Abstract
The cracking due to drying shrinkage is a major issue associated with the usage of cementitiously stabilised materials (CSM) in road pavement construction. Since the creep strain that develops in the mix has the effect of reducing the induced shrinkage stress, proper determination of shrinkage and creep strain is important in the accurate estimation of shrinkage/tensile stress that may develop, and, therefore, the onset of cracking. The aim of the project was to develop effective and convenient laboratory test equipment and procedures for evaluating the shrinkage cracking resistance of stabilised materials commonly used in road construction. Laboratory testing was carried out to investigate shrinkage, tensile strength, and creep behaviour using one conventional cementitious binder and one binder comprising industrial waste products. Locally available basaltic crushed rock was used as pavement materials. Test results highlighted the effects of binder types on the shrinkage and tensile strength development in the pavement material. It is established that cracking potential of a stabilised material could be evaluated by comparing tensile stress with the tensile strength. Creep had a significant effect on tensile stress development in the pavement material, and the pavement designer should take this into consideration.

1. Background

The cracking due to drying shrinkage is a major issue associated with the usage of CSM in road pavement construction. Tensile stress develops when CSM are not allowed to shrink due to some restraint (e.g., friction at pavement layer interface). This results in initiation of cracking in CSM while tensile stress exceeds tensile strength. Shrinkage cracks can deteriorate the pavement performance by reducing the overall stiffness of the pavement system, allowing water infiltration into pavement base and subgrade, and by providing pathways for erosion of cemented materials (1). The regular sealing of cracks tends to reduce the adverse effects of cracks, but sealing can increase the road maintenance costs, looks unsightly and affects the riding qualities of the road surfaces (2). It follows that the possibility shrinkage cracking should be considered from the early stage of mix design undertaken in the laboratory.

One possible solution to this problem is to modify mix designs such that CSM would be
less susceptible to shrinkage cracking while maintaining their other performance requirements. Unfortunately, the tendency of a cementitiously stabilised mix to undergo shrinkage cracking is not just a simple function of its free shrinkage. It is also affected by factors such as the constraints on the specimen, rate of strength gain, temperature and the elastic modulus of the mix. The creep of the mix during its plastic stage can also relieve some of the induced shrinkage stress. All this pertinent factors need to be fully considered in evaluating a stabilised mix for its resistance to shrinkage cracking.

At present, there is no effective and convenient test procedure, which could be used to assess the resistance to shrinkage cracking of a CSM in service. The main objective of this research is to develop an effective and convenient laboratory test procedure and procedure for evaluating shrinkage cracking resistance of CSM mixes.

2. Laboratory Experiments

2.1 Description of Materials

2.1.1 Cementitious Binders

Binders used in these experiments include general purpose Portland cement (GP), and general blended cement (GB). Cement consisting of Portland cement with no more than 5% of other mineral additions is classified as GP cement, and that consisting Portland cement and a quantity comprised one or both of (1) greater than 5% of flyash or granulated iron blast furnace slag (GIBFS), or both; and (2) up to 10% silica fume is classified as general purpose blended cement (GB) (3). GB cements comprising of flyash or GIBFS, or both are commonly used in Australia as slow setting binders. Advantages of such binders over traditional binders such as GP cement include greater working time and the beneficial use of waste products, which may otherwise end up as landfill.

2.1.2 Host Material

The selected host material was crushed basaltic rock, commonly used in road pavements in Victoria, Australia due to the abundant availability of natural basaltic rock deposits. Samples were collected from a local quarry and were split and stored in 20 kg airtight plastic bags. Samples from each four bags were mixed and again stored in bags to minimise any variation between the samples. Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) were determined from standard Proctor compaction method as per Australian Standard AS 1289.5.1.1 – 1993 (4), and were found to be 9.8% and 22.04 kN/m³ respectively. Specific gravity, liquid limit and plasticity index of the material were found to be 2.97, 22% and 3% respectively.

2.2 Mix Preparation

The basaltic crushed rock was mixed with water to achieve optimum water content and even distribution within the mix. The binder at the rate of 3% of dry weight of host material, which is commonly used in Australia, was then added and was mixed for further two minutes. The mixture was kept in a container, covered to prevent moisture loss for 2 hours prior to compaction. Specimens were prepared with standard compactive efforts, proportional to the maximum dry density corresponding to optimum moisture content for all types of tests.
2.3 Drying Shrinkage Test

No standard methods are available for determination of drying shrinkage of CSM. There are standard test for unrestrained shrinkage testing of concrete specimens, where the following dimensions are commonly used: 75 mm (wide) x 75 mm (high) x 280 mm (long) in AS 1012.13 (5). Drying shrinkage tests were performed according to this method. The test method achieved two important aims as follows:

(a) The dimensions of the specimen should be relatively large compared to nominal maximum aggregate size of the material i.e. 19 mm, so that a representative portion of the material is used in the test.

(b) The shrinkage of stabilised soil should be measured in a plane normal to the direction of compaction to reflect the field condition.

The known quantity of stabilised mix as per maximum standard dry density was compacted in two layers into a rectangular steel mould. Standard Proctor hammer with maximum cross sectional dimension of 50 mm (65 mm including the guide) was used to compact the material. A clear gap of 5 mm between the inner face of the mould and outer face of the guide of the hammer facilitated uniform compaction with compaction energy proportionate to the standard compaction. A steel tamping bar was used for compaction of local areas and for obtaining a levelled surface. Specimens in duplicate were covered with two layers of wet plastic films and cured for 24 hours at 90% or above relative humidity (RH) and air temperature between 21°C and 24°C. Two gauge points were glued on the surface with an epoxy compound commercially named as ‘Araldite’ on the specimen with a spacing of 152 mm between them. After demoulding, the one-face drying was achieved by covering five sides with wax and plastic film to allow drying process from the top surface, measuring 75 mm x 280 mm. After curing period, the specimens were dried in a controlled environment with 50% RH and air temperature of 22°C. Shrinkage strain between the gauge points were recorded at regular time intervals with a digital micrometer of 0.001 mm sensitivity.

2.4 Direct Tensile Strength Test

2.4.1 Test Equipment

As shown in Figure 1(a), the frame of the test equipment utilised a conventional (Wykeham Farrance) direct shear test rig. The specimen mould assembly comprises two halves of the split mould and removable base plates, removable rigid base plate covering both moulds and removable side inserts (6 mm thick). Several shear keys were provided inside the moulds to restrain the specimen against tensile loading. In order to allow specimen failure to take place at the gap between the moulds, a neck at the ends of the moulds is formed reducing the specimen cross-sectional area from 100 mm x 100 mm to 70 mm x 100 mm. One half of the mould is held fixed and the other half is free to move longitudinally on ball bearings. The tensile load was applied by a conventional motor and was measured by a load cell positioned between the moving mould and the motor. The tensile displacement was measured by a linear variable differential transducer (LVDT) positioned on the specimen itself Figure 1 (b).
2.4.2 Placement of Mix in Moulds

Firstly, the two halves of the mould were screwed onto the rigid base plate, which firmly connected the two halves of the mould and provided a firm base for soil compaction. The side inserts were also placed and taped. The materials were compacted into the moulds using standard Proctor hammer. The material around the shear keys were compacted by using the special hammer used for compacting soils. The specimens within mould assembly were cured for 1 day prior to drying. The curing was conducted by covering the specimen by two layers of wet plastic film at a temperature of about 22°C. After curing specimens were dried from top surface prior to testing to simulate the field condition. Specimens in the mould were kept on rollers to allow any free shrinkage that might have occurred during drying. After desired drying durations, base plate for each two parts of the moulds was screwed on. Subsequently, the mould assembly was carefully turned up side, down and was placed on the testing frame. The one part was fixed to the testing frame and other, which rests on the roller bearings, was attached to the loading assembly via a load cell. The rigid base plate, which became the topside of the two halves of the moulds, was then removed. It was helpful to apply some grease on the inside of the rigid base plate prior to compaction of soil in order to facilitate its easy removal at this stage. The two halves of the mould were now separate and connected only through the specimen. The side inserts were either removed or kept in place without inducing any restraint to tensile loading. The specimen was then ready for testing.

2.4.3 Test Procedure

The tests were conducted at a constant tensile displacement rate of 1.285 mm/min without any load being applied. But actual speed ranged from 0.045 mm/minute to 0.0025 mm/minute depending on the stiffness of the mix. A high precision LVDT of 0.6 mm range was mounted directly across the specimen neck as shown in Figure 1(b). The LVDT and the reference cylindrical rod were screwed onto two rectangular metal blocks, which were firmly embedded on the material at a centre to centre spacing of 70 mm. The metal blocks measured 12 mm x 12 mm x 20 mm. The tensile displacement and loads were continually logged using HP VEE software onto a personal computer.
2.5 Restrained Shrinkage / Creep Test

2.5.1 Test Equipment
The test method studied was a restrained shrinkage test using a long specimen with flare ends similar to those used by other researchers (6,7). Figure 2(a) illustrates the schematic of the apparatus. The specimen was 75 mm X 75 mm in cross section and 280 mm long. It increases gradually in width at the two ends, which fit into two end grips. One grip was fixed (#3 in Fig.2 (a)), and the other (#2 in Fig.2 (a)) was free to move. The fabrication of a test specimen involved casting of fresh mix directly into the apparatus. The specimen could then be exposed to a specific drying condition and tested.

2.5.2 Preparation of the Restrained Specimen

Before casting the stabilised mix, a thin layer of lubricating fluid (commercially named as ‘Innox’) was applied on the base and two sides of the specimen mould to minimise friction. The surface of the metal guides at the vertical sides of the specimen was also applied with a thin layer of lubricating fluid. The specimen was cured by covering with two layers of wet plastic film at temperature between 21-24°C for 24 hours. Two gauge points were glued with an epoxy compound commercially named as ‘Araldite’ on the middle section of specimen with a spacing of 152 mm between them. After curing, the vertical sides (#4 in Fig.2 (a)) were removed and the vertical side surfaces of the specimen were covered with petroleum jelly and plastic film to prevent surface evaporation. The specimen in the mould was dried in a controlled environment with
relative humidity of 50% and temperature between 21°C to 24°C. The induced load was monitored by means of the proving ring (#1 in Fig.2 (a)), while the horizontal movements between the gauge points in the specimen were measured by digital micrometer (Fig. 2(c)) with a precision of 0.001 mm for a period of about 40 days.

3. Results

Though the specimen prepared with stabilised crushed rock mix was restrained from movement at the two ends, the micrometer measured shortening of the specimen. This could be explained by the movement of the proving ring as load was induced. There could be three different component of deformation in the specimen. The first component is the shortening due to shrinkage ($\delta_{sh}$). The second component is the elastic lengthening due to induced tensile stress ($\delta_E$). The third component is the creep due to induced stresses ($\delta_{CR}$). The three components are related to the measured movement of the specimen $\delta_m$ as follows:

$$\delta_m = \delta_{sh} - \delta_E - \delta_{CR}$$

(1)

in terms of strains, the relationship can be written as:

$$\varepsilon_m = \varepsilon_{sh} - \varepsilon_E - \varepsilon_{CR}$$

(2)

The measured strain in the restrained long specimen ($\varepsilon_m$) can be calculated from the deformation read by the digital micrometer ($\delta m$) as follows:

$$\varepsilon_m = \frac{\delta m}{L_g}$$

(3)

where $L_g =$ gauge length $= 152$ mm.

The elastic strain ($\varepsilon_E$) can be calculated from the induced stress ($\sigma_E$) and the elastic modulus of the stabilised material ($E$) as follows:

$$\varepsilon_E = \frac{\sigma_E}{E} = \frac{F_{PR}}{AE}$$

(4)

where $F_{PR} =$ force measured by the proving ring; $A =$ cross-sectional area of the
specimen = 56.25 cm².

The free unrestrained shrinkage strain ($\varepsilon_{sh}$) can be assumed to be equal to the free shrinkage strain measured by the digital micrometer on drying face of prismatic unrestrained shrinkage test sample (75 mm X 75 mm X 280 mm) with five sealed faces.

From Equation 2, 3 and 4, the creep strain ($\varepsilon_{CR}$) can be calculated from other strains as:

$$\varepsilon_{CR} = \varepsilon_{sh} - \varepsilon_{E} - \varepsilon_{m} = \varepsilon_{sh} - \frac{F_{PR}}{A_{E}} - \frac{\delta_{m}}{L_{g}}$$

(5)

The creep strain of the restrained specimen, as calculated in this fashion and free and restrained shrinkages were plotted as a function of time in Figures 3.

If a stabilised material member is fully restrained from movement, the induced stress due to drying shrinkage could be expressed as:

$$\sigma_{FC} = (\varepsilon_{sh} - \varepsilon_{CR})E$$

(6)

where $\sigma_{FC} =$ induced stress in a fully restrained specimen.

The induced stresses in a fully restrained specimen were computed by using the Equation 6. The free shrinkage strains as obtained from the free shrinkage measurements under similar environmental conditions were used as the shrinkage strain, $\varepsilon_{sh}$, while the computed creep strains from the restrained specimen test were used as the creep strains, $\varepsilon_{CR}$.

The computed shrinkage induced stresses for CSM with and without creep effects and direct tensile strength are plotted as a function of time in Figures 4 and 5 for GB and GP cement respectively. It could be seen from figure 4 that the induced shrinkage stress in CSM with binder GB cement could exceed tensile strength at approximately 2nd and 9th day with and without accounting for creep respectively. It could also be seen from Figure 5 that the induced shrinkage stress of CSM with GP cement could exceed the tensile strength of the concrete at approximately less than 1 day and 3rd day with and without accounting for creep respectively. Therefore, Creep has a significant effect on determination of cracking potential for a mix, which may be defined as the ratio of tensile stress and tensile strength.

![Graph](image)

Fig. 4- Tensile stress and strength with time for GB cement

A separate test was undertaken to examine the prediction of the onset of cracking perceived from the above analysis. This involved a test using GP cement with the both
grips of the moulds were fully restrained against any movements. Cracks initiated after 2 days of drying and continued to propagate to the entire depth during further drying.

**Fig. 5-** Tensile stress and strength with time for GP cement

### 4. Concluding Remarks

On the basis of limited experiments undertaken for determination of free shrinkage, tensile strength and creep under laboratory conditions, the experimental apparatus appeared to be useful for evaluation and benchmarking cracking potential for CSM. Further they could be used for validation and calibration of numerical model that can eventually be used to simulate the onset of cracking and crack propagation under field situation. Binder with industrial waste products appeared to reduce susceptibility of early cracking CSM in comparison to traditional binder like GP cement.

### 5. Acknowledgement

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### 6. References