“CRACK CONTROL – Are we getting it right?”

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CIA Presentation
Sydney 1 October 2003

1. INTRODUCTION

What causes concrete to crack and what can we do to control cracking in concrete?

Cracking in concrete arises from numerous causes. Sometimes cracking is significant but in many instances it is not. Classification is often made into subjective categories such as structural and non-structural cracks. The cause giving rise to the stress involved in each instance of cracking can often be readily identified. However, it is more difficult to identify the underlying reason for significant cracks. For example, cracks in the category ‘drying shrinkage cracks’ in slabs might be put down to excessive drying shrinkage of the concrete. The reality is that while the prime mover may be drying shrinkage, activities as compaction and curing are important, and a slab with relatively low shrinkage concrete may still develop significant shrinkage cracks.

It is therefore worthwhile to reflect on the basic mechanisms of cracking to shed light on underlying causes.

In this paper, crack classification and the significance of cracking are reviewed. Some general comments regarding the appropriate methods of controlling cracks are made and basic mechanisms of cracking are discussed. Test data showing the influence of compaction and curing on early and later age concrete properties is presented.

2. TYPES OF CRACKS

Figure 1 (Ref. 1) shows part of a structure with a variety of crack types. Most of the cracks actually shown could be broadly classified as non-structural cracks, the term taken to mean cracks which arise from causes not associated with the primary load carrying function of the structure. This category includes

- Plastic settlement cracks
- Plastic shrinkage cracks
- Thermally induced cracks
- Drying shrinkage cracks
- Corrosion spalling
- Alkali aggregate cracks and cracks due to other chemical effects

Included in the category of structural cracks are bending and shear cracks referred to in the figure but not shown. Note that cracks in the non-structural category are often the ones of concern. In many instances these can be prevented by good construction practice.

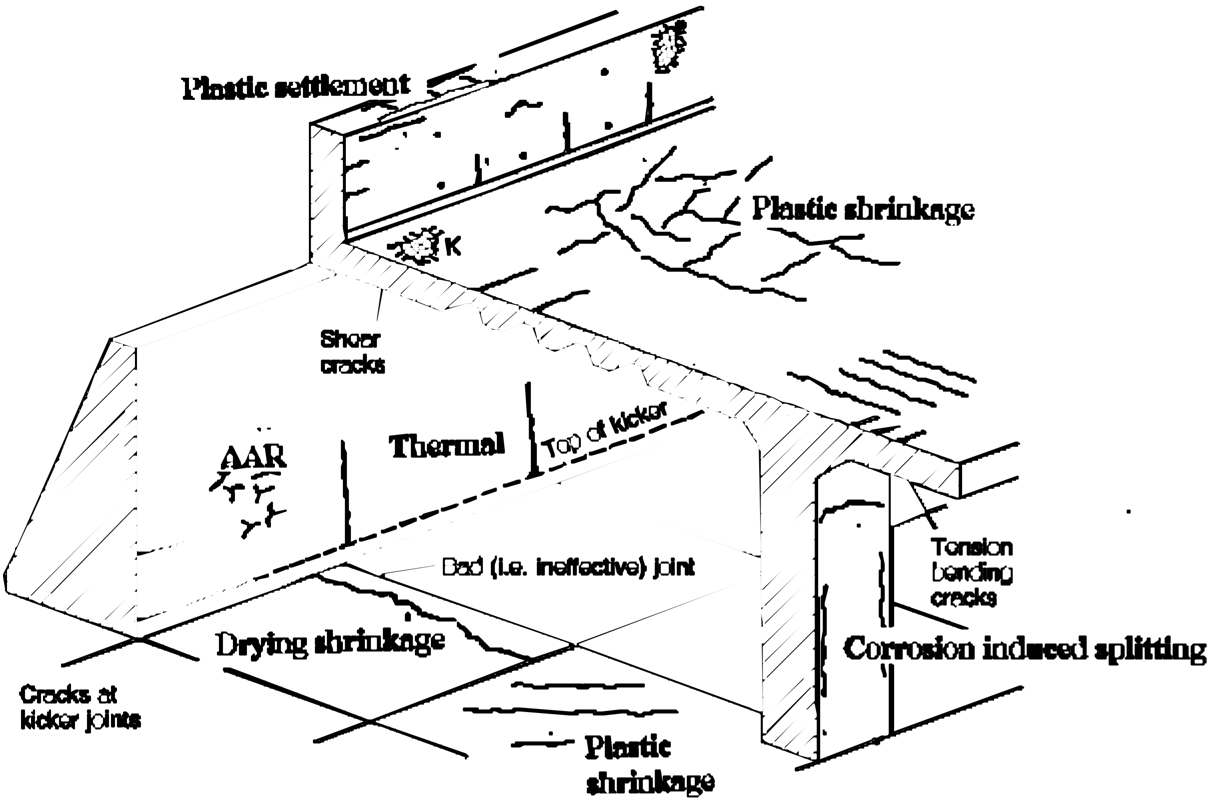

Figure 1: Examples of Crack Patterns (Ref 1)

Cracks initiate at defects in the presence of stress. Provided certain conditions are fulfilled, the crack may propagate. The propagation may be slow or fast. For example, load added to a simply supported beam can cause rapid development of flexural cracks. Shrinkage induced cracking in a slab can be slow to develop, taking many months for propagation across the full width of the slab. While the effect that produces the tensile stresses necessary for cracking may be different in each instance, the initiation and propagation of the cracks is governed by the same concrete properties and crack mechanics. Some crack mechanisms are reviewed in the section 4.

3. CONTROL OF CRACKS IN CONCRETE SLABS – STANDARD PRACTICE

The following is a brief review of the general approach to controlling cracking in concrete.

The control of cracks in concrete can be divided into three components:

- Reinforcement and Detailing;
- Jointing/ Saw cutting; and
- Prevention, through adequate compaction and curing.

The provision of adequate reinforcement in a slab will not prevent the formation of cracks. It will reduce the size and spacing of cracks, so that the cracks that inevitably form are smaller in width and smaller in number. Detailing issues are more pertinent to suspended slabs and will not be discussed further.

It is essential that a large expanse of slab-on ground be broken into smaller components through the provision of construction joints and/or saw cutting. Appropriate aspect ratios for these slabs segments should lie between 1.5:1 and 1:1. For typical slabs on ground, spacing of joints should lie somewhere between approximately 6m and 8m. The influence of ambient conditions (temperature, humidity etc), efficiency of curing and sub-base preparation can also influence optimal spacing of joints.

Saw cutting generally takes place somewhere within the first 5 to 16 hours after the placement of concrete. It is generally possible to early age, or “soft” saw cut in approximately half the time that “green” saw cutting can take place. That is, a slab that can be green cut at 8 hours may be soft cut at around 5 hours. The essential issues governing the effectiveness of saw cutting are ensuring adequate depth of the saw cut and ensuring that the saw cut is installed in a timely manner (ie before the concrete has cooled). A delay in the installation of saw cuts will usually ensure that cracks will form.

Prevention is always better than cure, and adequate compaction and curing are important factors in avoiding or minimizing cracking in slabs on ground. Particular care should be taken when compacting concrete in the vicinity of key and dowel joints. Timely, early and adequate curing will ensure that the in situ strength of the concrete maximized and the effects of early age shrinkage minimized.

In the following sections, the reasons behind the importance of compaction, curing and timely saw cutting will be explored by looking at the mechanisms that lead to the formation of cracks in slabs.

4. CRACK MECHANISMS

4.1 Fracture Energy

Figure 2 shows the result of a displacement-controlled test on concrete in uniform tension. The figure plots the applied tensile stress against extension (deformation) of the specimen. The applied stress has a maximum value equal to the tensile strength of the concrete. Beyond this point, the stress reduces as a crack gradually opens. The notional width of the crack is zero when the stress is at its maximum. As the overall deformation increases beyond this point, the elastic deformation away from the crack reduces and the crack gradually opens. When the stress finally reduces to zero, the total deformation is present as crack width.

An important observation from the figure is that it takes work for a crack to open or propagate. The area under the curve in Figure 2 is called the fracture energy and is a material property. It measures the work that needs to be done per unit new crack surface area (or the energy that needs to be expended per unit new crack surface area) in order for a crack to fully open. Fracture concepts are sometimes useful in design and appear in design codes (e.g. European Model Code, Ref 3).

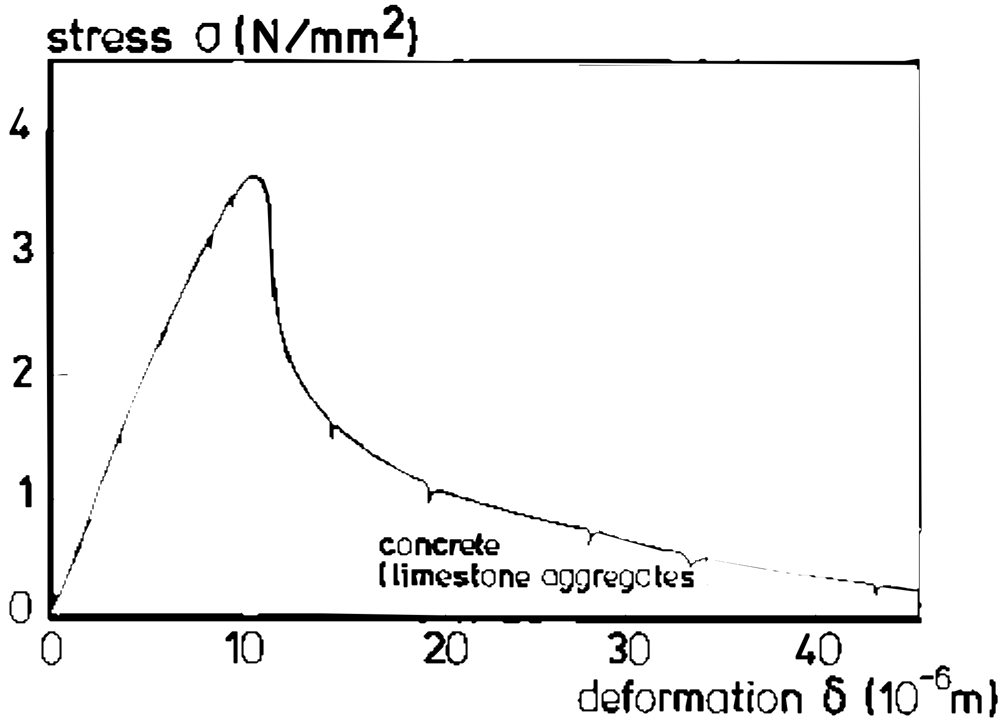

Figure 2: Stress – extension curve for concrete in tension (Ref. 2)

4.2 Defects

Figure 3 shows the relationship between the presence and size of voids and the development of flexural tensile strength.

Stress concentrations caused by large defects will assist in the initiation of cracking. When stresses at the tip of a void exceed the tensile strength of the concrete, a crack is initiated. Concrete stresses in front tip of the crack increase under load until the tensile stress is again exceeded and the crack propagates. Concrete failure will finally occur when the rate at which the damaged concrete sheds stress is greater then the ability of the concrete in front of the crack to accept increased tensile stresses.

By achieving good compaction of a slab, the number and size of voids will be decreased. Figure 3 shows that the larger the void and the closer the void is to the surface, the greater the reduction in flexural tensile strength. With a reduction in the flexural tensile strength, the tensile stresses required to initiate cracking are reduced. Hence the likelihood of the formation of cracks increases.

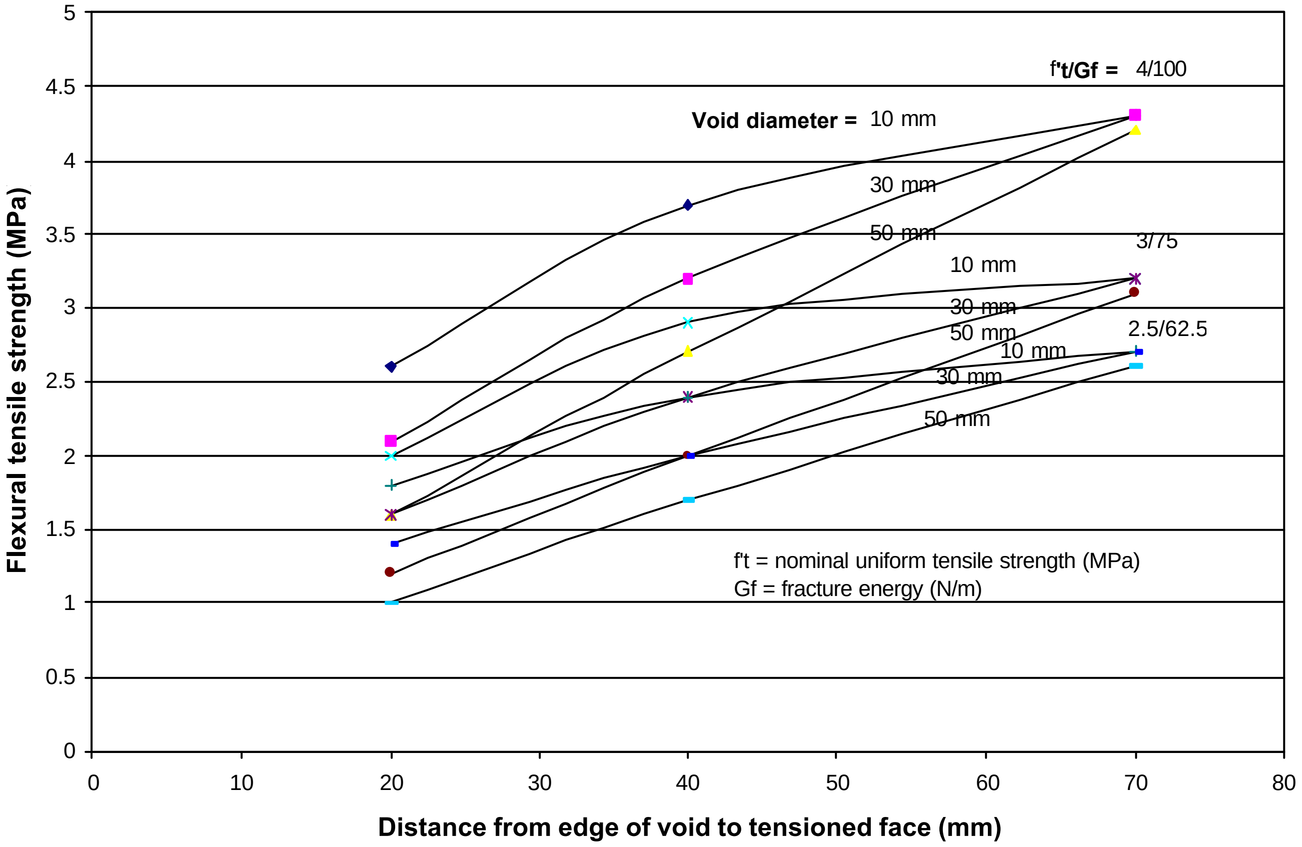

Figure 3: Effect of Void Size and Location on Flexural Tensile Strength

The impact of figure 3 is to confirm that poor compaction will increase the chance of cracking in the concrete. Standard laboratory tests for flexural tensile strength may not provide an accurate indication of in situ values. These results will be exacerbated if curing is inadequate.

4.3 Early Age – Plastic shrinkage

If drying of freshly placed concrete proceeds at an excessive rate, then the plastic concrete within the surface zone will shrink and eventually crack. As noted in section 2, these cracks may form in roughly diagonal and/or parallel pattern, or in a random "crazed" pattern.

Figure 4 is relevant to early age cracking. The figure shows how the capacity of concrete to deform in tension varies with time. During the first hours, the concrete loses its semi-fluid properties and enters the semi-solid or plastic state in which it is possible for cracks to form. The figure can be interpreted as indicating either the imposed strain or the prevented strain required for cracking.

Plastic shrinkage cracking is caused by capillary tension in pore water within the upper concrete. If atmospheric conditions are such that the rate of evaporation of bleed water is greater than the rate of production, the upper concrete becomes partially saturated, while the lower concrete may remain fully saturated. The resultant moisture suction places the concrete into compression. If volume reduction is resisted (eg locally by reinforcement or globally by differential suction) it becomes possible for cracks to form in the upper concrete, sometimes random, sometimes following reinforcement or prestressing ducts.

Once a crack of reasonable length and depth has formed, it is sometimes possible for the crack to propagate through the full depth of the concrete. As the upper concrete on either side of the crack tends to contract, tension is created at the crack tip. The crack propagates downwards. A typical full-depth plastic shrinkage crack is not fully formed at the base and much wider at the top. Full depth cracks can widen later under the effects of drying shrinkage or temperature. The same effects combined with the fracture behaviour of the concrete can cause some partial depth cracks to propagate to full-depth at a later stage.

It is generally accepted that if the ambient conditions (temperature, humidity and wind velocity) combine to generate an evaporation rate in excess of 0.5kg/m^2/hr, then protective measures to control excessive moisture loss should be instigated. A better measure of the possible risk of plastic shrinkage is the bleed rate of the concrete. This is particularly true for large expanses of higher strength concrete. The increased fines content in higher strength concretes significantly reduces the bleed rate. This leaves higher strength concrete at increased risk of high moisture loss from the top surface of the concrete and the critical evaporation rate will be significantly lower than normally expected.

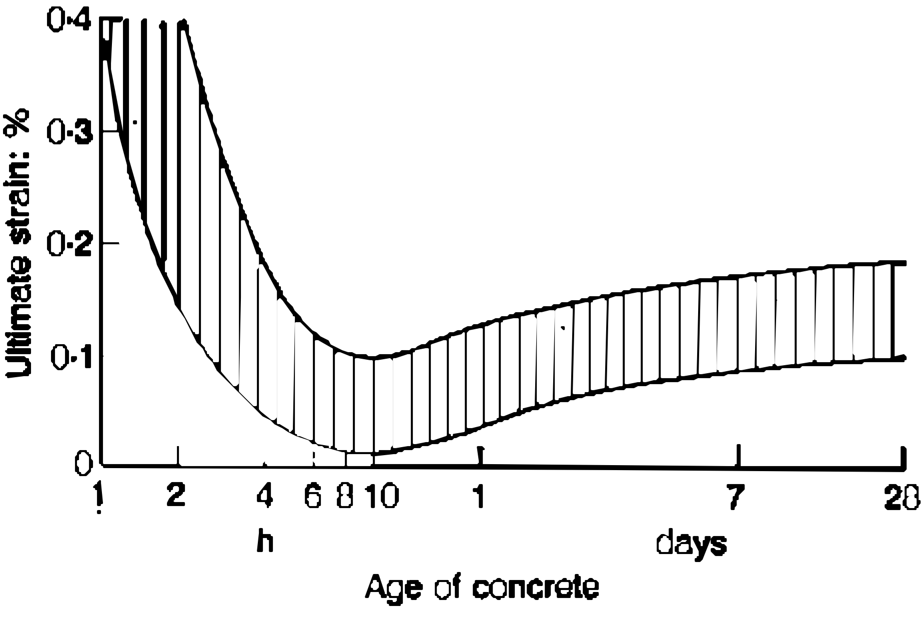

Figure 4: Tensile strain capacity variation with time (Ref. 1)

4.4 Early Age - Hydration

The following section discusses the early age shrinkage/volumetric change behaviour of concrete slabs as measured in various field and laboratory experiments. The set of experiments considered involves instrumented slabs with a normal slump concrete.

4.4.1 Experiments with Normal Slump Concrete - Laboratory Slab Details and Instrumentation

Experiments on laboratory slabs have been underway for 3 years. These experiments have been conducted on two different sizes of slab, large slabs measuring 1510 x 2655 x 250(H) and smaller box slabs measuring 350 x 350 x 250(H). Commercial mixes of 32 MPa concrete with specified slump of 80mm were used. Slabs with a free base condition were cast on a 50mm layer of sand in moulds lined with plastic while those with a fixed base condition were cast on a layer of 5mm aggregate bonded to a concrete floor. While experiments were conducted to consider the effects of curing, base friction and temperature on early strain development, the findings will only be briefly outlined to give an overall picture of the identified mechanisms behind experimental observations.

Embedment strain gauges were used to instrument the slabs. The gauges have steel ends connected by an epoxy composite cylinder within which resides a vibrating wire (Fig. 5). Each gauge has a thermistor for temperature measurement. The gauges are very flexible and are able to follow early strains in the concrete. Gauges were placed centrally and near edges in clusters of two or three at varying depths at each location. Where two gauges were used, bottom and top gauges were located at 85mm and 165 mm respectively from the slab soffit. Where three gauges were used, bottom, middle and top gauges were located above the soffit at 40mm, 125mm and 210mm respectively.

Figure 5 Cluster of 3 gauges being installed in highway pavement.

The strain gauges have an error in recording thermal strains of the order of $10\times10^{-6}/C^{o}$ in fresh concrete reducing to $-3\times10^{-6}/^{o}C$ in hardened concrete. Variation of temperature through the depth of specimens was small, as seen in several subsequent figures. The coefficient of thermal expansion of very young concrete is quite high (Ref 4) and allowance can be made for the gauge error. Data presented in subsequent figures have not been thus adjusted.

4.4.2 Initial data from laboratory slabs

Figure 6 shows typical strain and temperature data gathered during the first day following a pour. The data acquisition registers compressive strain as positive. This convention has been retained in Figure 6 and subsequent figures.

The uppermost curve shows that during the first 3-4 hours, the temperature remained largely unchanged. The effects of hydration are later seen as temperatures rise over the following 8-10 hours. The remaining curves in the figure show strains registered by the embedment gauges. Note that differential strains establish rapidly within the small box specimen as well as between small and large specimens.

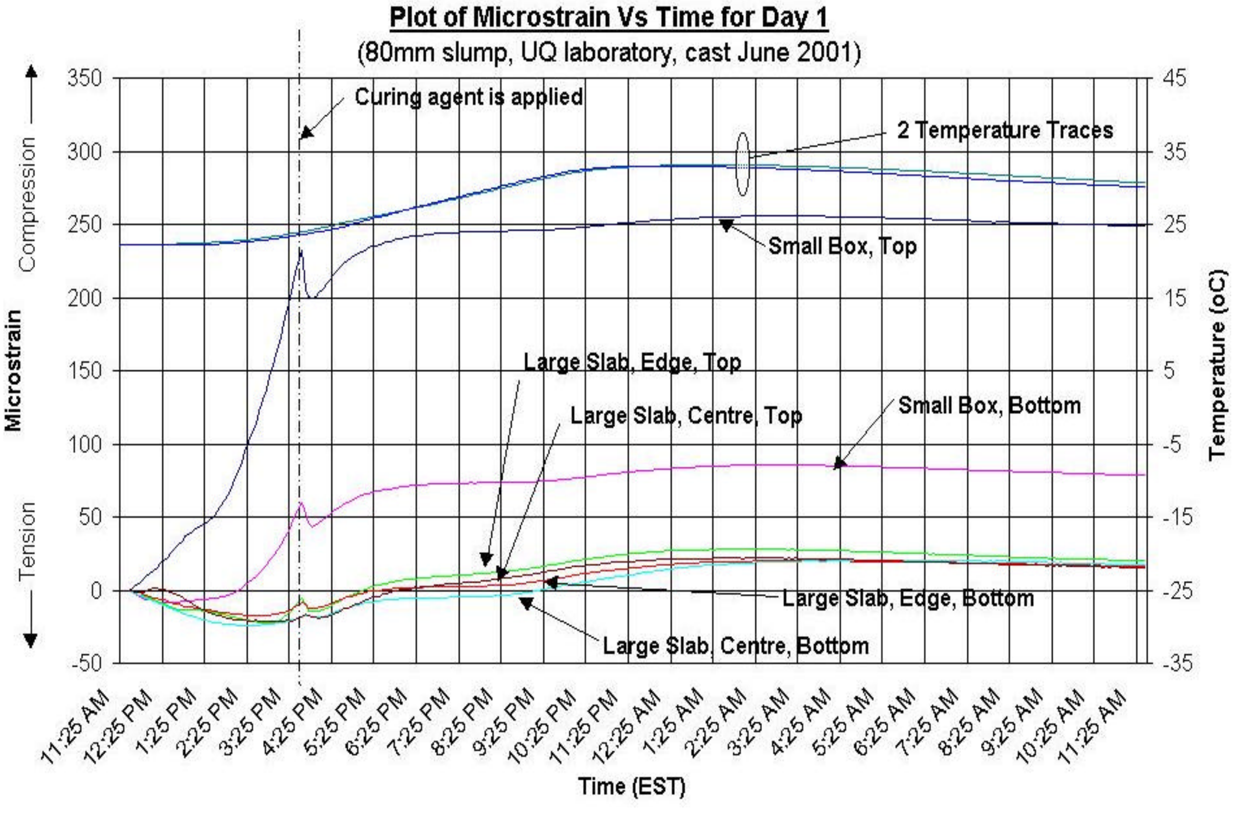

Figure 6 Strain versus time for six strain gauges
(80mm slump, free base, cast June 2001)

4.4.3 Experiments with Normal Slump Concrete - Field Slab Details and Instrumentation

The field experiment involved an industrial slab 190mm thick, with 32Mpa and 80mm slump concrete from the same supplier as for the laboratory slabs. The slab which is in an external environment, was cast in one pour on a sandy base without a moisture barrier. It was sawn into 6.1 x 6.1m panels during the first day. A curing agent was applied some time after the finishing operation. Bottom, middle and top gauges were placed at elevations 40mm, 95mm and 150mm above the base in the centre of a panel.

4.4.4 Initial data from field experiment

Initial data for temperature and strain are presented in Figure 7. Note again the strain differentials between large and small specimens.

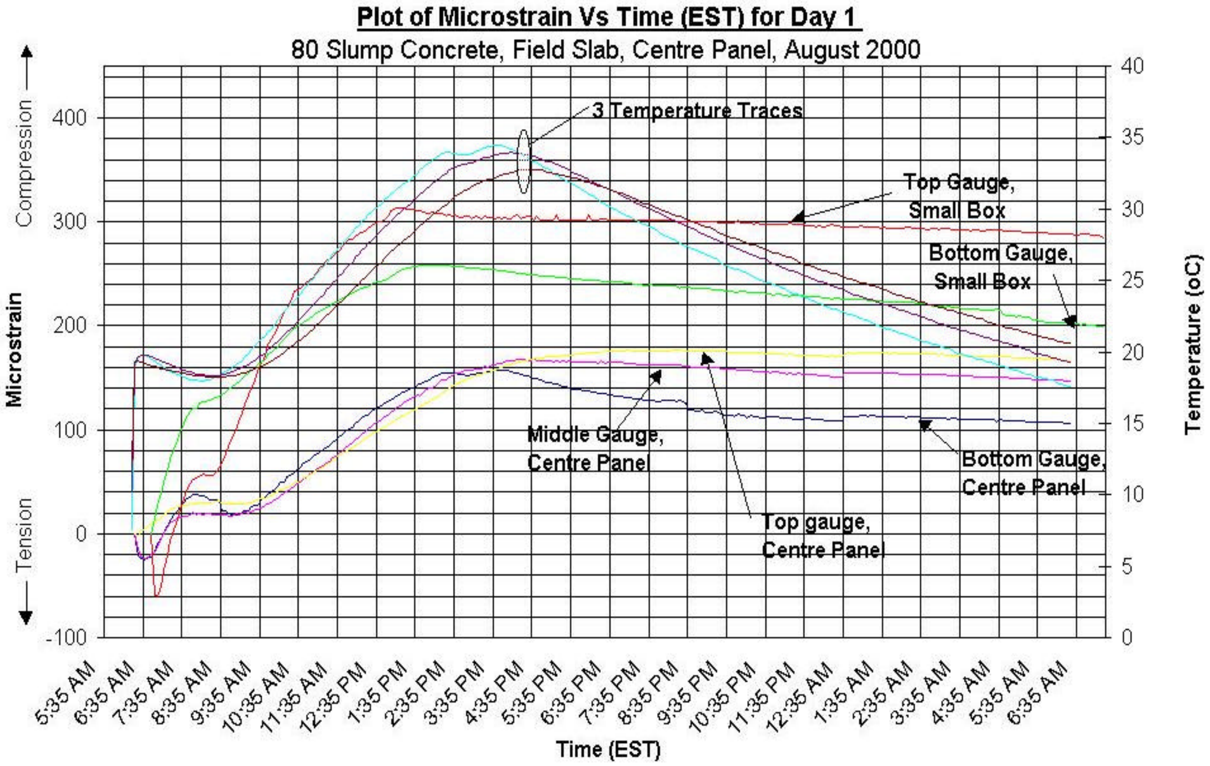

Figure 7 Strain versus time for five strain gauges (80mm slump, field slab, cast August 2000)

4.4.5 Normal Slump Concrete - Strain Development Mechanism

- Immediately following casting the concrete enters a dormant period typically lasting a few hours. Concrete strains in the test specimens during this period tend to be small and tensile and are caused by consolidation and the reduction of positive pore pressures;
- As bleed water slowly dries and as hydration commences, internal suction is established primarily in the upper concrete. This occurs when voids become partially rather than fully saturated. This is seen in Figures 6 and 7 in particular, for small box slabs which have close, free boundaries. Larger contraction occurs in these specimen especially in the upper concrete;

- In large specimens, restraint prevents the growth of these strains to the same degree, depending on the location within the specimen;
- Internal restraint in large specimens is due to differential suction arising from differential desiccation, combined with the absence of close, free boundaries. This is seen in the lesser strains for large specimens in Figures 6 and 7.
- The large compressive strains are suction driven. In Figure 8, strains in two small box slabs are compared, one uncured the other continuously moist cured from the time of casting. The strains in the fully cured specimen are much less. A strain differential between upper and lower concrete is established for both specimens, but that in the uncured specimen is substantially the greater.

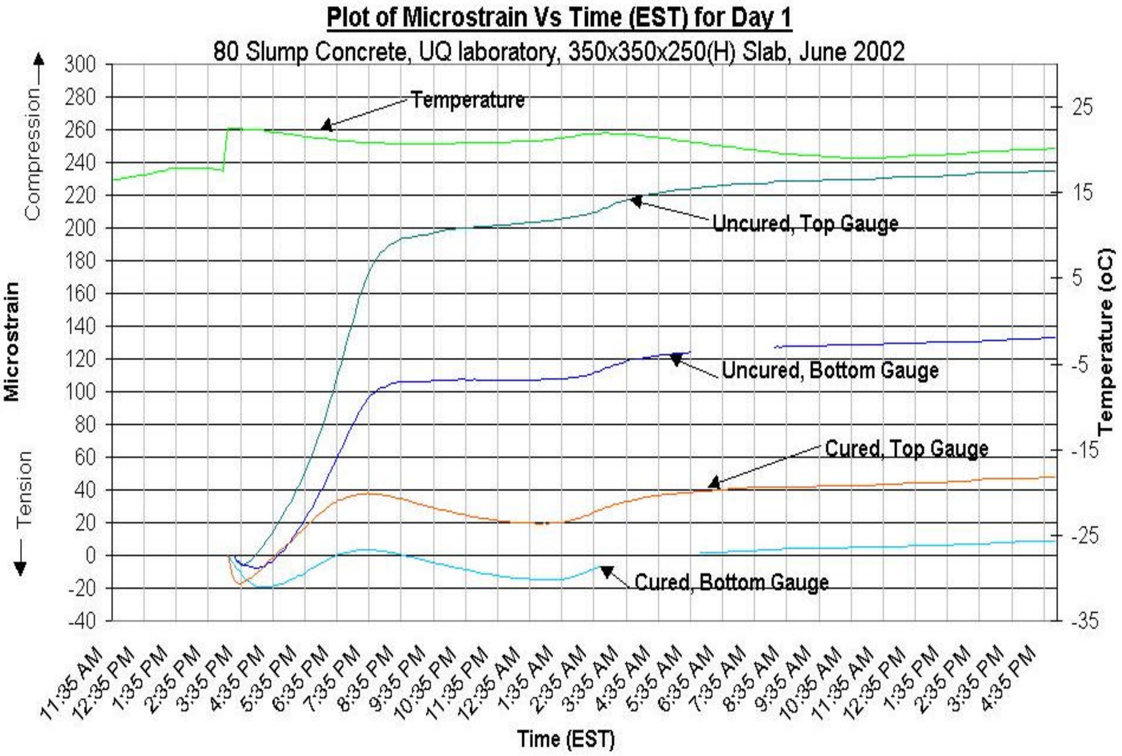

Figure 8 Strain versus time for four strain gauges
(80mm slump, free base, cast June 2002)

4.5 Drying shrinkage & restrained slabs

4.5.1 Interior Slabs – Shrinkage Testing

Shrinkage test results

Figures 9 and 10 show the strain versus time recorded by the embedment strain gauges located at the centre (top/middle/bottom) as well as the edge (top/middle/bottom) of a fixed and a free slab respectively. Figure 11 shows the strain versus time recorded by the three gauges located at the centre (top/middle/bottom) of the box slab. Internal temperature plots recorded by thermistors in the box slab and the centre of the free slab are plotted in Figure 12.

There is a noticeable difference in the behaviour of the slabs with fixed and free base conditions at age of 8 months. The fixed slab strains at the centre are only marginally compressive (38 µε), indicating that base restraint has largely prevented shrinkage movement. The concrete is in a state of tensile stress. Near the slab edge, concrete away from the base has been able to undertake shrinkage strain due to proximity to the free boundary. Strains near the edge showed differential shrinkage through the thickness – compressive strains at the top/middle/bottom were 354, 193 and 0 µε (Figure 9).

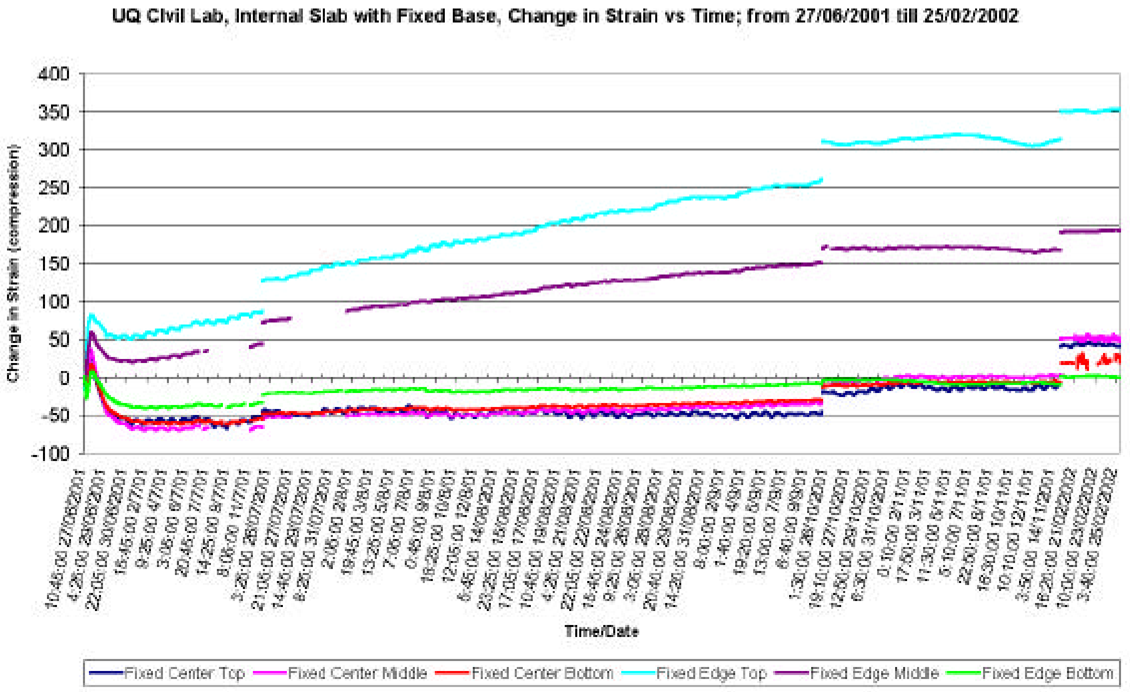

Figure 9: Strain versus time for six embedment strain gauges- fixed base slab.

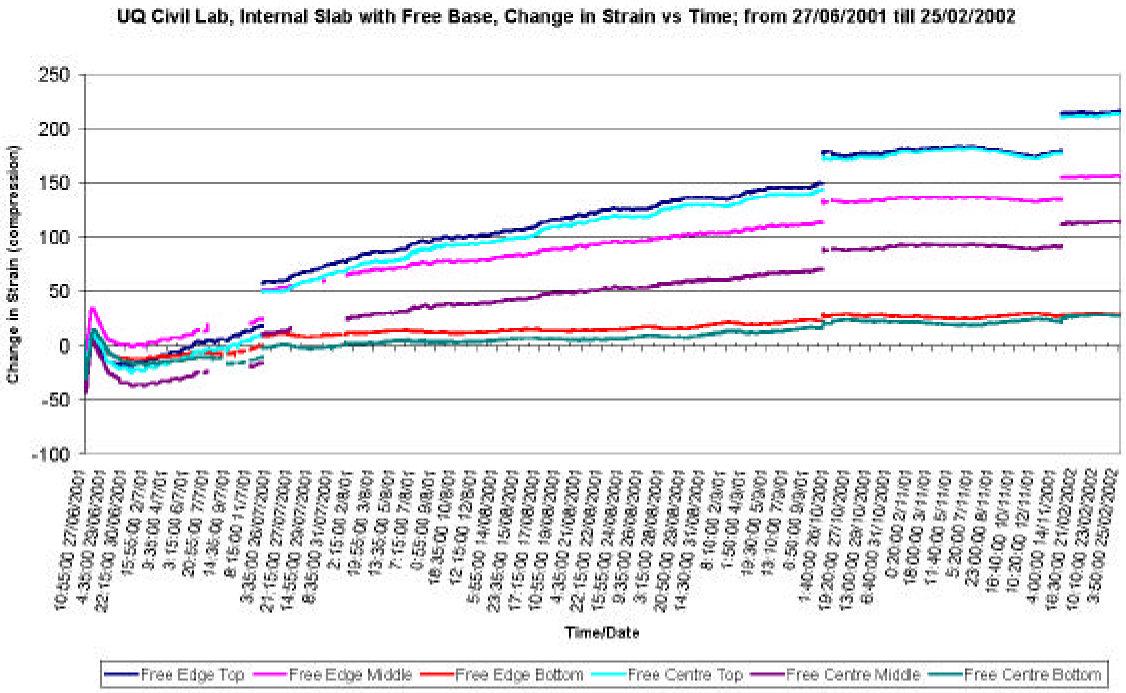

Figure 10: Strain versus time for six embedment strain gauges – free base slab.

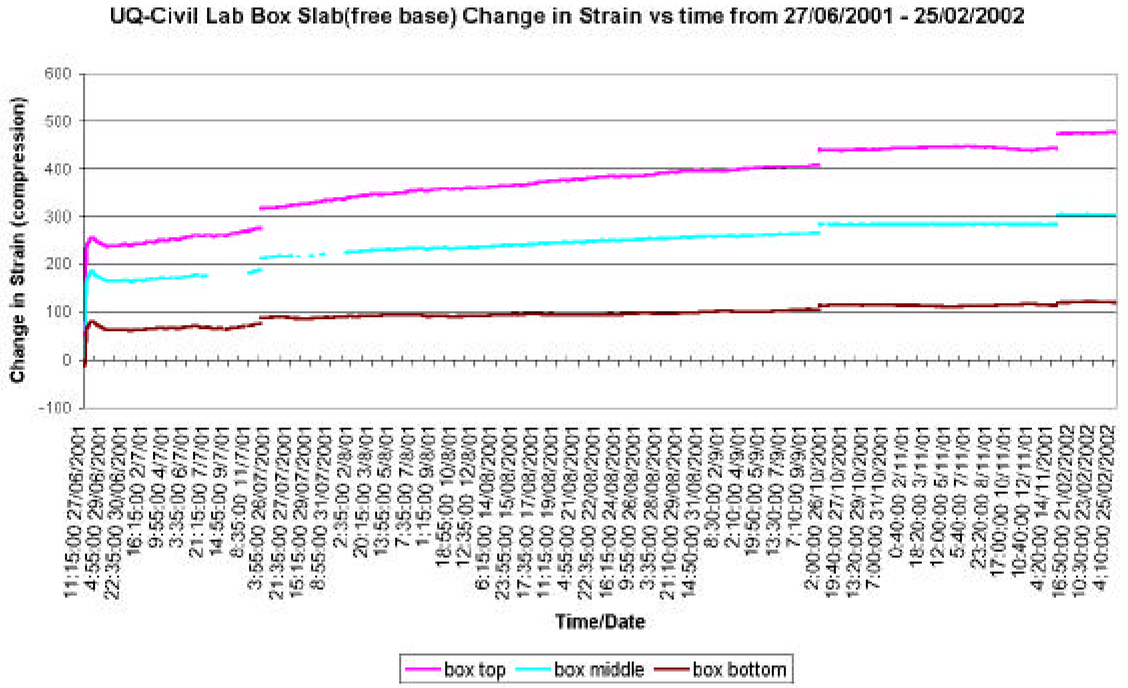

Figure 11: Strain versus time for three embedment strain gauges – box slab

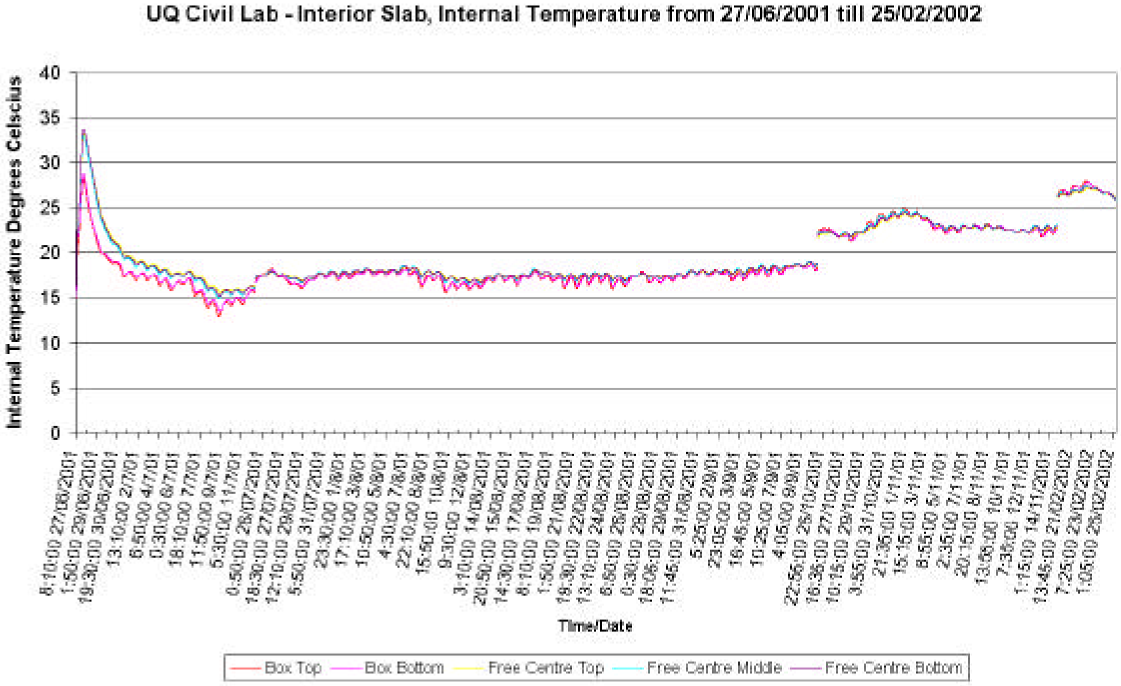

Figure 12: Temperature versus time from thermistors within five embedment strain gauges – two in the box, three at the centre of the free slab.

For the free slab there seems no significant difference in shrinkage patterns. Both center and edge gauges showed differential shrinkage throughout the thickness of the slab. As can be seen in Figure 10, strain at the top gauge is the same for centre and edge slab locations.

Similarly, bottom centre gauge and bottom edge gauge recorded the same strain. However gauges at the middle location recorded different values, 156 and 114 με for the edge and centre locations respectively at 8 months. The difference between these values was established within the first day and has remained constant since that time.

Strains at the centre of the box slab show differential shrinkage (see Figure 11). The box slab represents the closest approximation to free concrete. Strain development in box slab and the free slab shows very similar trends after the first day.

Figure 12 shows a small difference in internal temperatures between the large (free) slab and small (box) slab in the first month after casting. As the time goes by, the difference disappears.

Conclusions

- Free shrinkage has an approximately linear variation with depth within the interior slabs which have sealed bases and sides (see box & free slab results).
- Base shear resistance can lead to suppression of shrinkage strain (see centre gauges, fixed base slab) with corresponding tensile stresses.
- Values of drying shrinkage since 2 days after casting have a maximum of around 240με at the surface of the free base slab and box slab. The code predicts the average (mid-depth) strain reasonably well in the box and free-base slabs but not the total strain or the strain differential.

4.5.2 Exterior Industrial Slab

Field shrinkage monitoring – observations and conclusions

Strain versus time plots are presented for box, edge and centre gauges in Figures 13, 14 and 15. Measurements have been recorded over a 15 months time period. Data from different periods of recording have been compressed along the time axis to create generally piecewise continuous graphs. The following observations and conclusions can be made:

- Significant compressive strains are recorded in the hours following casting, the highest registration being at the top gauge of the box slab (Fig. 13).
- During the first week the strain differential between top and bottom gauges in the uncured box slab became fully established and has remained essentially constant following 15 months (Fig. 14).
- The edge gauges show rapid growth of a strain differential following deterioration of the curing agent and possibly with cracking at the saw cut over the dowels (Fig. 14). This differential has remained essentially constant over the following 15 months.
- Strains at the centre of the slab have remained reasonably uniform with depth, indicating compatibility restraint of differential shrinkage and hence differential shrinkage stresses (Fig. 15).
- The average strains at 15 months in the box gauge, edge gauges and centre gauges were around 370, 190, and 225 microstrain respectively. Increases in average strains since the first day are around 150, 130 and 110 microstrain respectively. Increases in average strains since the first week are around 75, 100 and 80 microstrain respectively. Increases in average strains since the first month are negligible at all locations.

The code model (AS3600 Ref 5) does not predict the observed growth of shrinkage strains to date. The model addresses only drying shrinkage and hence makes no prediction of early age shrinkage due to suction and hydration effects. The trend of all readings suggests that the code model is likely to substantially overestimate long-term drying shrinkage for the slab. Over the period reported, the code model using the standard shrinkage test result for the concrete (685 microstrain), predicts gradually increasing strains to the order of 280 microstrain following commencement of drying by the atmosphere. This approximately aligns with the period when the recorded slab shrinkage has been nominal.

It is likely that the magnitude of very early shrinkage strains are not related to the drying shrinkage properties of the concrete; if so, it follows that they can not be controlled by the specification of drying shrinkage.

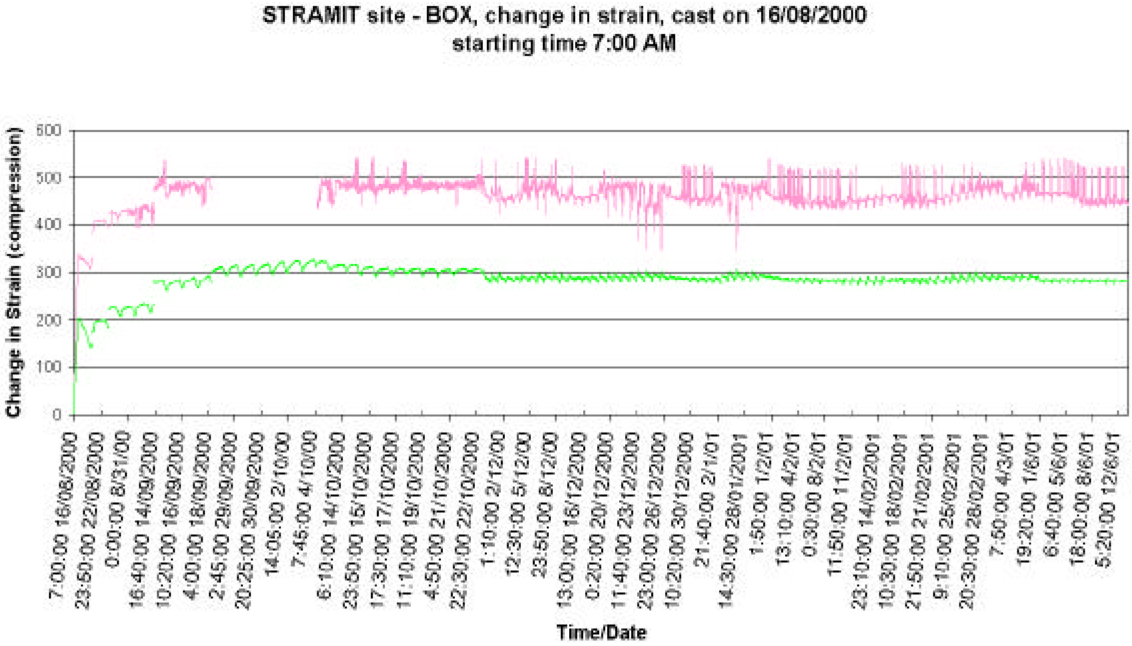

Figure 13: Strain versus time for box-slab – industrial pavement.

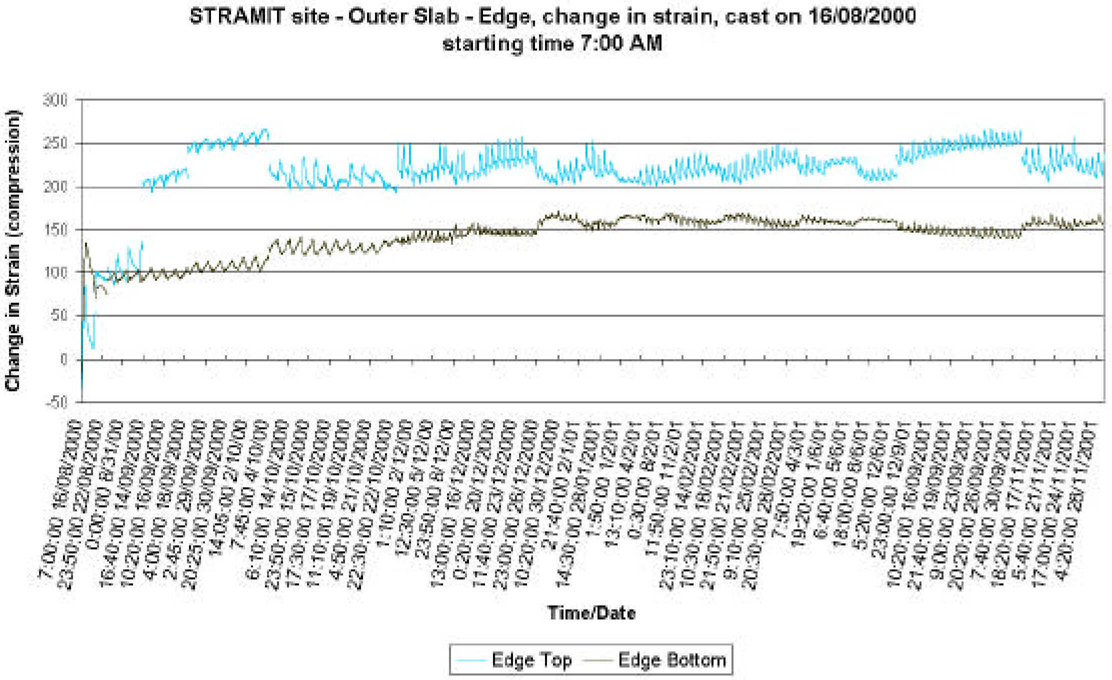

Figure 14: Strain versus time at a joint of the exterior slab-strain perpendicular to the dowelled joint adjacent to the joint.

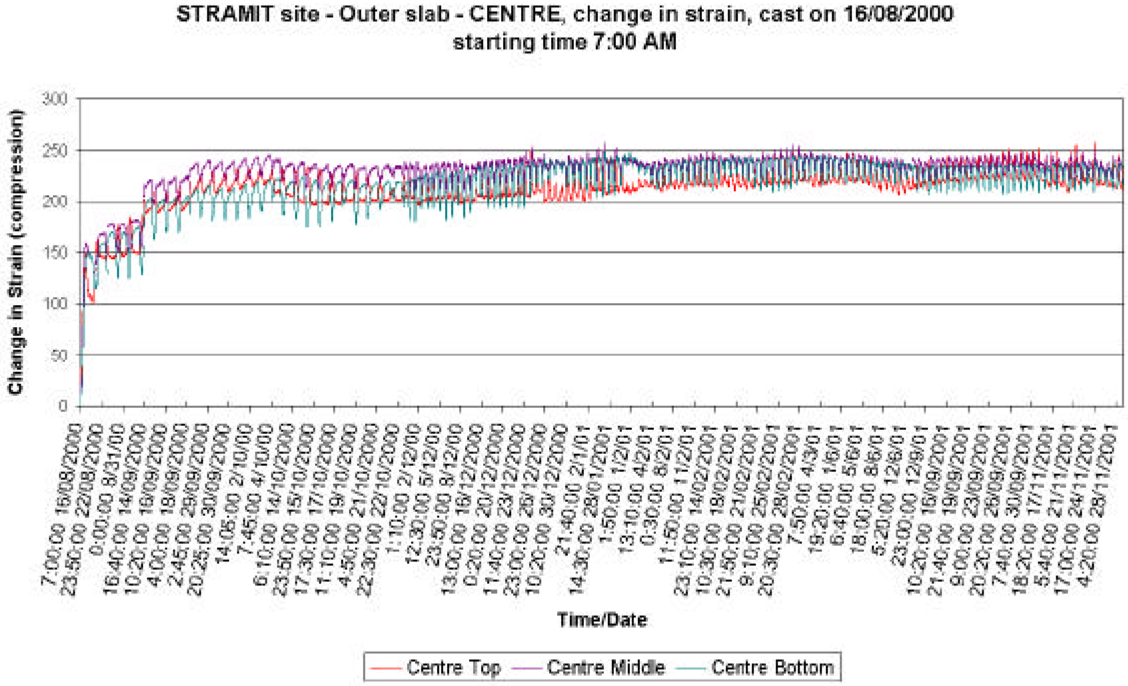

Figure 15: Strain versus time at the centre of the exterior slab – strain perpendicular to the control joint.

The difference between the strains in the box slab and the other slabs during the first few days is due to internal restraint. The stresses that results have the potential to initiate cracks that may then grow over time and eventually be incorrectly blamed on long-term drying shrinkage.

5. EFFECT OF ALIPHATIC ALCOHOL ON SUCTIONS AND TENSILE STRENGTH OF EARLY AGE CONCRETE

Figure 16 (Ref 6) shows the variation with age (time after mixing) of the total *Y* at the exposed surfaces of two specimens of early-age cement mortar with an initial water-cement ratio of 0.5. Here, *Y* is taken to denote the (moisture) suction expressed in MPa.

The surface of one specimen was left unprotected, while aliphatic alcohol was applied to the other to retard evaporation. The protected specimen did not crack, but the unprotected specimen cracked at an age of 4.9 hr. Because the *Y* shown in Figure 16 include osmotic *Y*, they might overstate the *Y* contributing to crack formation. Figure 16 clearly shows that aliphatic alcohol reduces tension in the surface layer of the concrete. This is why it is important to ensure that aliphatic alcohol is applied as soon as possible, and is re-applied when the surface is re-finished.

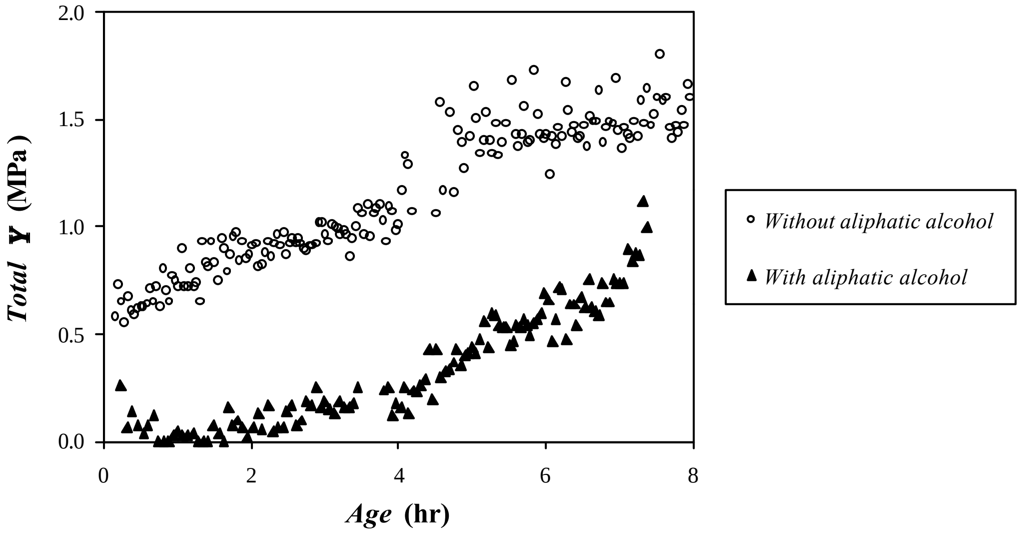

Figure 16 : Variation with age of total *Y* in early-age cement mortar (Ref 6)

6. EFFECT OF EARLY AGE STIFFNESS AND TENSILE STRENGTH DEVELOPMENT

In this section, the development of early age tensile strength and stiffness is reviewed (Ref 7).

A dog-bone specimen of dimension 145 mm wide, 372 mm long and 100 mm deep as shown in Figure 17 was chosen for the direct tension test. Specimens were cast inside two mould halves connected by a removable middle panel, A, as identified in Figure 18. The specimens were tested horizontally with one mould half fixed via a load cell and the other half being moved by a screw crank with a constant displacement rate. The mould encased the sample completely except for a straight central test length of dimension 70x70x100 mm. To minimise frictional resistance, two linear bearing plates were used to support the two halves of the specimen, as shown in Figure 18. Frictional resistance was negligible (78 – 106 Pa).

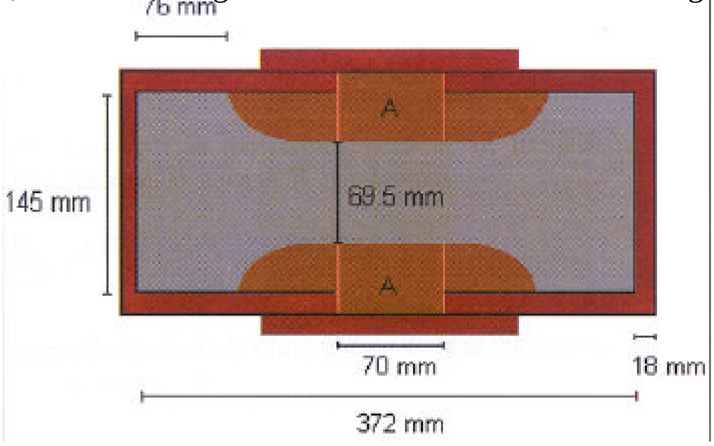

Figure 17: Plan view of tensile test specimen, showing mould, semi-elliptical transitions and removable side panels A.

Figure 18 shows the full test arrangement. The sample ends are supported on horizontal linear bearing plates. The right hand side mould is restrained through a load cell. The load cell records the tensile force exerted by the crank at the left hand end and transmitted through the specimen. Top-hat strain gauges mounted on the sides of the test length record extension. One such gauge with its lead can be seen between two mounting bars at the center of the figure. Figure 19 shows a typical crack pattern that emerged in the straight section. Note that the fracture occurs well away from the transitions in shape.

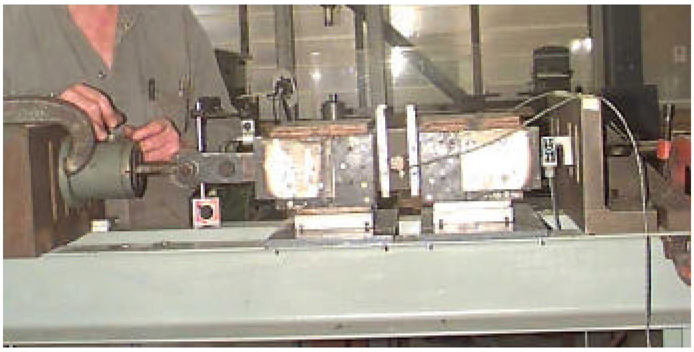

Figure 18: Full test arrangement

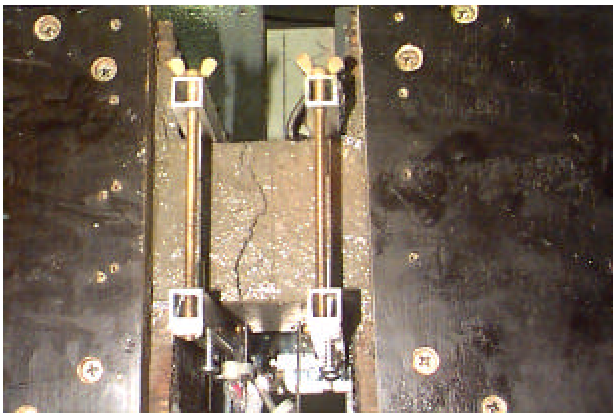

Figure 19: Typical failure mode**.**

Two nominally 32 MPa mixes were adopted with slumps 25 mm and 80 mm. Because of the limited dimensions of the test length cross-section, a maximum aggregate size of 10 mm was used. Actual 28 day average compressive strengths were 47 MPa and 36.6 MPa for 25 mm and 80 mm slump concretes respectively. A total of 28 tensile tests were carried out.

The early age tensile test results for tests 5-20 are shown in Figure 20. The tests were carried out in the months of August to October 2001. Two distinct patterns emerge. Tests 5-10 (full circular test points) were conducted in August and the cooler ambient and material temperatures are reflected in the slower growth of tensile strength. The remaining tests 11-20 were conducted in warmer days towards the end of the test period and more rapid strength gain is evident, with a dormant period of 4 to 5.5 hours and a rapid tensile strength gain from about 5.5 hours.

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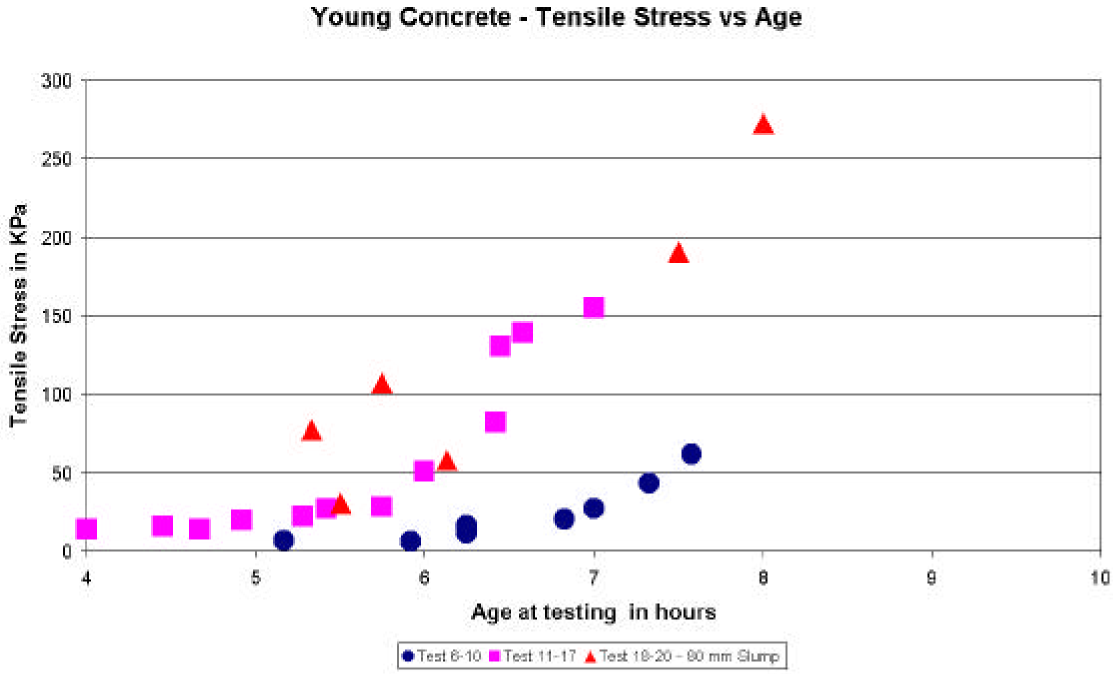

Figure 20: Tensile strength gain versus age

The square and triangular test points refer respectively to 80 and 25 mm slump concretes. There appears little difference in their rates of gain of strength

Tensile modulus is plotted against age in Figure 21. Early age modulus increases quickly to significant values. For example, at 7 hours in warm weather, the modulus for both test concretes is of the order of 3000 MPa, or about 10% of the 28 day value. At the same age, the tensile strength is around 150 kPa which is about 4% of the 28 day strength. The relationship between modulus growth and strength growth is further examined in Figure 22 where a linear relationship is evident.

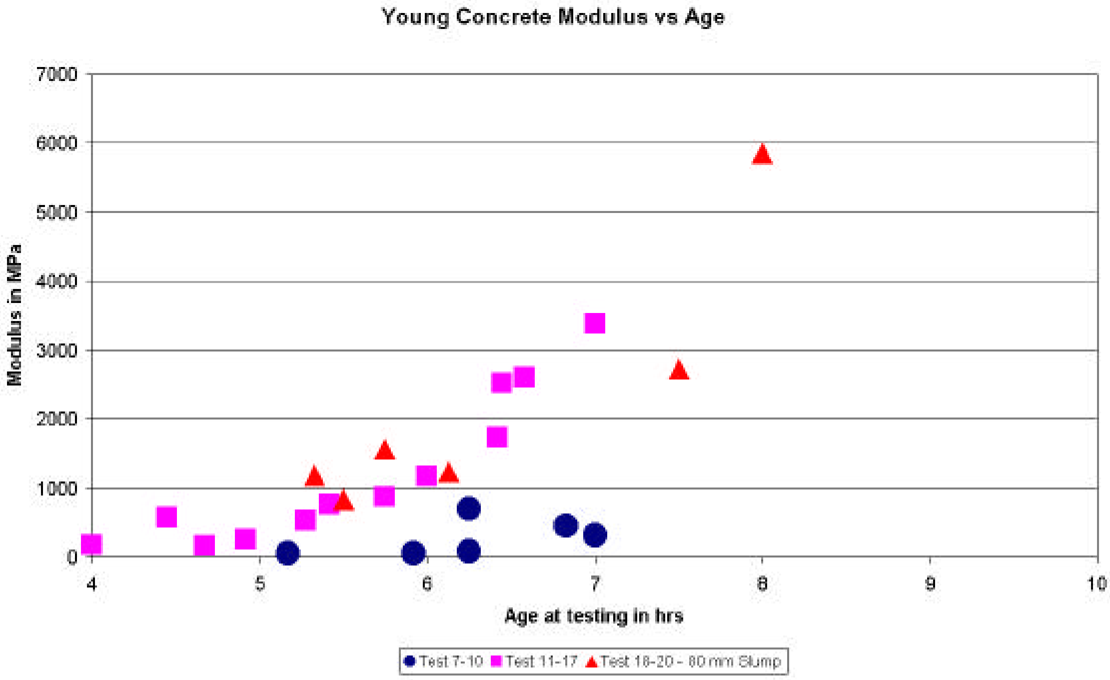

Figure 21: Modulus versus age.

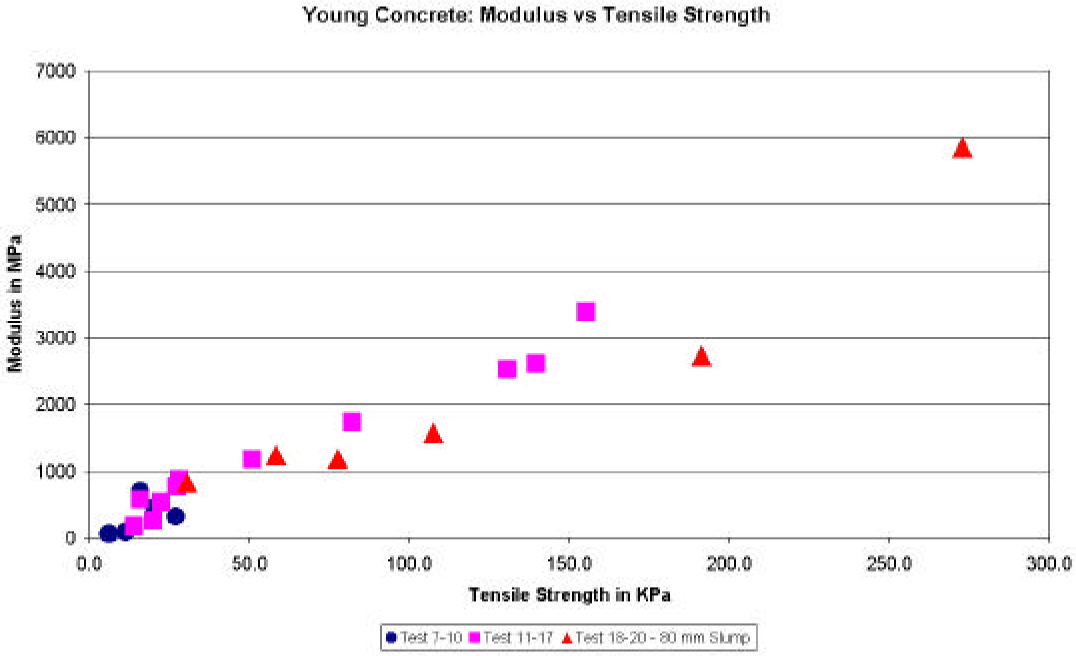

Figure 22: Tensile strength versus modulus

Compressive strength via uncapped 100mm diameter cylinders was determined prior to and after each tensile test.

The relevance of this data to the cracking of concrete is the relationship between the development of tensile strength and stiffness. The rate of increase of stiffness is much greater than the rate of increase of strength (either tension or compression) ie. an appreciable fraction of the 28 day modulus develops within the first 7~8 hrs in warm weather, indicating that restraint can lead to rapid development of stress at a time when strength is very low.

7. EFFECT OF COMPACTION AND CURING ON THE PROPERTIES OF HARDENED CONCRETE

In this section, the effect of compaction and curing on the properties of hardened concrete is reviewed (Ref 8).

Figure 23 shows compressive strength versus density for samples with standard as well as non-standard compaction/curing. Strength and density have been normalised with average 28 day strength of standard specimens takes as 1.0 and average density at 28 days of standard cured specimens also taken as 1.0. In Figure 23, the compaction rates 90-100% relate to compactive effort and do not represent actual compaction achieved. Specimens were aged 28 days at testing.

The following observations are made:

- The standard specimens have the highest compressive strength and density when compared with non-standard specimens.
- Density increases with increased time in the mould.
- As density reduces through ineffective compaction, the compressive strength reduces significantly, e.g., a 4% increase in voids caused by ineffective curing, poor compaction or both, is sufficient to reduce compressive strength by 30%.

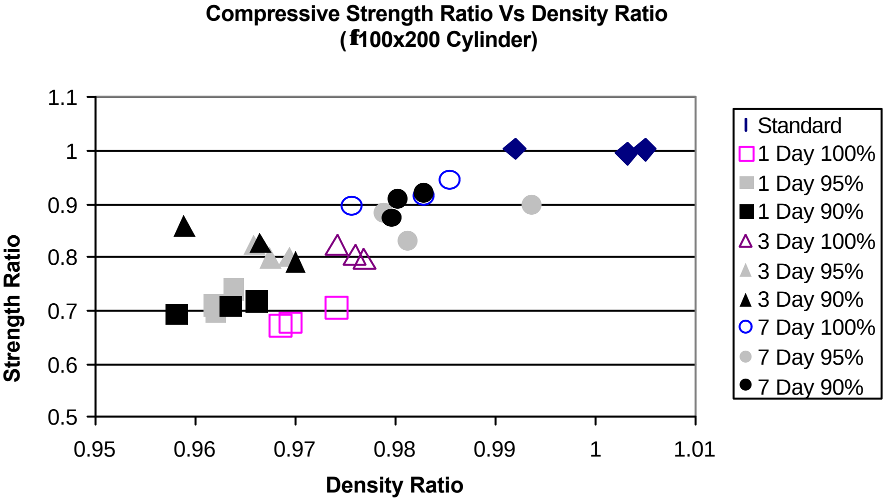

Figure 23: Normalised compressive strength versus density for specimens with standard and non-standard compaction/curing.

The relationship between Modulus of Rupture and the density is shown in Figure 24. The following observations hold:

- Modulus of Rupture (flexural tensile strength) and density were the highest for the standard moist cured specimens.
- As the volume of voids increased, the tensile flexural strength reduced rapidly. This facilitates cracking.

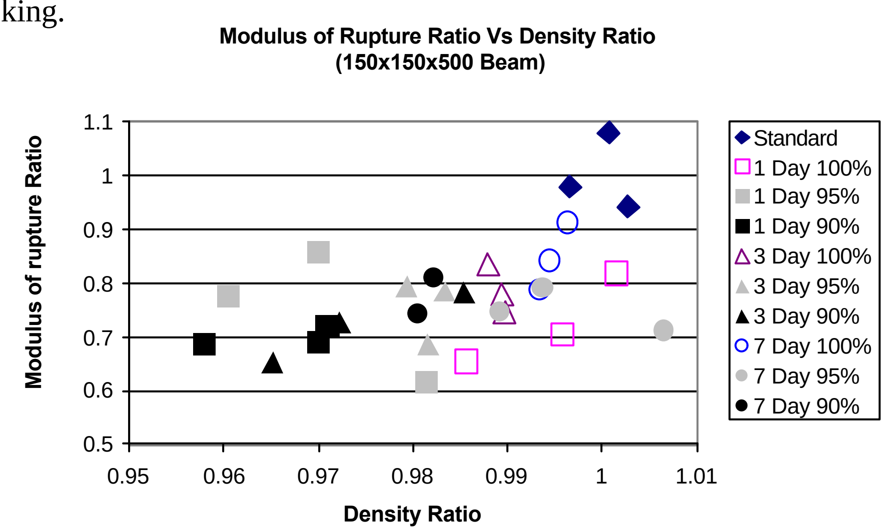

Figure 24: Modulus of rupture versus density for specimens with standard and non-standard compaction/curing.

In Figure 25, the relationship between Young's modulus (tensile) and density is shown for specimens with standard and non-standard compaction and curing. There appears to be no well-defined trend with regard to modulus and voids over the range of densities in test specimens. This may be due to the fact that modulus is measured over the lower part of the elastic range of stress and strain. In comparison, strength testing goes beyond the elastic range and progressively damages the specimen. Voids, even individual voids, are likely to be more significant at higher stresses and hence lead to consistent trends of strength reduction.

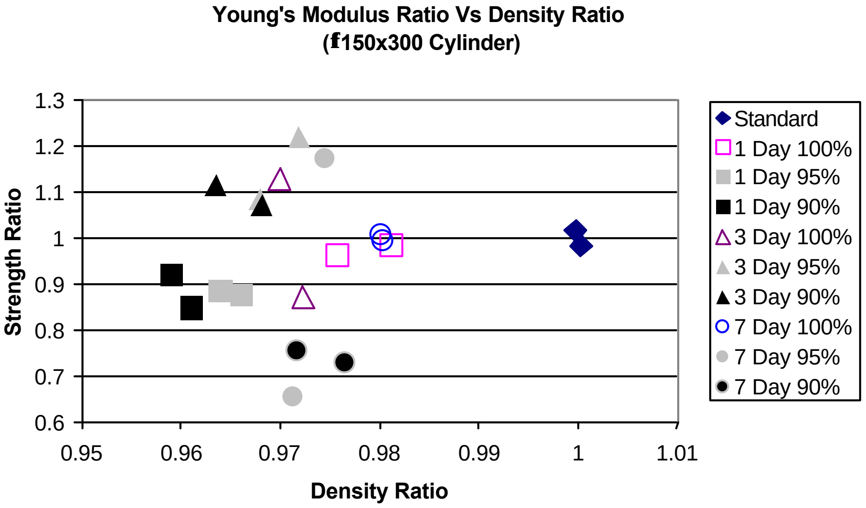

Figure 25: Young's modulus versus density for specimens with standard and non-standard compaction/curing.

8. CONCLUSIONS

CRACK CONTROL – Are we getting it right?

In this paper the basic mechanisms of cracking have been reviewed and research into the effect of age, compaction and curing on basic concrete properties has been presented.

The findings in this paper support the argument that the most effective approach to controlling cracks in concrete requires:

- Good quality preparation of sub-grade;
- Adequate compaction – This can be achieved through good construction practices on site;
- Early and adequate curing – Again, this can be achieved through good construction practices. “Policing” of this requirement is an issue;
- Timely saw-cutting – This is also an issue for good construction practice.

Specification of low 56-day drying shrinkage strains will not necessarily ensure adequate control of cracks (Ref 9). Whilst drying shrinkage may be the “driver” behind cracks in slabs and pavements, the “initiator” of the cracks will be early-age activities (curing, compaction, saw-cutting) and early-age tensile strains.

The code model does not incorporate the effects of early age shrinkage due to suction and hydration and the trend of all readings suggests that the code model is likely to substantially overestimate long-term drying shrinkage for the slab.

Further work is required to establish an analytical approach to saw cutting. This needs to include the influence of the age of the concrete and its early age properties, ambient conditions and slab restraint and their relationship to saw cut spacing, depth and timing. The issue of the specification of the bleed rate of concrete in certain circumstances requires further clarification.

9. ACKNOWLEDGMENTS

This research was funded by the University of Queensland, the Queensland Department of Main Roads, the Australian Premixed Concrete Association, and the Co-operative Research Centre for Sustainable Tourism.

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AUSTRALIA

Friday, 2 April 2004

Dr Peter Dux
Department of Civil Engineering
University of Queensland

Facsimile: 07 3365 4599

Re: Peer Review of "CRACK CONTROL – Are we getting it right?"

The paper *"CRACK CONTROL – Are we getting it right?"* by Dr Liza O'Moore and Dr Peter Dux of the Department of Civil Engineering, the University of Queensland Presented at the joint Concrete Institute of Australia/Engineers Australia technical seminar on 1 October 2003 in Sydney was peer reviewed prior to publication and is available as a separate from the Concrete institute of Australia's office.

Yours faithfully

Ian Booth
Chief Executive Officer

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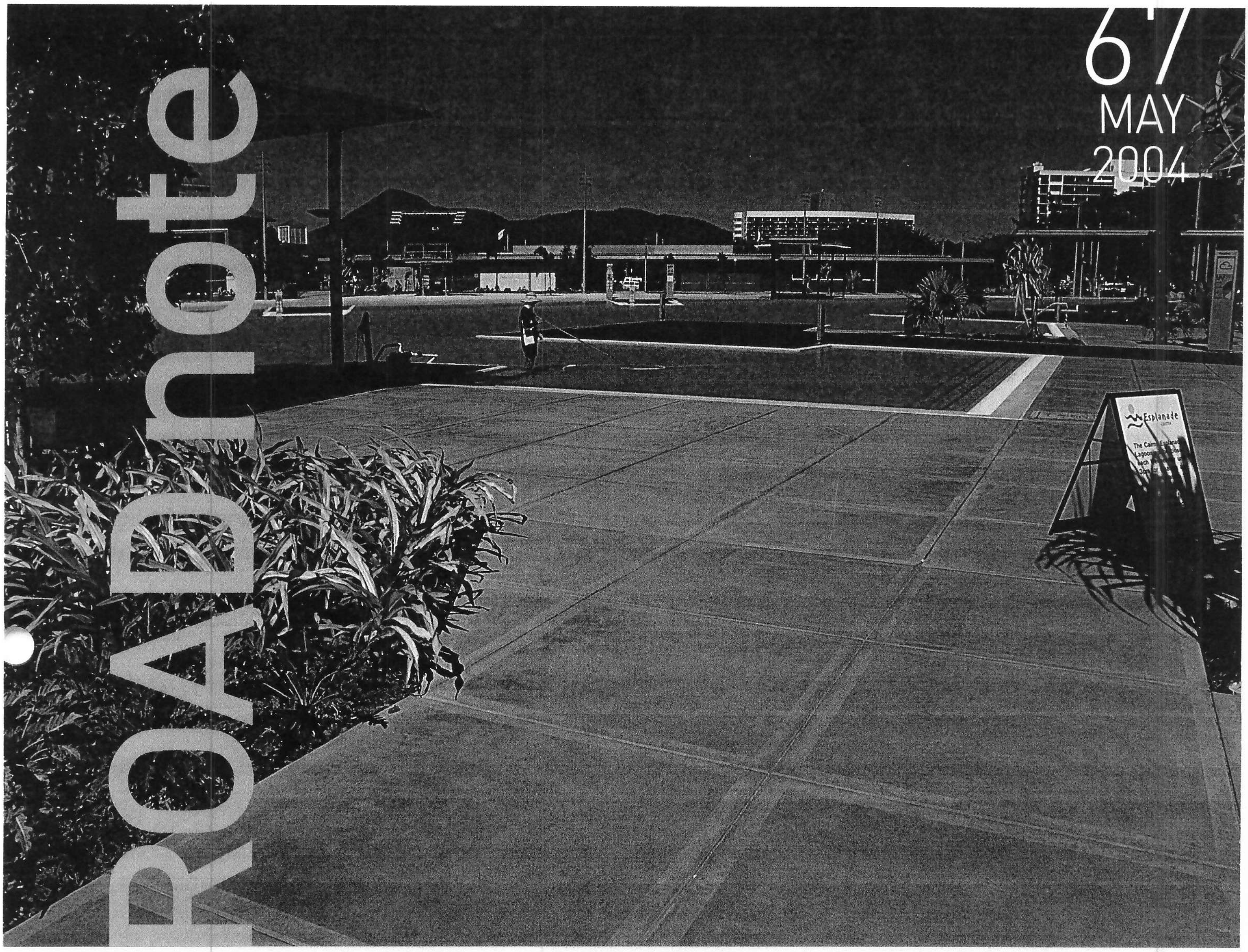

CEMENT & CONCRETE ASSOCIATION OF AUSTRALIA

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Non-Structural Cracking of Concrete

04

Unplanned cracking in concrete, especially decorative pavements, can be aesthetically displeasing, and is one of the major quality issues experienced in the field. Cracks can develop either in the plastic or hardened concrete and are often related to construction conditions and practices. Cracking is usually controlled by measures such as providing reinforcement, specifying low-shrinkage concrete mixes and addressing construction practices.

By improving the understanding of why cracking occurs, and the contribution that various factors such as compaction and curing have on the process, both cracking and related defects can be minimised and better pavements produced.

Researchers at the University of Queensland are investigating the mechanisms and causes of cracking in various applications, particularly in pavements. This article is based on a paper **Crack Control – Are we getting it right?** by Dr Liza O'Moore and Dr Peter Dux and presented at a joint Concrete Institute of Australia and Engineers Australia seminar on Developments in Slab and Pavement Construction, October 2003.

This article considers the types of non-structural cracking that occur in concrete slabs, the general approach to controlling them, and then explores the reasons behind the importance of compaction, curing and timely saw cutting by looking at the mechanisms that lead to the formation of cracks in slabs. Covered in the paper, but not dealt with here are the early-age shrinkage/volumetric-change behaviour of concrete slabs, drying shrinkage and restrained slabs and the effect of early-age stiffness and tensile strength development.

The research group is also investigating saw cutting in relation to pavement cracking. The outcome of this work will be included in a later Roadnote issue.

Types of Non-structural Cracks

Cracks are divided into two basic categories.

Prehardening Cracks. These are cracks that occur while the concrete is in its plastic or non-hardened state. The three main types are:

- Plastic shrinkage cracks
- Plastic settlement cracks
- Cracks caused by formwork movement

All occur as a result of construction conditions and practices although, obviously, faulty formwork design may lead to its movement and/or failure. Prehardening cracks are usually preventable by the adoption of good construction practices.

Cracks in Hardened Concrete. Non-structural cracks in hardened concrete occur for two principal reasons: volume changes in the concrete and chemical reactions within the body of the concrete that cause expansion and subsequent cracking. The common types of cracks in this category include:

- Crazing
- Drying shrinkage cracks
- Thermal movement cracks
- Cracks due to corrosion of reinforcement
- Chemically induced cracks (eg AAR)

Volumetric change in concrete cannot be prevented. Concrete expands or contracts due to movement of moisture or temperature changes. If such movements are excessive, or if adequate measures have not been taken to control their effects, the concrete will crack.

Chemical reactions within the body of the concrete, which can cause it to expand and crack, include reinforcement corrosion, sulphate attack and alkali-aggregate reaction. This cracking can be minimised by careful selection of materials and the use of appropriate quality concrete that is properly placed, compacted and cured.

Control of Cracking

The general approach to controlling cracking in concrete can be divided into the following three components.

Reinforcement and Detailing

Reinforcement alone will not prevent cracks, but in hardened concrete can control crack width and spacing. Reinforcement detailing issues generally apply more to suspended slabs to control the extent of cracking caused by factors such as flexure.

Jointing and Saw Cutting

For aesthetic reasons relating to cracking, large expanses of slab-on-ground must be broken into smaller panels by formed joints or saw cuts. The ratio of the longer to the shorter side of these panels should be in the range of 1:1 to 1.5:1. For typical slabs-on-ground it is generally recommended that joint spacings do not exceed six metres, with closer spacings preferable. However, the influence of ambient conditions (temperature, humidity, etc), efficiency of curing and subbase preparation can also influence the joint spacing. For example, the C&CAA's experience with driveways suggests that for the typical slab and subgrade preparation, joints should be spaced no more than about three-and-a-half metres apart.

Saw cutting generally takes place somewhere within 5 to 16 hours after the placement of concrete. It is generally possible to early-age, or 'soft' saw cut in approximately half the time that 'green' saw cutting can take place. The essential issues governing the effectiveness of saw cutting are ensuring the adequate depth of the saw cut and ensuring that the saw cuts are made at the appropriate time. A delay in carrying out the saw cutting will usually result in unplanned cracking. If the saw cutting is undertaken too early, ravelling of the edges and other damage may arise.

Prevention

Adequate compaction and curing are important factors in avoiding or minimising cracking in slabs-on-ground, these are dealt with later.

Crack Mechanisms

Immediately after placing, the concrete enters a dormant period typically lasting a few hours. Consolidation of the plastic mix usually leads to bleeding – settlement of the heavier particles forcing the water to the surface. This bleeding of the concrete results in a reduction of the positive pore pressures. The pores are the spaces between the cement and aggregate particles in a concrete mix, and initially the water in these spaces exerts a positive pressure on the particles within the mix.

If conditions are such that the rate of evaporation of bleed water is greater than the rate at which it is produced, the upper layer of the concrete becomes partially saturated. This results in capillary tension in the pore water, creating a suction force, which draws the solid particles closer, ie the water is in tension and the concrete particles are in compression. This is similar to the surface tension mechanism that results in the water at the edge of a glass curving up the surface of the glass. If the concrete is restrained from contracting, then tensile stresses within the upper layer of concrete are induced.

In this context, cracking of concrete pavements at early ages is caused by restraint, which may be external or internal. In the case of plastic shrinkage cracking, the restraint is typically internal, either globally by the saturated lower layer of concrete or locally by reinforcement. For thinner pavements and toppings, the influence of external restraint (against the shrinkage) from the slab or subgrade below will increase. Sometimes a slip layer is provided between the base and subbase to reduce this restraint, and lower the differential tensile stresses between the top surface and bottom of a slab, that can lead to cracking.

When the tensile stresses reach the concrete's tensile strength, cracking commences. As the crack forms, the concrete on either side contracts, consistent with the reducing tensile stress across the partially formed crack interface. The crack thus continues to widen and propagate until the stress finally reduces to zero, and the total local deformation is present as crack width.

Depth of Cracks

Once a crack of reasonable length and depth has formed, it is sometimes possible for the crack to propagate through the full depth of the concrete. As the upper concrete on either side of the crack tends to contract, tension is created at the crack tip, and the crack propagates downwards. A typical full-depth plastic shrinkage crack is not fully formed at the base, and much wider at the top. Full-depth cracks can widen later under the effects of drying shrinkage or temperature. The same effects combined with the fracture behaviour of the concrete can cause some partial-depth cracks to propagate to full-depth cracks at a later stage.

Defects

The presence of voids within the concrete mix, mainly from poor compaction, reduces the tensile strength of the concrete. This increases the chance of cracking in the concrete, as the average tensile stresses required to initiate cracking are reduced.

Figure 1 presents the effects of voids on the cracking of a highway pavement under vehicular loads. It shows that the larger the void and the closer the void is to the tension surface, the greater the reduction in flexural tensile strength.

When stresses at the tip of a void approach the tensile strength of the concrete, a crack is initiated. Concrete stresses in front of a crack increase under load until the tensile strength is again approached and the crack propagates. Uncontrolled extension of the crack will occur when the rate at which the damaged concrete sheds stress is greater than the ability of the concrete in front of the crack to accept increased tensile stress.

Good compaction of the concrete will reduce the number and size of voids. This will decrease the risk of cracking as the flexural tensile strength of the concrete is maintained.

Evaporation

It is generally accepted that if the ambient conditions (temperature, humidity and wind velocity) combine to generate an evaporation rate in excess of 0.5 kg/m^2/hr, then protective measures to control excessive moisture loss should be instigated to reduce the risk of plastic shrinkage cracking. While there are both nomographs and formulas for calculating the rate of evaporation, they do not take into account the bleed rate of the concrete.

The increased fines content of higher strength concretes significantly reduces the bleed rate, leaving the concrete at increased risk of high

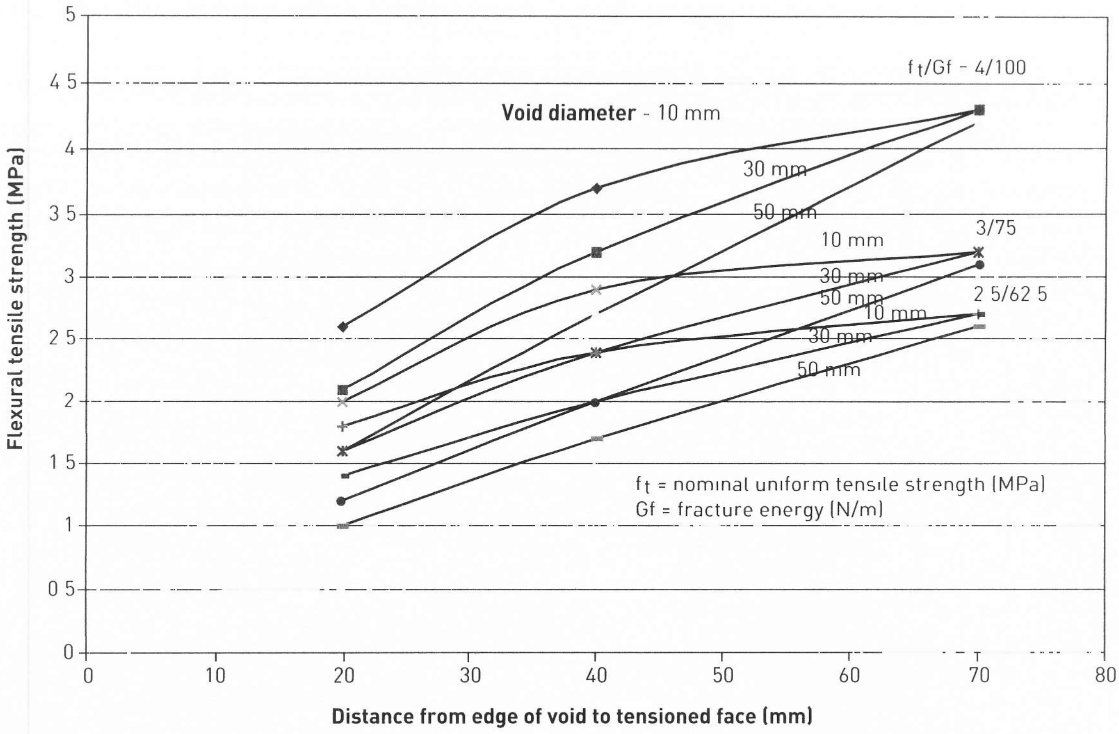

Figure 1. Effect of void size and location on flexural tensile strength

moisture loss from the upper layer, even when the rate of evaporation is less than 0.5 kg/m^2/hr For large areas of higher strength concrete, precautions should therefore be taken to control the moisture loss Evaporative retarders such as aliphatic alcohols are designed specifically to reduce the rate of evaporation and hence defer an increase in the suction forces leading to possible cracking, until the concrete has developed enough strength to resist the tensile stresses

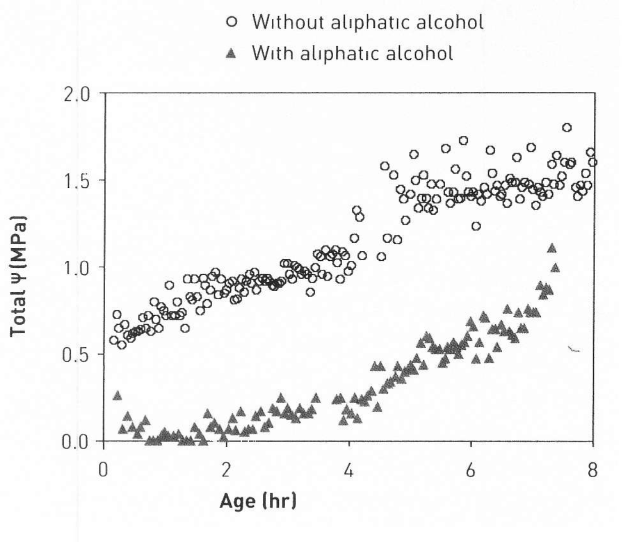

Figure 2: Variation with age of total Ψ in early-age cement mortar[1]

Early-Age Protection

(use of Aliphatic Alcohol)

Figure 2 shows the variation with age (time after mixing) of the moisture suction, ψ expressed in MPa, at the exposed surfaces of two specimens of early-age cement mortar with an initial water-cement ratio of 0.5

The specimen with aliphatic alcohol applied to the surface did not crack, but the unprotected specimen cracked after 4.9 hr As aliphatic alcohol clearly reduces capillary tension in the upper layer of concrete, it should be applied as soon as possible after screeding, especially for higher strength concrete mixes. Re-application is necessary if intermediate activities such as bull floating, work the aliphatic alcohol into the concrete surface.

Note that aliphatic alcohol is not a curing compound, and the concrete will still require adequate curing

Compaction and Curing

Figure 3 shows the compressive strength versus density for samples with standard and non-standard compaction and curing All results are compared to that of the standard specimens (normal compaction and curing) at 28 days

Note that the standard specimens have the highest compressive strength and density As density reduces through a combination of ineffective compaction and inadequate curing, the

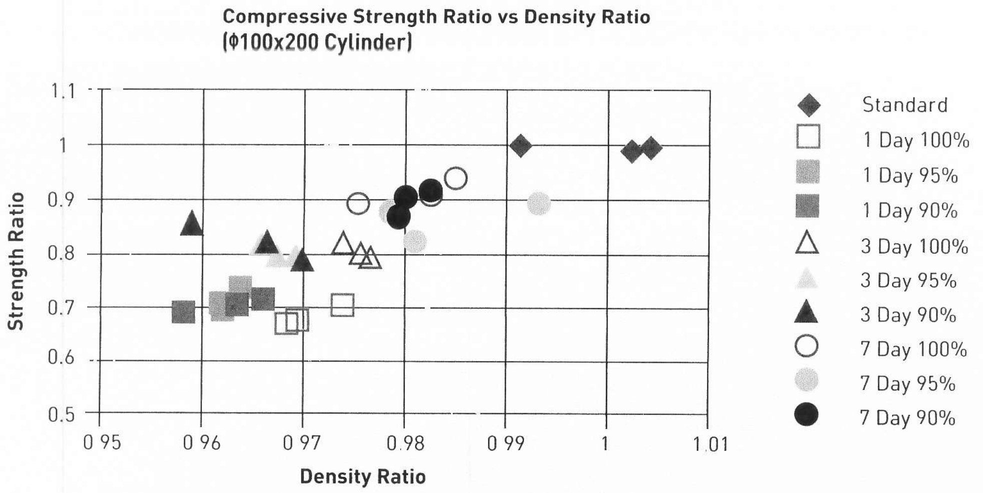

Figure 3· Normalised compressive strength versus density for specimens with standard and non-standard compaction/curing

compressive strength reduces significantly (ie a 4% increase in voids caused by poor compaction combined with ineffective curing, was sufficient to reduce the compressive strength by 30%)

Compaction must be thorough, and apart from early-age protection of the concrete as discussed above, longer-term curing must be applied directly after finishing to enhance the concrete's ability to resist cracking

Conclusions

The paper concludes that the most effective approach to controlling cracks in concrete generally involves looking after the concrete in the important early age Good construction practices for concrete pavements include

- Preparation of the subgrade to reduce restraint
- Adequate compaction to reduce voids and increase strength
- Protection against risk of plastic shrinkage
- Early and adequate curing to reduce tensile stresses and improve tensile strength
- Timely saw cutting

Dux[2] showed that the specification of low-shrinkage concrete mixes will not, on its own, necessarily ensure adequate crack control Whilst drying shrinkage may be the 'driver' behind cracks in slabs and pavements, the initiation of the cracks is more likely to be related to restraint and early-age activities (curing, compaction, saw cutting)

Based on the work that has been completed to date, it is evident that by controlling construction conditions and practices, it is possible to avoid or minimise problems associated with cracking Some conditions such as high winds on hot days are impossible to control on large exposed areas of pavement, and consideration should be given to delaying the placement of concrete under these conditions Having a quantity of evaporative retarder on site is always good insurance if conditions change during placement As a general rule, it is essential to control the evaporation from low-bleed mixes typical of high-strength concretes

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2 Dux PF *Mechanisms and Significance of Cracking in Concrete*, CIA Symposium, Brisbane, September 2000

Further Information

- Contact info@ccaa com au to request a copy of the full paper
- *Guide to Concrete Construction* - Cement and Concrete Association of Australia/Standards Australia publication SAA HB 64 - 2002, available through Standards Australia
- Cement and Concrete Association of Australia web site at www concrete net au