetic fibres. Both sets of specimens were made with the same shotcrete mixture dosed with differing types of fibre (Table 1). This mix was a commercial shotcrete mix supplied by a local ready-mixed concrete supplier. Unrestrained drying shrinkage specimens were produced by spraying accelerated and non-accelerated shotcrete into beamlet moulds and screeding the surface level immediately after spraying. All specimens were wet-cured for only one day and AS1012.13 shrinkage measurements out to 5 years were based on the initial beamlet length measured at one day's age.

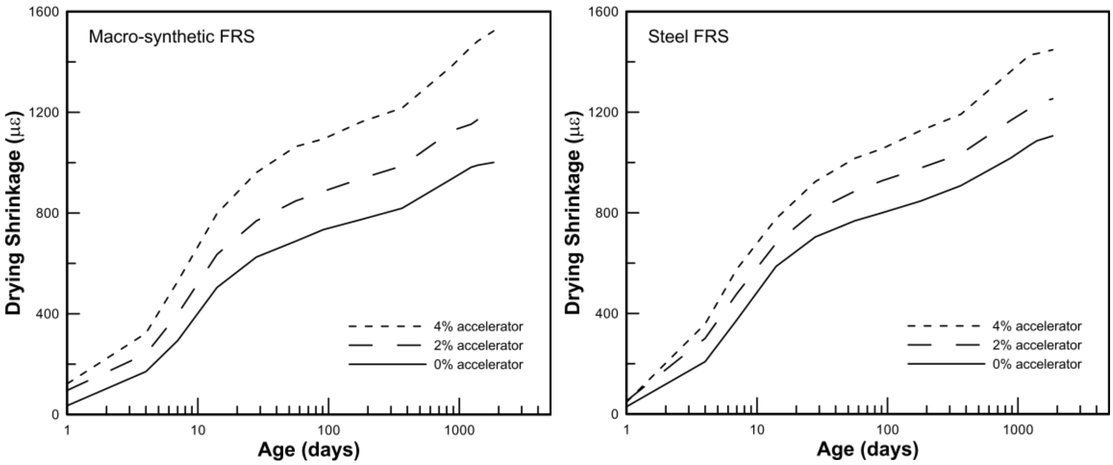

Figure 8. Drying shrinkage to 5 years for sprayed shotcrete reinforced with a) macro synthetic fibres (L), and b) steel fibres (R), for varying dosages of set accelerator (bwc).

The results indicated that addition of 2% bwc SA160 set accelerator increased the drying shrinkage by an average 17% compared to the non-accelerated sprayed mix, and addition of 4% bwc SA160 increased the drying shrinkage by an average 41% at 5 years (Figure 8). The mean 5 year drying shrinkage strain was 1485 με for the 4% mixes compared to 1050 με for the non-accelerated mix and 1226 με for the 2% mixes. However, in these trials the as-delivered shotcrete included some inadvertent entrained air, which was expelled upon spraying and caused the as-delivered cast shrinkage specimens to exhibit a 5 year drying shrinkage strain similar to the sprayed specimens with 2% set accelerator. The 28 day UCS was 34 MPa and 365 day UCS was 53 MPa. These results are consistent with shrinkage data obtained by Goodier et al (2007) for shotcrete sprayed with and without set accelerator tested to an age of three years.

When assessing the significance of measured unrestrained drying shrinkage according to AS1012.13, it should also be noted that these tests (even when based on only one day of curing) do not include autogenous shrinkage, which is largely related to the strength of the concrete and is independent of drying effects. For a 40-50 MPa shotcrete mixture the typical magnitude of autogenous shrinkage is about 50 με at an age of one day. Autogenous shrinkage is unavoidable in situ and therefore must be added to the drying shrinkage values measured using tests such as AS1012.13 to arrive at the total expected unrestrained shrinkage.

The results of the trial described above indicate that measurements of cast non-accelerated unrestrained drying shrinkage obtained at 56 days under-estimates the long-term drying shrinkage likely to occur in shotcrete sprayed with realistic dosages of set accelerator. This needs to be taken into account in estimating the long-term potential for shrinkage cracking. The results also confirm that the type of fibre used in the mix has a minimal effect on unrestrained drying shrinkage at the dosage rates typical of shotcrete (Zhang and Li, 2001). This data indicates that limits on the maximum allowable dosage rate of set accelerator should not be based solely on the potentially damaging effect these admixtures can have on long-term strength and durability but should also be based on their potentially deleterious effect on drying shrinkage.

Table 1. Mix design for shotcrete used to assess effect of set accelerator on drying shrinkage

Ingredient	Quantity
Coarse aggregate (10/7 mm basalt)	610
Coarse sand (Clarence sand)	350
Fine sand (beach sand)	680
Cement (Gladstone SL)	345
Fly Ash (Gladstone)	100
Undensified Silica Fume	10
PCE Super (L/m^3)	1.0
Slump (mm)	150

6 PREVENTION OF SHRINKAGE CRACKING

The conclusion from the discussion and test data presented above is that drying shrinkage cracking is a problem that cannot easily be remedied in arrears but is best addressed by prevention. The available methods of achieving this are most likely restricted to only three options: development of a more effective means of curing, development of low-shrinkage shotcrete mixtures, or imposition of stricter limits on dosage rates of set accelerator.

6.1 *Surface Curing*

In the absence of water-based curing, using, for example, misting or regular hosing, curing membranes could be applied as soon as the final layer of shotcrete is completed. This could possibly be combined with the black paint that is normally applied to shotcrete linings. However, surface curing may not be effective if the final lining is applied weeks or months after the initial layer. Moreover, a surface layer will interfere with bond between the lining and any supplementary shotcrete that might be applied at a later date, say, in the event of large cracks occurring in the lining or construction damage. Constructors are therefore reluctant to use surface-curing compounds on shotcrete linings.

6.2 *Internal Curing Compounds*

Internal curing compounds (ICC) have often been cited as a possible solution to the problem of drying shrinkage cracking of tunnel linings, but evidence from comparative trials (using shotcrete dosed with and without ICC, Bernard, 2006) has shown that these additives have a minor effect on unrestrained drying shrinkage strains (Figure 9). The mean reduction in 56 day drying shrinkage for shotcrete dosed with the recommended dosage of ICC was only 5% compared to plain controls in dry cure (DC) conditions (one day of wet cure followed by continuous atmospheric cure at 50% RH and 23°C). As expected, shrinkage in continuous wet-cure conditions was negligible. The control contained 50 kg/m^3 of steel fibres, 420 kg/m^3 of cementitious material, and had a 28 day UCS of 32 MPa.

In the absence of any evidence to the contrary, internal curing compounds do not appear to reduce drying shrinkage strains by a meaningful amount compared to plain shotcrete, so they are not going to be effective in controlling drying shrinkage cracks in shotcrete linings.

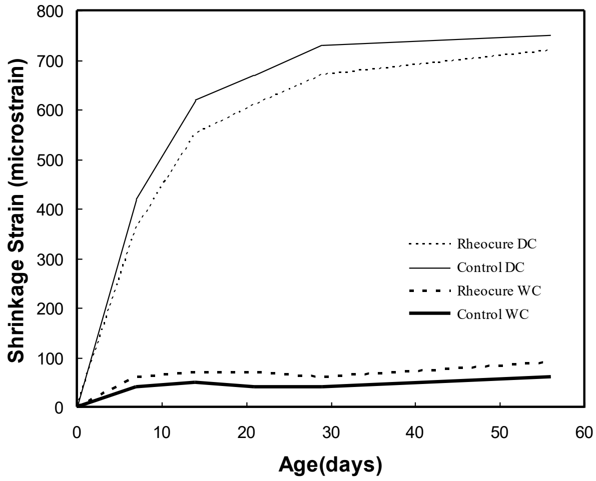

Figure 9. Unrestrained drying shrinkage strain results for Rheocure 736 ICC (Bernard, 2006).

Greater success was observed with the inclusion of Shrinkage Reduction Agents (SRA) in shotcrete (Bernard, 2006; Holter et al, 2023). This type of admixture was found to reduce drying shrinkage by about 20% compared to a plain control when used at the recommended dosage rate. Although their effects on other properties of shotcrete remain to be examined, this type of admixture may prove useful in limiting the extent of drying shrinkage cracking especially if used together with other measures. Other materials, such as Crack Reduction Admixtures and Type K cement, also present opportunities for drying shrinkage reduction.

6.3 *Low Shrinkage Shotcrete*

An alternative approach to controlling drying shrinkage cracking is to develop mix designs that exhibit inherently lower levels of drying shrinkage. There are several possible approaches to achieving low shrinkage: either use a geo-polymer or produce a very dense conventional mix with a very low water/binder ratio. Such a mix can be developed within the context of the B82 Base Mix evaluation requirements for the development of a mix conforming with the B82 Shotcrete Work specification (TfNSW, 2022), but with an emphasis on minimising drying shrinkage to values less than the presently permitted 800 $\mu\varepsilon$ at 56 days. However, the B82 guideline primarily focuses on the development of a base mix produced in a batch plant so additional consideration must be made to the effect of accelerators.

7 COMPLICATING FACTORS

The main factor that is not accounted for in most design estimates of in situ drying shrinkage strains and crack widths for shotcrete linings is the influence of the restraint provided by the rock or underlying primary shotcrete lining. A stiff high-friction substrate will limit the magnitude of shrinkage strain experienced locally within a bonded lining. That is why membranes such as FRS linings, which almost always exhibit post-crack strain-softening behaviour in direct tension, experience distributed cracking rather than one large crack in response to shrinkage. As outlined in CIRIA C766D (Bamforth, 2018) and described by Raoufi et al (2011), shrinkage crack spacing (and consequently crack widths) will depend on the stiffness and coefficient of friction with restraining surfaces that are in contact with the shrinking concrete member. For the case of shotcrete sprayed on hard rock, the stiffness of the rock substrate is largely fixed, but the coefficient of friction will depend on roughness, cleanliness, and other factors. Additionally, the presence of a water-proofing membrane will reduce the effective stiffness of the substrate as a result of the time-dependent shear characteristics of the materials typically comprising the membrane. Finally, the stiffness of a thin lining is lower than that of a thick lining hence the substrate will induce a higher relative degree of substrate restraint for a thin lining than a thick lining (Destrée et al, 2016).

A problem will arise if bond between the lining and substrate is lost with the passage of time. An unbonded lining will be subject to less restraint against shrinkage than a fully bonded lining, with the likely outcome that cracks are fewer in number but greater in width. However, given the uncertainty that exists regarding the rate and pattern of bond loss that a lining may experience, it is difficult to quantify precisely how bond loss is likely to affect crack widths. Moreover, no agreed method of analysis exists to estimate drying shrinkage crack spacing for a strain-softening bonded lining so this critical aspect of lining design for serviceability and durability is difficult to implement.

Tensile creep is another phenomenon that tends to mitigate the damaging effect of shrinkage but only if restraint against shrinkage exists. The most common manifestation of the effect of tensile creep is the advantage provided by high levels of tensile reinforcement across cracks (Granju, 1997). Reinforcement will not prevent the occurrence of cracks but may act to limit crack widths even for a strain-softening material. It does this by inducing tension in the surrounding shotcrete, which leads to tensile creep in the uncracked material, thereby reducing the total tensile strain that is manifested at the crack (Destrée et al, 2016). However, the effect of creep and time-dependent slip at the fibre-paste boundary, which occurs for both steel and macro-synthetic fibres (Boshoff and Nieuwoudt, 2017; Babafemi et al, 2018), reduces the restraint provided by fibres in relation to crack widening (Bernard and Amin, 2023). Unfortunately, this aspect of shotcrete behaviour is very complex to model and remains within the realm of research and is ignored in most designs.

7.1 *"Thicker is Better" for Drying Shrinkage*

Apart from the protection against drying that the outermost exposed layer of shotcrete provides to shotcrete located deeper within a newly sprayed lining, two other factors combine to reduce the degree of drying shrinkage a thick lining will experience compared to a thin lining of similar composition.

The in situ drying shrinkage exhibited by a slender lining will be affected by rebound during spraying. Internal restraint against drying shrinkage of the shotcrete is strongly affected by the amount of coarse aggregate present in the mix (all other factors being equal). Rebound of coarse aggregate is generally highest as the first 15-20 mm of shotcrete is sprayed onto a hard surface (Armelin and Banthia, 1998). As the thickness of the lining increases, the surface becomes relatively soft and sticky and thus the rebound of coarse aggregate decreases. This means that thin shotcrete linings (say, of 50 mm thickness) are relatively devoid of coarse aggregate particles compared to thicker linings (of 100-150 mm thickness) even if the same mixture is used to spray both. The result is a higher degree of potential drying shrinkage in thin linings.

Thin linings also have a smaller reservoir of embodied moisture available to supplement evaporation at the drying surface of a freshly sprayed surface than thick linings. This increases the risk of desiccation in the event of rapid evaporation from a freshly sprayed surface and generally reduces the degree of hydration achieved in the surface regions of a thin lining in the event of poor curing. The result is that thin linings are more sensitive to poor curing practices than thick linings and may potentially exhibit higher levels of drying shrinkage cracking in the event of sub-optimal curing.

8 SUMMARY

Drying shrinkage of shotcrete used in tunnel linings is significant compared to other forms of concrete and continues well beyond the normal 56-day period of specification and measurement. The result in recently constructed tunnels in Australia is a high incidence of shrinkage cracks. Shrinkage cracks in shotcrete linings are not benign as they can have a detrimental effect on both the durability and the structural capacity of a lining in addition to facilitating water ingress. For this reason, they must be addressed seriously during the design, construction, and service of shotcrete linings.

The present paper describes several mechanisms of lining deterioration observed to occur in some Australian tunnel linings and discusses the merits of alternative approaches to the prevention of shrinkage crack formation such as low shrinkage mix development, lower maximum allowable accelerator content, better wet curing practices (including misting), and reduced reliance on thin linings for long term support. It also addresses the problem of managing existing cracks, with particular attention given to the difficulties associated with water ingress and durability when numerous leaking shrinkage cracks arise and widen over a protracted period of time.

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