TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING
ISSN 1021-2019
Vol 61 No 4, December 2019, Pages 50–58, Paper 0118

Concrete properties for ultra-thin continuously reinforced concrete pavements (UTCRCP)

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Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP) is an innovative road paving technology that can have significant advantages over traditional road paving techniques. Tests have shown that UTCRCP can carry in excess of one hundred million E80s (standard 80 kN axle loads). The laboratory tests used for quality control of conventional concrete are not adequate to fully capture the effects of the steel fibres added to the high strength concrete used in UTCRCP. In this study the concrete strength and fibre content were varied and the mechanical and physical properties of the concrete were measured. The tests included compressive strength, split cylinder, modulus of elasticity and four-point bending slab tests. The results of these tests are reported in this paper, and the suitability and shortcomings of the tests are discussed.

Keywords: UTCRCP, ultra-thin continuously reinforced concrete pavements, fibre-reinforced concrete, energy absorption

INTRODUCTION

An Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP) as defined by Perrie and Rossman (2009) is a thin concrete layer with a thickness in the region of 60 mm constructed from concrete with a compressive strength in the order of 100 MPa that contains both steel and plastic fibres. Two types of ultra-thin pavements are defined by Perrie and Rossman (2009):

- UTCRCP for highly trafficked pavements
- UTRCP for lower trafficked pavements.

Although these pavements share many features, they have some distinct differences. This study focused on UTCRCP intended for highly trafficked pavements.

With the ageing road network in South Africa and the limited budget available to perform maintenance of roads, there is a need to consider innovative and cost-effective rehabilitation options (Kannemeyer *et al* 2007). UTCRCP can be an option for the structural rehabilitation of roads. A number of experimental and trial sections have been constructed to test the performance of UTCRCP under vehicle loads, including accelerated pavement tests with the Heavy Vehicle Simulator (HVS) and trial sections on national highways.

The main components of UTCRCP are concrete, reinforcing mesh, steel fibres and polypropylene fibres. The high fibre content and concrete strength result in concrete that is relatively expensive compared to normal concrete. Higher-strength concrete can be less workable, while increased fibre content also reduces workability. Therefore increasing fibre content and concrete strength not only results in a product that is more expensive per unit volume, but the handling and placing difficulties also result in higher construction cost. Workability of the concrete can be increased by the appropriate use of concrete technology. However, this also has cost implications. If the fibre content and concrete strength can thus be reduced, this will result in a saving in the construction cost of UTCRCP. The risk, however, is that reducing concrete strength and fibre content will compromise the long-term performance of UTCRCP. An optimised UTCRCP design will balance construction cost with long-term performance. This study aimed to investigate the effects of varying the concrete strength and fibre content on the performance of UTCRCP.

UTCRCP COMPONENTS

Concrete

The concrete compressive strength specified for construction is in the region of 90 MPa to 120 MPa. Laboratory tests have shown that the optimum thickness of UTCRCP is between 50 mm and 60 mm in order to

Mackellar A, Kearsley E. Concrete material properties for ultra-thin continuously reinforced concrete pavements (UTCRCP).
J. S. Afr. Inst. Civ. Eng. 2019:61(4), Art. #0118, 9 pages. http://dx.doi.org/10.17159/2309-8775/2019/v61n4a5

Table 1 Concrete mix designs

	Unit	Relative density*	Desired concrete mean strength		
			90 MPa	70 MPa	50 MPa
Water-cement ratio			0.48	0.59	0.75
Cement (CEM1 52.5N)	kg/m^3	3.14	267.8	217.9	171.4
Fly ash	kg/m^3	2.26	45.1	36.7	28.8
Condensed silica fume	kg/m^3	2.32	22.5	18.3	14.4
Water	kg/m^3	1.00	161.0	161.0	161.0
Dolomite 9.5 mm aggregate	kg/m^3	2.82	759.4	759.4	759.4
Dolomite sand	kg/m^3	2.84	1 268	1 333	1 393
Superplasticiser	l/m^3	1.05	5.9	4.8	3.8
Defoamer	ml/m^3	0.81	0.5	0.5	0.5
Polypropylene fibre	kg/m^3	0.92	2	2	2
Steel fibre (30 mm long 0.5 mm diameter hooked-end cold-drawn wire fibres)	kg/m^3	7.68	0,50,70,90	0,50,70,90	0,50,70,90
*Relative density measured by helium gas pycnometer					

maximise bending resistance (Kannemeyer *et al* 2007). Reinforcing mesh needs to be placed at the centre of the UTCRCP. Placing concrete within these tight confines limits the maximum aggregate size that can be used in the concrete. The experimental sections constructed at Heidelberg used 6.75 mm stone (Kannemeyer *et al* 2007; Mukandila *et al* 2009). After placing, during curing and thereafter, concrete shrinks, and because this shrinkage is restrained the reduction in volume places the road pavement in tension. De Larrad (2005) observed that the concrete shrinkage can be used to the advantage of engineers. Placing the pavement in tension assists in restraining buckling of the pavement as a result of excessive thermal expansion.

Reinforcing mesh

It was found that increased diameter of the steel mesh resulted in increased bending resistance. However, thicker mesh also resulted in higher cost and increased the difficulty of placing the concrete. The mesh diameter recommended by Kannemeyer *et al* (2007) was 5.6 mm (Y6) with a spacing of 50 mm by 50 mm as a good compromise between cost and constructability. Shrinkage of the concrete can result in high-tensile forces in the reinforcing mesh, and this can be large enough to snap the reinforcing mesh (Perrie *et al* 2011). It is thus important to supply sufficient ductile mesh reinforcing.

Steel fibres

The inclusion of steel fibres can delay and control the tensile cracking of the concrete, thus increasing the load-carrying capacity of the concrete (Elsaigh *et al* 2005; Chen 2004). The use of the incorrect geometry fibres was found to lead to rapid failure of UTCRCP. The HVS and associated laboratory tests showed that 30 mm hooked-end fibres can prevent sudden failures (Kannemeyer *et al* 2007).

Polypropylene fibres

The function of polypropylene fibres added to concrete is different to that of steel fibres. Polypropylene fibres do not significantly contribute towards the flexural performance of concrete (Zhang & Stang 1998). The purpose of the polypropylene fibres is to modify the properties of the fresh concrete. In particular, these fibres have been found to reduce plastic shrinkage cracking of the concrete (Illston & Domone 2008).

EXPERIMENTAL SETUP

As the aim of this investigation was to determine the effect of both concrete strength and fibre content on the properties of the concrete, concrete mixes with target compressive strengths between 50 MPa and 90 MPa with steel fibre content up to 90 kg/m^3 were used. Specimens were cast to determine and compare the 28-day compressive strength, split tensile strength, bending strength and stiffness of the different mixes.

Concrete mix design

The concrete mix designs are given in Table 1.

Preparation of specimens

Specimens (cubes, cylinders and slabs) were prepared in the laboratory and cured in water at 24°C for 28 days.

Cube and split cylinder test results can be used to provide material parameters of UTCRCP, but these results do not give any indication of the flexural capacity of the material. The intricate interactions that a full pavement structure is subjected to cannot be replicated in the laboratory and the flexural capacity can only be estimated from slab tests reflecting the geometry of the pavement. The following tests were carried out:

- The standard cube test (SANS 5863, 2006b) on 100 mm cubes to measure compressive strength. The results reported are the average of three test results.
- The modulus of elasticity or E-value test on three 150 mm diameter cylinders (300 mm high). A gauge length of 198 mm was used and the deformation for loads up to 40% of the cube strength was used to calculate the chord modulus of elasticity. The E-values reported are the average of three specimens tested. After the chord modulus was measured, specimens were loaded to 70% of the cube strength with deformation readings taken in 50 kN increments. This was done to examine the extent of linear elastic behaviour of the concrete.
- The split cylinder test (SANS 6253, 2006a) on three 150 mm diameter cylinders to measure indirect tensile strength.
- Flexural tests on three 700 mm × 250 mm × 55 mm slabs to measure

Modulus of Rupture (MOR), maximum load and energy absorption.

TEST RESULTS

Compressive strength

The effect of fibre content on compressive strength of concrete is shown in Figure 1. It is observed that fibre content has a minimal effect on compressive strength, even at high fibre contents. This concurs with the findings of Illston and Domone (2008), as well as Song and Hwang (2004). Thus the addition of steel fibres can be expected to have little effect on the compressive strength of concrete.

Although cube testing is a vital quality control test and should be used during the construction of UTCRCP, engineers must be aware that the compressive strength does not give any indication as to the quantity or effectiveness of the steel fibres in the mixture.

Modulus of elasticity

The chord modulus of elasticity and its relation to concrete strength is shown in Figure 2. Modulus of elasticity increases with increasing concrete compressive strength. While there is some difference in stiffness between specimens with differing fibre content, this difference appears not to be significant.

When taking multiple deformation readings during loading it was observed that the stress-strain response was not in fact linear. In order to distinguish between the standard test and the results obtained from taking additional readings, the term "stiffness" will be used for the stress-strain relationship obtained from the additional readings. Figure 3 shows the change in stiffness with increasing applied stress. It is observed that stiffness is not constant under increasing stress, and that fibre content has a small to negligible effect on stiffness.

In Figure 4 the stress applied to each specimen tested was normalised based on the ultimate compressive strength of the concrete for that mix. Additionally the stiffness was normalised based on the stiffness of the first loading increment. It can be observed that at 70% of the ultimate compressive strength, the stiffness reduces to 80% of the initial stiffness. It is also observed that, when the data points are normalised in this manner, all the results fall in a narrow group. This allows a curve to be fitted; the equation describing the observed behaviour is given in Figure 4. Understanding the nonlinear behaviour of concrete will be an advantage when finite

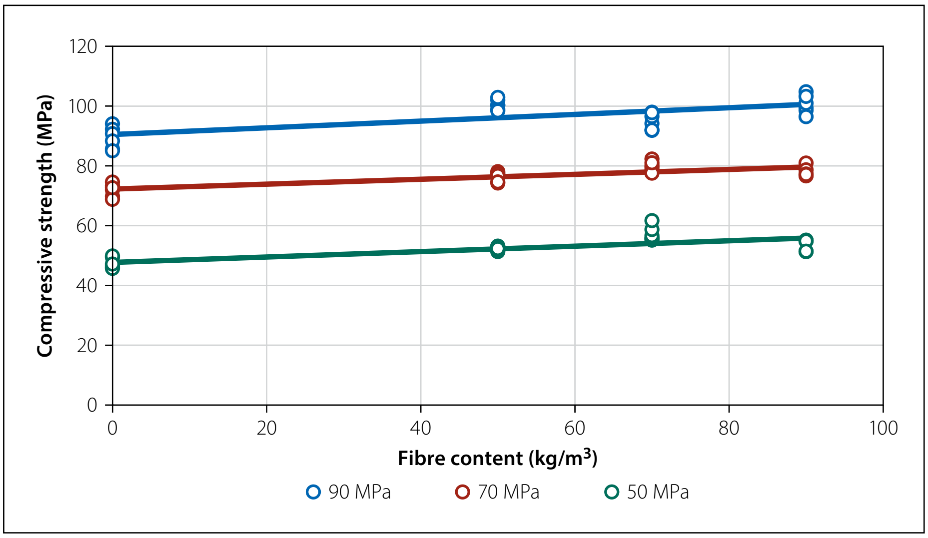

Figure 1 Compressive strength and fibre content

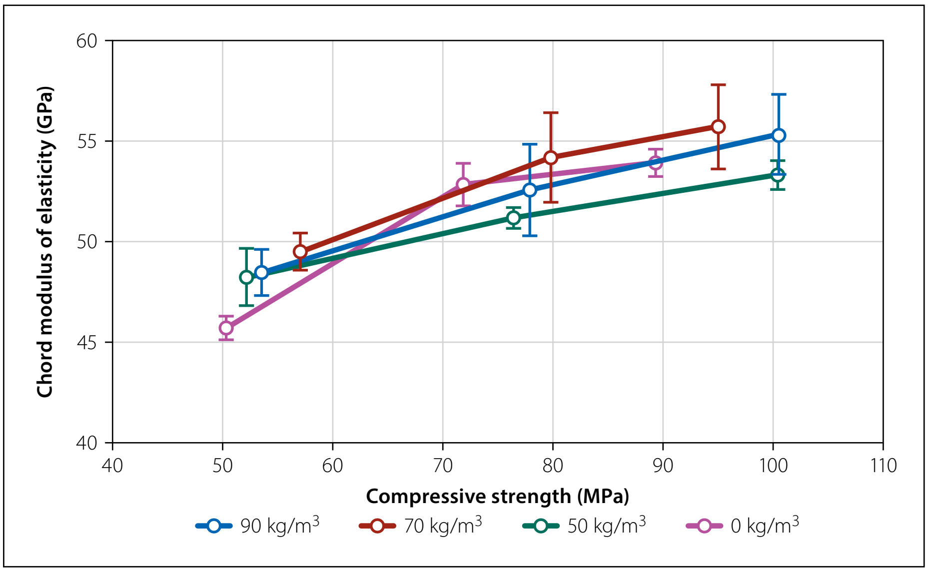

Figure 2 Chord modulus of elasticity for different fibre contents (one standard deviation above and below mean indicated)

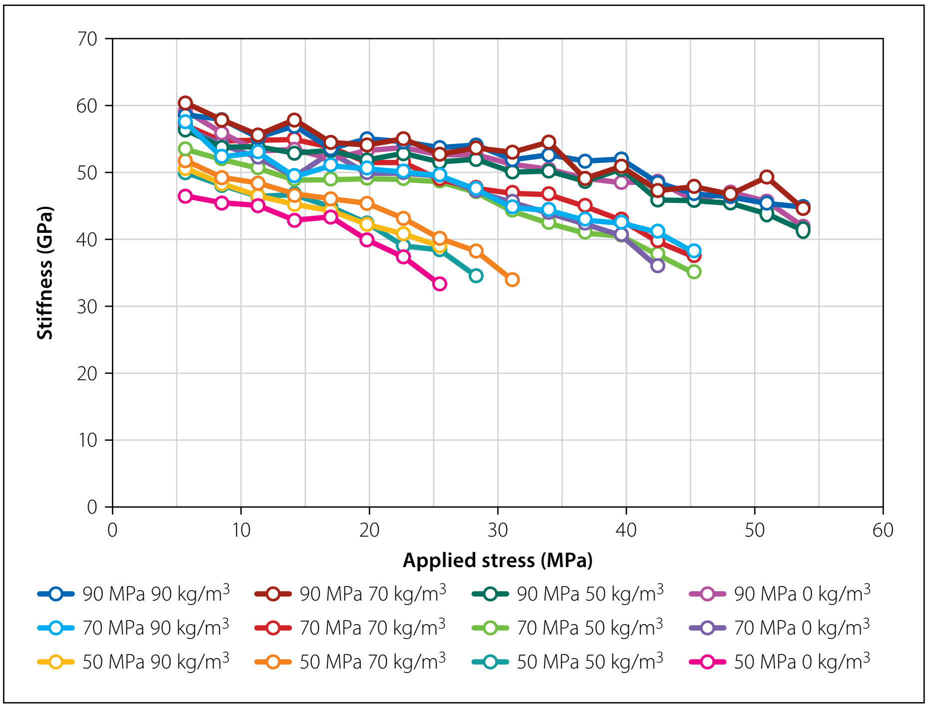

Figure 3 Stiffness as a function of applied stress

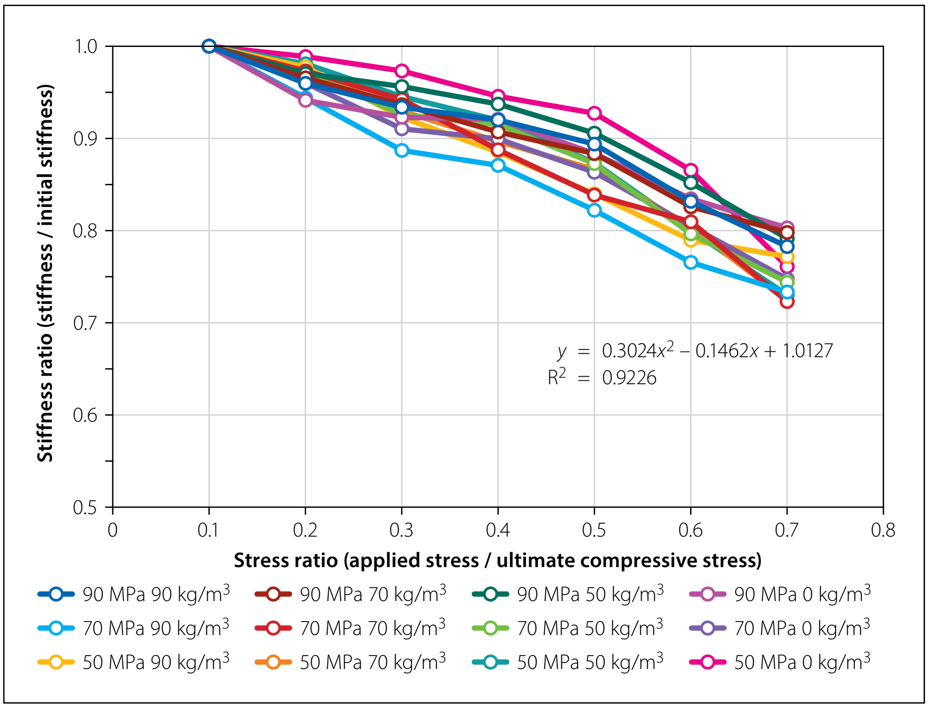

Figure 4 Normalised stress and normalised strain relationship

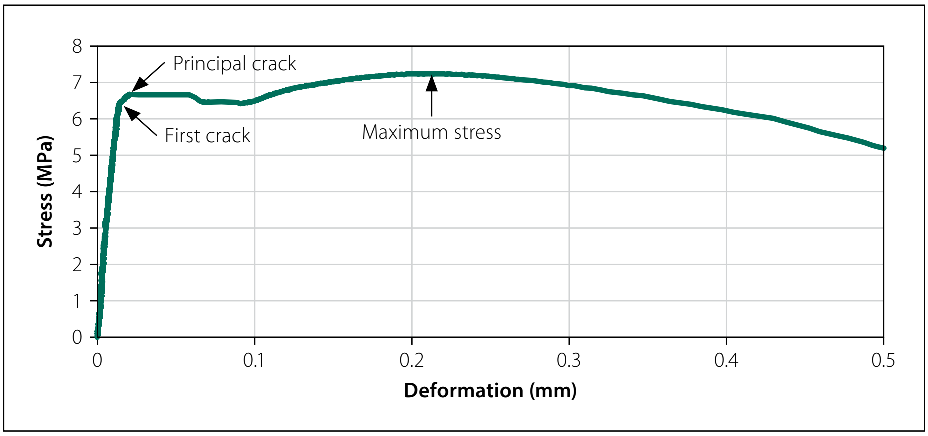

Figure 5 Typical split cylinder test result for a specimen of 90 MPa concrete containing 90 kg/m^3 fibre

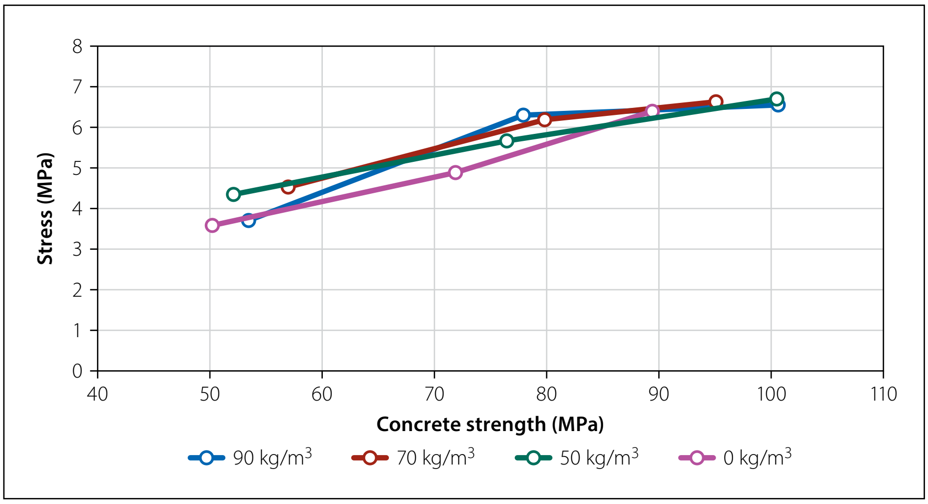

Figure 6 Split cylinder principal crack stress results

element modelling is conducted. Nonlinear finite element models are available, and the nonlinear elastic behaviour of concrete can be incorporated into finite element models to enhance the accuracy of these models.

Split cylinder strength and cracking stress

The indirect tensile strength of the concrete was determined by using the split cylinder test. This is a standard test and the method is described in ASTM C496/C496M-04 (ASTM 2009a&b) and SANS 6253 (SANS 6253, 2006a). For the purpose of measuring the post-crack behaviour of the concrete, the horizontal deformation of specimens was recorded using Linear Variable Differential Transformers (LVDTs) attached to metal pins that were inserted into holes that had been drilled into the specimen. Two LVDTs were used, one at either end of the specimen, and the horizontal deformation was measured over a length of 50 mm. This method was described by Denneman *et al* (2011) and Denneman *et al* (2012).

The formula recommended by both the SANS (SANS 6253, 2006a) and ASTM (2009a) is derived from Boussinesq's theory and was initially solved by Hertz (Timoshenko & Goodier 1951). The assumption made is that the load is applied as a line load. In practice, however, the load is applied over finite width. In order to take this effect into account Tang (1994) suggested the use of the modification indicated in Equation 1.

$$f_t = \frac{2P}{\pi l D}\left[1 - \left(\frac{b}{D}\right)^2\right]^{2/3} \quad (1)$$

Where:
f_t is the tensile stress (MPa)
P is the load (N)
l is the length of the specimen (mm)
D is the diameter (mm)
b is the width of the load strip (mm).

The formula with the adjustment for load width has been successfully used by other researchers when numerically modelling the fracture behaviour of fibre- reinforced concrete (Denneman 2010). The result of a typical split cylinder test is shown in Figure 5. Values used are indicated in the figure as:

- First Crack Stress: this is taken as the stress at which the stress-strain relationship ceases to be linear (Johnston & Zemp 1991; ASTM 2004).
- Principal Crack Stress: the peak or plateau stress following shortly after the First Crack Stress.
- Maximum Stress: the maximum stress resisted by the specimen.

It should be noted that concrete with no fibres fails in a brittle manner. Thus the maximum stress will be equal to the principal crack stress.

The results in Figure 6 show a clear increase in principal cracking stress with increasing concrete compressive strength. The results also show that fibre content has little influence on the principal crack tensile strength of the concrete. This result was expected, because steel fibres can only carry significant tensile load after a crack has formed in the concrete. Fibres bridging the crack transfer load across the crack. Principal crack stress is governed by concrete strength and therefore fibre content does not play a significant role. While the split cylinder test gives a good measurement of the concrete tensile strength, it can be concluded that this test is not a good measure of the behaviour of the fibres in the concrete.

In order to measure the effect of the fibres, the post-crack behaviour of the specimen must be examined. Post-crack strength can be quantified using various methods. The comparison made here is to use the maximum stress results of the split cylinder test as shown in Figure 7. Similar to the principal crack strength results shown in Figure 6, there is an increase in tensile strength with increasing compressive strength; however, higher stresses are now exhibited for specimens with higher fibre contents.

Another method of evaluating post-crack performance of the split cylinders is to evaluate the strain energy. Strain energy is calculated as the area under the load deformation curve up to a specific deflection. This is equivalent to the work done up to that deformation. For the purposes of comparison, horizontal deformation limits of 0.25 mm and 1 mm were selected. These results are shown in Figures 8 and 9. It is clear from these graphs that at any strain level the fibres vastly improve the strain energy performance. At low strain levels there is little difference in the strain energy for different fibre contents; however, as the strain increases, the benefit of increased fibre content becomes apparent. There is an increase in strain energy with increased concrete strength. As reported by Abu-Lebdeh *et al* (2011), this result can be expected as the improved bond between the fibres and concrete matrix increases the energy required to mobilise and pull out the fibres. For lower strains the effect of the concrete strength on strain energy is greater than that of fibre content. At higher strains this effect becomes less pronounced, to the point where increasing concrete strength no longer results in increased strain energy. It is at this point that increased fibre content starts to have more influence on strain energy than the concrete strength.

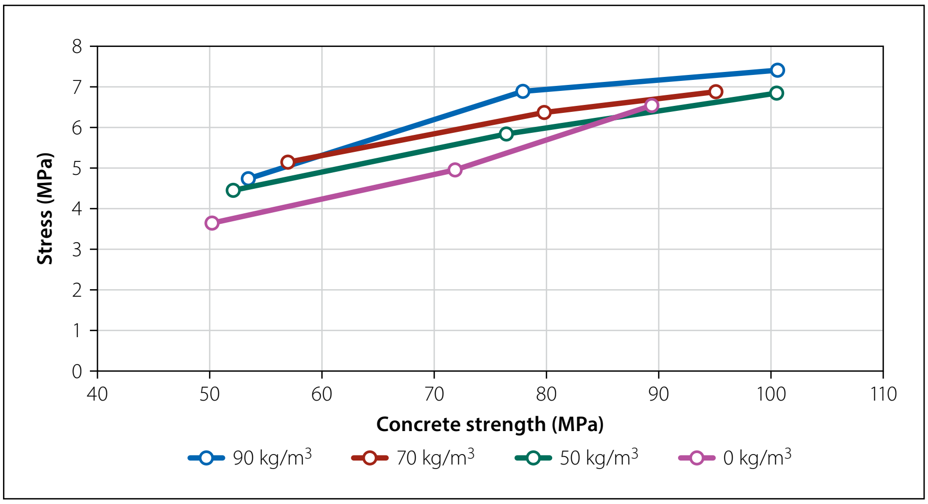

Figure 7 Split cylinder maximum stress results

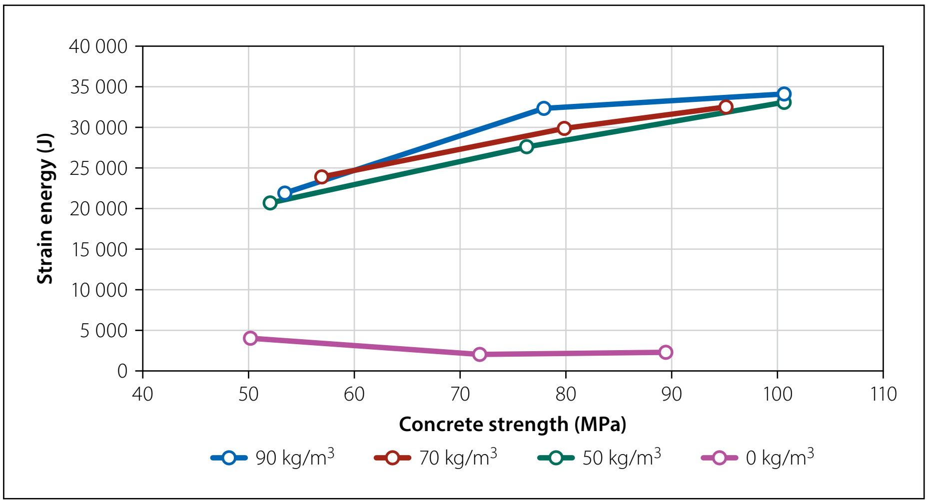

Figure 8 Strain energy at 0.25 mm horizontal deformation

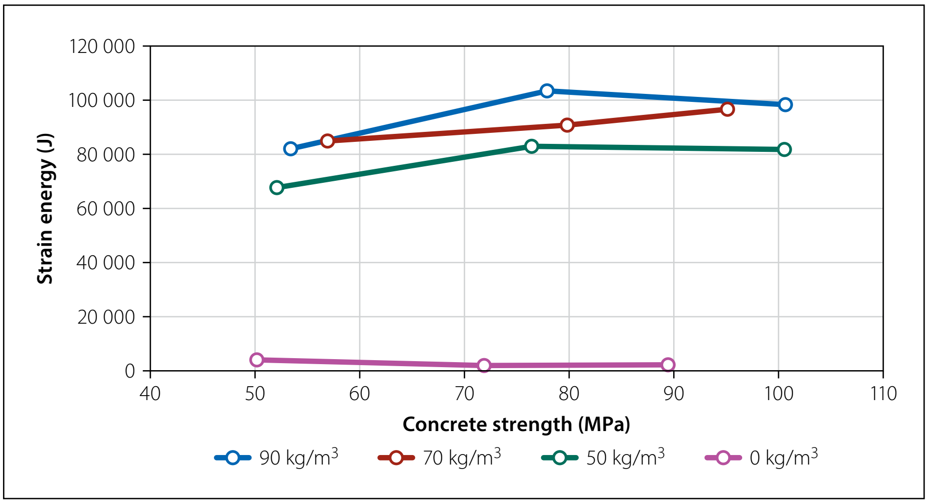

Figure 9 Strain energy at 1 mm horizontal deformation

Flexural slab tests

Slab tests have an advantage over both cube and split cylinder tests because they give an indication of the performance of the pavement structure. Pavements are flexible and transfer force by bending. While it is not possible to replicate all the interactions a full pavement will be subjected to, slab testing attempts to measure the flexural capacity of UTCRCP by applying loads that cause bending of the slabs.

Flexural or beam tests are frequently used as an indirect measure of the tensile strength of concrete used in pavements. The standard test uses a concrete prism of 100 mm by 100 mm spanning 300 mm, loaded in 4-point bending (ASTM 2004). Using elastic theory the tensile strength of the concrete is determined. Denneman (2010) showed that fibre-reinforced concrete exhibits a strong size effect due to its high post-crack tensile capacity. The implication

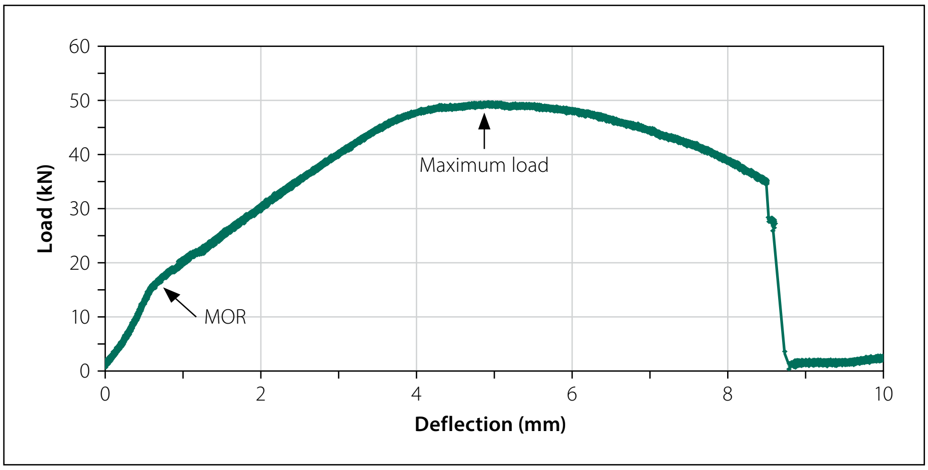

Figure 10 Typical slab load deflection response for 90 MPa concrete containing 90 kg/m^3 fibre

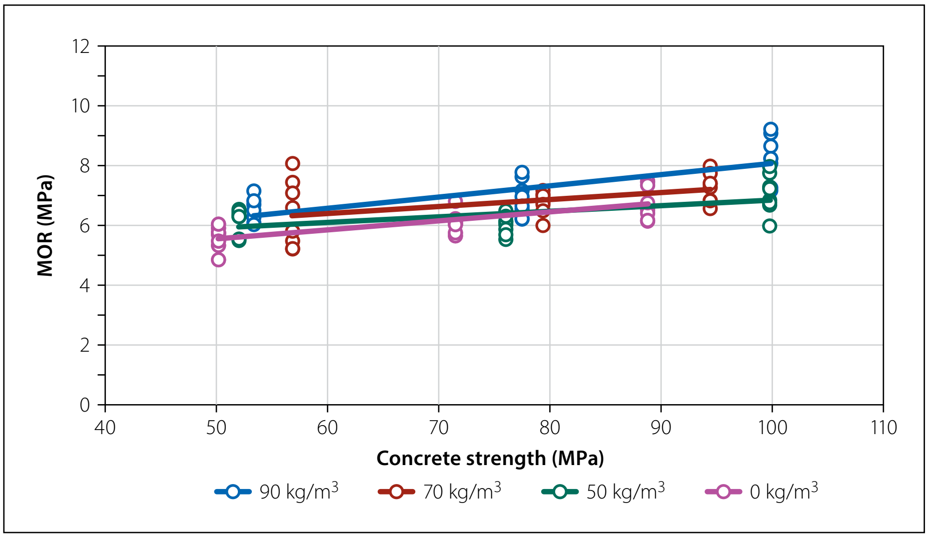

Figure 11 Cracking strength of slabs

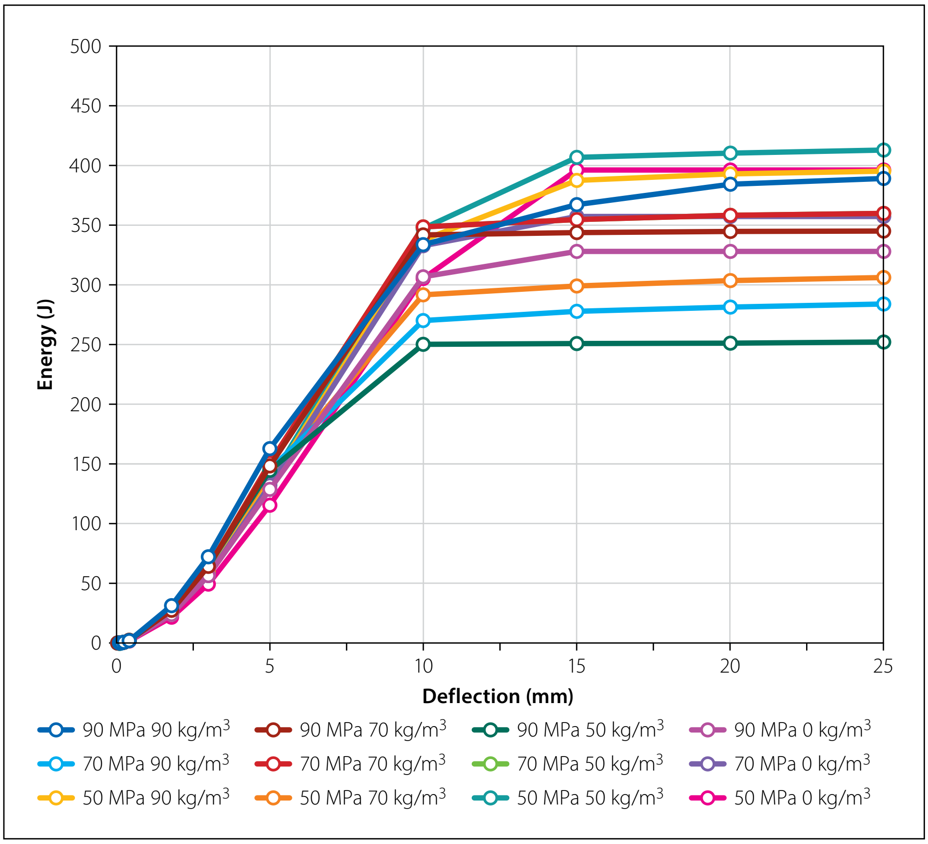

Figure 12 Energy absorption with deflection

of this is that, in order to properly measure the performance of fibre-reinforced concrete, the laboratory specimen must be of the same depth as the UTCRCP. By testing 55 mm thick slabs (the thickness is the same as that of the constructed pavement) the size effect can be neglected, giving a better indication of the actual pavement performance.

Slab tests do not only provide information on the material properties of the concrete, but also the strength of the whole system, as the contribution of the reinforcing bars can also be taken into account.

Flexural tests were conducted on slab specimens that had the same thickness as the UTCRCP. Steel reinforcing mesh of 5.6 mm diameter high-yield steel with a spacing of 50 mm centre-to-centre was placed in the mid-height of the slab specimen. Slabs were supported to span 450 mm and loaded at third points in deflection control at a rate of 0.025 mm/min. From these results cracking strength, maximum load and energy absorption were determined.

The typical load deflection behaviour of a slab is shown in Figure 10. At the onset of loading the relationship between load and deflection is linear. This linear relationship continues up to the point where the principal crack occurs. This point is chiefly a measure of the tensile strength of the concrete. Without steel reinforcing or steel fibres, this would be the ultimate load carried by the sample. The stress in the outer fibres of the concrete, when the failure occurs, is known as the cracking strength or Modulus of Rupture (MOR). Thus the flexural strength of the concrete can be determined from the slab test.

The results of the slab MOR are shown in Figure 11. As expected, MOR is largely influenced by concrete strength, while fibre content has a marginal effect. The flexural strength of the concrete relative to its compressive strength can also be seen in this figure. Flexural strength of concrete is, as expected, approximately 10% of the compressive strength. The results do, however, show that this fraction decreases with increased compressive strength to less than 8%, indicating a diminishing benefit for flexural strength as compressive strength increases.

Energy absorption is a measure of the work done in order to deflect the specimen to a certain point. It is measured in Joules and calculated as the area under the load deflection curve to a specified deflection limit. The energy absorption values for slabs are presented in Figure 12. This shows that energy absorption increases as deflection increases. Beyond 15 mm deflections the specimens broke and little further energy was absorbed. (Not all specimens exhibited the behaviour of the slab in Figure 10, breaking after approximately 8.5 mm; some continued to carry load beyond this point.)

In order to evaluate differences in energy absorption at low, medium and high deflections, three deflections were chosen – 1.8 mm for low deflection, 10 mm for mid-range deflection and 15 mm for large deflection. The energy absorption at these three deflections is plotted in Figure 13. At the low deflections the energy absorbed increases with increasing concrete strength. Increased fibre content also contributes to increased energy absorption (see Figure 13a). At high deflections this trend is reversed. Energy absorption decreases with increased concrete strength and fibre content (see Figure 13c). At mid-range deflections the energy absorption is approximately constant with increasing concrete strength (see Figure 13b).

The reason for this behaviour, i.e. the weaker concrete recording higher energy absorption at large deflections, could possibly be attributed to the concrete crushing in compression. The crushing of the compression concrete in the slab delays the failure of the reinforcing mesh as the strain is relieved. Thus, at larger deflections more energy can be absorbed. The mode of failure could be clearly observed during testing. Figure 14 shows a slab of 90 MPa concrete being loaded to high deflection. Cracking has advanced through the slab. The compression block at the top of the slab is very small. Figure 15 shows a specimen of 50 MPa concrete where cracking has not advanced through the slab. In the compression zone a horizontal crack is visible. This is an indication of the concrete crushing in compression.

CONCLUSIONS

The results of this study showed that the current quality control tests used for plain concrete need to be used with caution when applied to UTCRCP. While the mechanical properties, such as concrete compressive and indirect tensile strength, can be measured, the current standard tests do not reflect the added advantages of the fibres on the performance of the road pavement.

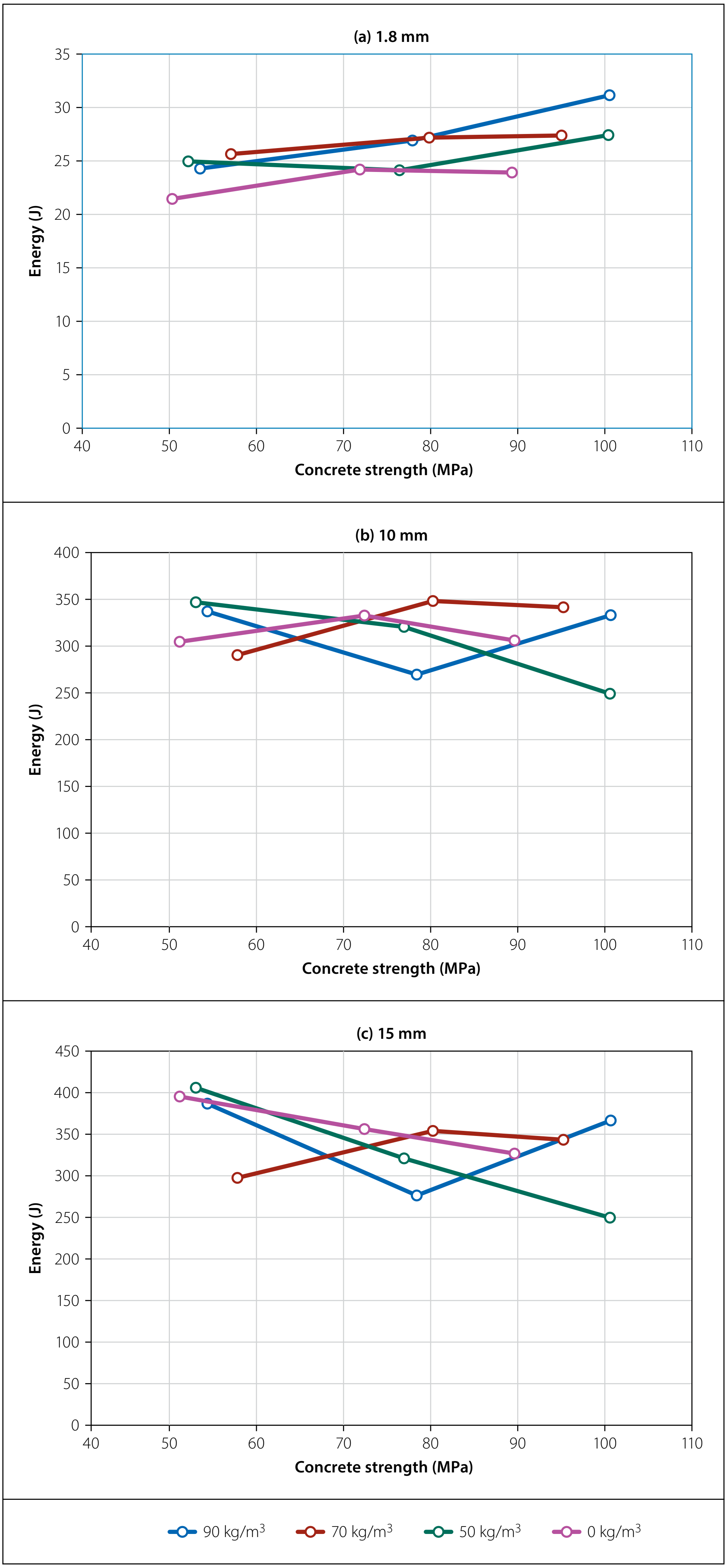

Figure 13 Energy absorption of slabs at deflections: (a) 1.8 mm, (b) 10 mm, (c) 15 mm

Figure 14 90 MPa concrete slab with fibre content of 70 kg/m^3

Figure 15 50 MPa concrete slab, no steel fibres

In summary the results of this study showed that:

- The cube test can be used as a quality control test for concrete strength, but does not yield information on the quantity or effectiveness of the fibres.
- Modulus of elasticity increase with increasing concrete strength. Fibre content does not appear to have a significant influence. The compressive stress-strain relationship of concrete is not linear. When normalised, the stress-strain behaviour can be described by a single equation. This equation is applicable over a range of different concrete strengths.
- The standard split cylinder test can also be used to measure concrete tensile strength, but is a poor measure of the quantity and effectiveness of the fibres. However, if lateral displacement is measured during the test, the effect of the fibres can be measured.
- The flexural slab test is an effective quality control test in that it produces a number of performance measures. The slabs are cast with the same thickness as UTCRCP and also include reinforcing steel mesh. From the results of the slab tests, concrete strength, maximum load and energy absorption can be calculated. However, the results of this study show that these tests must be used with caution.
- Modulus of Rupture (MOR) is a good measure of concrete flexural strength, but is not a good measure of fibre content or performance. There is correlation between the flexural strengths measured from the slab tests and the splitting cylinder tests. This means that MOR could be used in place of split cylinder testing, streamlining on-site quality control tests.
- Maximum load is a poor indicator of performance. From these results it appears that it is not sensitive to concrete strength or fibre content. It is recommended that maximum load is not used as a quality control measure for UTCRCP.
- The energy absorption must be used with caution. At present the quality control specifications for energy absorption measured at large deflections favour the production of weaker concrete. It is recommended that the quality control specification should be adjusted for UTCRCP to energy absorbed at low deflections which are more appropriate to pavements.

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