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A PILOT STUDY OF CEMENT-TREATED BASECOURSES FOR USE IN PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

OESER, Markus, markus.oeser@unsw.edu.au
SHACKEL, Brian, b.shackel@unsw.edu.au
DE OLIVEIRA DA LUZ, Glaoco

The University of New South Wales, School of Civil and Environmental Engineering, UNSW, Sydney, 2052, AUSTRALIA.
Tel.: +61-2-93855016, Fax.: +61-2-93856139.

KABITZKE, Ute

Dresden University of Technology, Faculty of Civil Engineering, Institute of Urban and Pavement Engineering, D-01062 Dresden, GERMANY.
Tel.: +49-0-35146332718, Fax.: +49-0-35146337705, kabitzke.ute@googlemail.com

Note: The following is the notation used in this paper: (.) for decimals and ( ) for thousands.

Summary

Most studies of permeable basecourse materials for PICP have hitherto concentrated on unbound granular materials. This paper presents a pilot study of cement-bound granular material for use as basecourse in permeable pavements.

Experimental studies of a range of cement-treated materials using uniform gradations of aggregate yielded properties that were often superior to the basecourse materials currently recommended for PICPs. Materials with different sizes of aggregates and cement contents were tested in order determine the impact of these factors on the hydraulic and structural properties. Details are given of the voids ratio, permeability, compressive and tensile strength and the resilient tensile moduli obtained under repeated triaxial loading. These properties are compared with those previously reported for conventional and permeable basecourse materials.

The implications of these findings in the design and construction of PICPs are then discussed. It is shown that cement-treated basecourses can combine high voids ratios and permeabilities with the mechanical properties needed to support significant traffic loads.

1. INTRODUCTION

Conventional pavements are designed to be impermeable to prevent surface water from penetrating into the structure and causing damage to it. Thus, impermeable pavements seal the pavement surface and act as a major generator of runoff. The rising awareness and importance of sustainability and ecology in building and design requires rethinking on the use of impermeable pavements and will lead to a more frequent construction of permeable pavements, which allow water to infiltrate through the pavement surface.

In case of a rainfall event, the water can be drained quickly and immediately through the surface of permeable pavements, which reduces the runoff volume. By this means the risk of aquaplaning is also reduced, which improves traffic safety and riding comfort [Tennis et al, 2004]. The reduction of surface water runoff also lessens the impact on stormwater drainage systems and lowers the risk of flooding, which in turn minimizes the need for retention ponds, swales and other precipitation runoff containment strategies. Thus, land can be used more efficiently. The water that infiltrates the pavement increases the rate of groundwater recharge and provides trees and plants in the proximity of the pavement with excellent growing conditions. Previous research has shown that the quality of the water, that exits the pavement, iscleaner than the rainwater falling on the pavement surface [UniSA, 2002]. Pervious pavements can control the amount of pollutants that get into the ground. In this respect, PICP can trap about 90% of particulate contaminants [UniSa, 2002; Shackel, 2008].

Material requirements for basecourse for PICP include the need for high void ratios so that as much water can be stored within the pavement as possible, the need for high permeability so that water can infiltrate the pavement quickly and adequate stiffness and strength to resist the effects of traffic without failure. Essentially, permeable base materials must achieve the mechanical properties required for traditional pavements whilst, at the same time, balancing the conflicting requirements of good stiffness with high voids ratio and permeability. Conventional base materials used in highways generally do not meet these requirements. There is therefore a need to develop new base materials for PICP. Hitherto, for PICP use has been made of open graded, single sized granular materials which provide high void ratios but whose mechanical properties are barely adequate to resist the effects of even light vehicular traffic. However, using repeated triaxial loading tests, it has already been shown that it is feasible to modify the gradations of granular materials to give a more optimal blend of hydraulic and mechanical properties for use in PICP [Shackel et al, 2001]. The work now described here explores the possibilities of extending such studies to cement bound basecourses for PICP.

Careful proportioning is crucial to meet both mechanical and hydraulic requirements. A uniform grading and the elimination of fines ensure for good hydraulic properties (high void ratio and permeability). The aggregates are bound together by cement ensure for adequate strength and stiffness. On the one hand permeability increases with the void ratio, but on the other hand an increase in the void ratio leads to a decrease in stiffness and strength. Thus, proportioning of pervious materials must always be a compromise between permeability and strength.

Hydraulic design generally leads to the design thickness of the pavement layers (as a result of storage capacity combined with controlled infiltration to the subgrade or to stormwater systems), which may be different to the thickness necessary to meet the mechanical requirements of traffic. The fact that the pavement is permeable and that the base-course will often be fully saturated with water, carries additional effects that differ from impermeable pavements. It must be understood that in permeable pavements a mechano-hydraulic interaction between water, air and solids takes place when vehicles traverse the pavement. This interaction has a significant impact on the load bearing behavior of pervious pavements. In order to realistically capture the behaviour of those pavements and to achieve a suitable structural design, these effects must be considered by means of adequate analysis and design models, which in turn require accurate knowledge about the material behaviour. The key parameters used for coupled mechano-hydraulic analysis and design may be summarized as follows: void ratio, permeability, suction, modulus of elasticity, Poisson’s ratio, compressive strength and tensile strength. These key parameters have been determined on the basis of material tests using the pavement laboratory of the University of New South Wales.

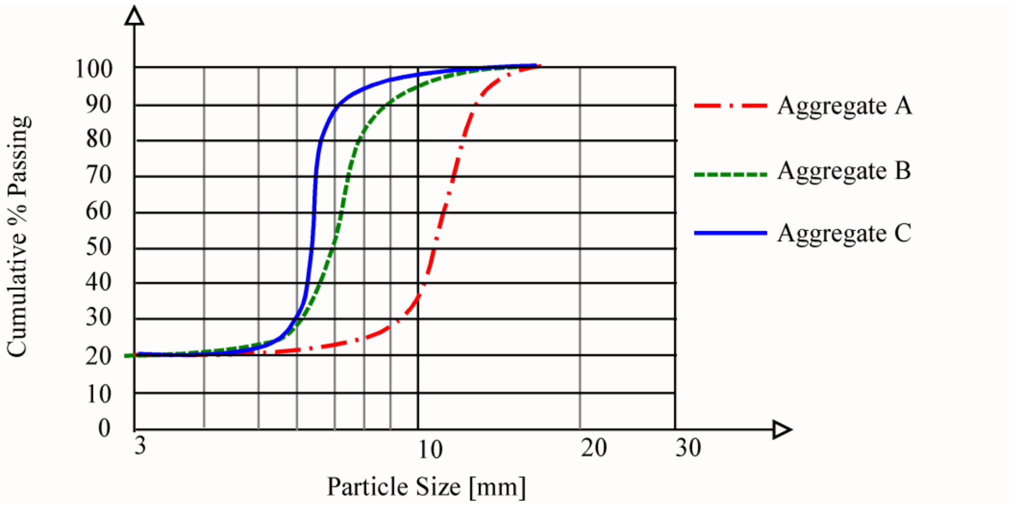

Figure 1. Grading curves.

2. EXPERIMENTAL WORK

The concept of using open graded concrete mixes in PICP is not new and the German Best Practice Guide [Krause, M., 1998] includes specifications for "drain concrete". However, this does not appear to be supported by any experimental studies. The recommendations for drain concrete in the German standard are not detailed but are based on the use of single sized aggregates. This is consistent with earlier studies that show that the permeability and voids ratio of granular materials tend to increase with increase in the Coefficient of Uniformity [Shackel et al, 2001]. For this reason work began with a 9.4 mm to 12.7 mm aggregate having the grading shown as A in Figure 1 and falling within the range of materials recommended in the German Guide.

Having chosen an aggregate it was next necessary to select a cement content. This was done experimentally over a range of cement contents from 200 kg/m^3 to 400 kg/m^3. This was consistent with customary proportioning of pervious concrete where the cement content usually ranges from 270 kg/m^3 to 415 kg/m^3 with aggregate contents between 1 190 kg/m^3 and 1 480 kg/m^3 and an aggregate-cement ratio of 4 to 4.5. The water-cement ratio is usually recommended to be between 0.27 and 0.34 [Tennis, 2004].

For cement contents of 250 kg/m^3 or less, it proved impossible to mould specimens that were robust enough to test. For this reason, higher cement contents of 300 kg/m^3, 350 kg/m^3 and 400 kg/m^3 were selected for study. The effects of cement content on the voids ratio, stiffness, strength, and permeability are summarized in Table 2. Each value in this table is the mean of 3 tests.

Table 1. Effects of Cement Content on Mechanical and Hydraulic Properties.

CEMENT CONTENT kg/m^3	MECHANICAL PROPERTIES			HYDRAULIC PROPERTIES	
	UNCONFINED COMPRESSIVE STRENGTH MPa	INDIRECT TENSILE STRENGTH MPa	STATIC MODULUS MPa	VOIDS RATIO	PERMEABILITY m/s
300	6.3	1.1	7.33	37	0.030
350	7.0	0.9	6.59	35	0.025
400	9.7	1.3	11.49	33	0.029

From Table 2 it may be seen that, as would be expected intuitively, the compressive and tensile strengths and the static moduli tended to increase with cement content. However, there was little effect on permeability and only a small reduction in voids content with increase in cement content. For this reason and because the hydraulic properties are the major consideration for many forms of PICP it was decided to adopt a cement content of 300 kg/m^3 for the rest of the experimental work.

Proportioning is normally a compromise between the hydraulic and mechanical properties of a basecourse material and strength. Three different mixtures were tested, using different types and sizes of aggregate. The proportioning is given in Table 2. Basalt was used for the first and second mix and river gravel for the third mix. All fines were sieved out in order to obtain uniform grading. The size of aggregate was varied from coarse aggregate (9.5mm to 12.7mm) for the first mix to medium (4.75mm to 9.5mm) for the second and third mixes. The grading curves for each mix can be seen in Figure 1. No additives or admixtures were used.

Table 2. Proportioning of Mixtures.

	MIX A	MIX B	MIX C
Aggregate size	9.5-12.7mm	4.75-9.5mm	
Material of aggregate	Basalt		River gravel
Aggregate content	1 300 kg/m³		
Cement content	300 kg/m³		
Aggregate-cement ratio	4.34		
Water-cement ratio	0.28		

2.1 Manufacturing of the specimen

The specimen were made and cured according to Australian Standard AS 1012.8.1-2000. First, the aggregates and cement were dry-mixed for five minutes before water was added and all components were mixed together for three minutes. After the completion of the mixture a slump test was performed and the specimens were cast in steel moulds. 18 cylinders of a height of 200 mm and 100 mm diameter were manufactured for each mixture. The concrete was filled into the steel mould in two layers. In order to obtain a permeable material vibration was not applied to the specimen, rather, compaction was achieved by rodding each layer with 10-15 strokes.

The specimens were removed from the mould one day after casting and were moist cured at a temperature of 23°C according to the Australian Standard.

2.2 Void ratio and Permeability

The specimen was weighed in saturated condition to determine the mass of water. After that, the concrete was dried for 24 hours in a drying oven to obtain the mass of the solids. The Volume of the solids was determined by measuring the volume of displaced water, when immersing the specimen into water. From these measurements the voids ratio, e was determined,

The permeability of each mixture was determined using a falling head permeameter.

2.3 Compressive strength and Tensile Strength

The compressive strength of the mixtures was determined by a compression tests according to obtained by the determination of the tensile stress at failure of the material according to Australian Standard, AS 1012.10-2000, an indirect tensile test. Three specimens of each mixture were tested at seven (7) days and 28 days after casting. The compressive and tensile tests were conducted in dry conditions. Australian Standard, AS 1012.9-1999. Because of the porous structure of the material the surface of the specimen was capped for this test to obtain an even interface between loading plate and specimen and to prevent stress concentrations when applying the load. The static tensile strength is

2.4 Stiffness

The static modulus of elasticity and the Poisson's ratio were determined in accordance with Australian Standard, AS 1012.17-1997 with the peak load set to 40 % of the average compressive strength determined previously. The tests were repeated in dry conditions for different stress levels in order to detect non-linear material behavior on three specimen of each mixture at 7 and 28 days after casting.

The Resilient Tensile Modulus was determined using repeated indirect tension in accordance with Australian Standard AS1289.6.8.1 . Here the samples were tested in a saturated surface dry condition.

3. TEST RESULTS

3.1 Void ratio

The void ratio was determined for each mixture. The void ratio for mixture A is 37%, for mixture B 36% and mixture C 31%. Mixtures A and B, which use broken aggregates with grain sizes ranging between 9.5mm to 12.7 mm for mixture A and 4.75 mm to 9.5 mm for mixture B, show a higher void ratio than mixture C, which used river gravel with an aggregate size between 4.75 mm and 9.5mm.

3.2 Permeability

Figure 3 shows the permeability of the single mixes and the required permeability according to [Krause 1998].

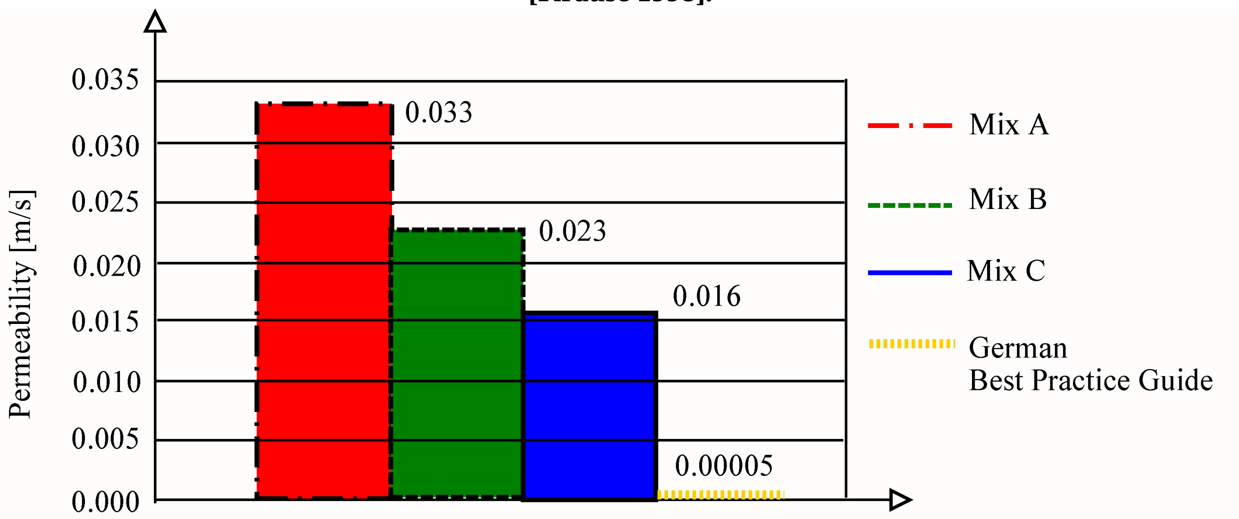

Figure 3. Permeability Results.

The results confirm that permeability increases with increase of the void ratio, which was discussed earlier. Additionally, the impact of gradation on permeability can be seen, as mixture A (coarse aggregate) showed higher permeability than mixture B and C. The permeability of mix B differed from mix C due to the different void content.

3.3 Compressive Strength

As noted earlier the compressive strength of the mixtures was determined at 7 and 28 days. Over that period the compressive strength increased about 9% on average.

The results of the twenty-eighth day compressive strength test can be seen in Figure 4. This figure also shows a comparison with both normal concrete and unbound material. It can be seen that the strength is higher than for unbound granular material, but is much less than the strength of normal concrete.

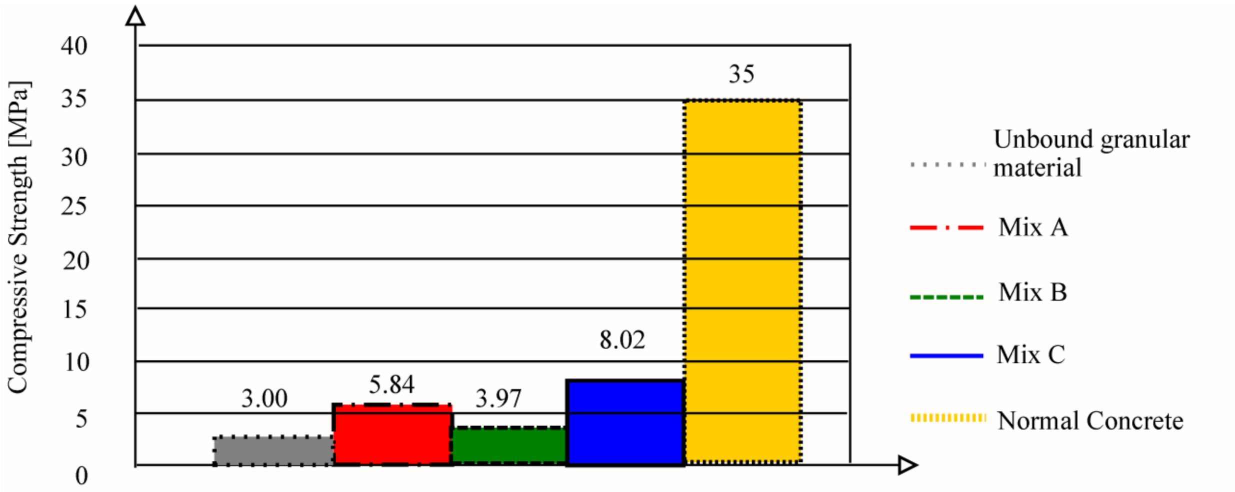

Figure 4. Unconfined Compressive Strength Results.

It was expected that the compressive strength would be smallest for mixture A, which used broken and relatively coarse aggregate, leading to higher void ratio and lower density, and larges for mixture C, which had the lowest void ratio and the most aggregate to aggregate contact points. A visual inspection of the samples after test showed that the cement interface between the aggregates failed and not the aggregates themselves and that the entire surface of the aggregates was covered with cement. Because the cement content was the same for all mixtures the strength of the cement interface binding the aggregates together varies with the interface thickness. The fact that mixture B contradicts the expected relationship between void ratio and strength may be explained by the cement interface thickness. Mixture A had the lowest specific surface area as the aggregates were significantly larger than those of mixture B and C. Mixtures B and C had almost an identical grading. However, mixture B used broken aggregates and mixture C consisted of river gravel with almost spherical aggregates. Hence, mixture B had a significantly higher specific surface area than mixture A and C [Harr, 1977]. A higher surface area leads to a thinner and therefore weaker cement interface between the aggregates. Mixture B had roughly the same number of aggregate to aggregate contact points as mixture A, but weaker bounds between them. Mixture C exhibited the best combination of interface thickness and number of contact points.

3.4 Tensile Strength

Three specimens of each mixture were tested at 7 and 28 days. The growth of strength due to hardening of the concrete was 8.5%. Mixture A showed a tensile strength of 0.8 N/mm^2, mixture B 0.7 N/mm^2 and mixture C 0.9 N/mm^2.

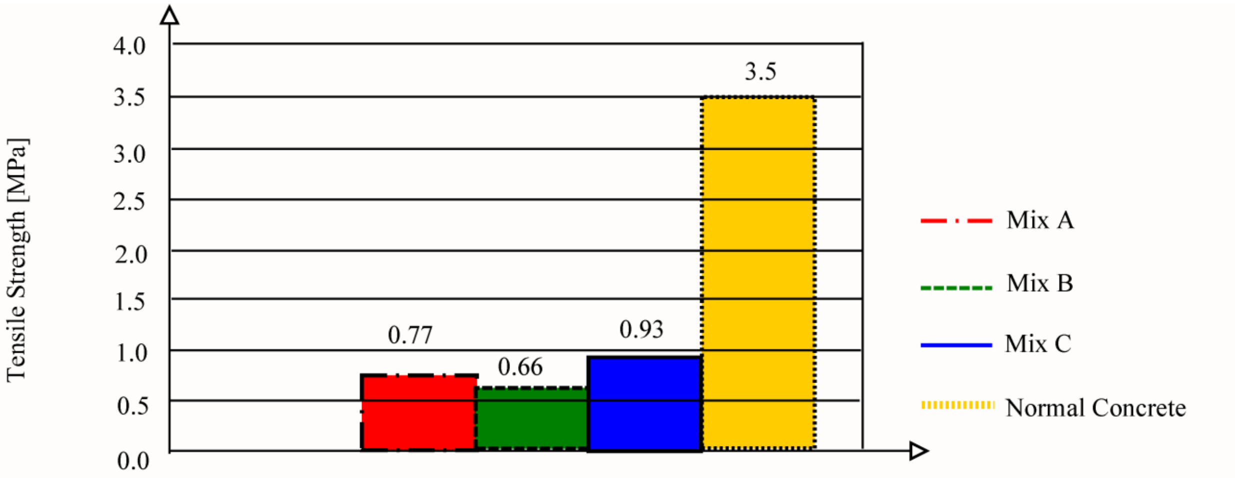

Figure 5. Indirect Tensile Strength Test Results.

The relationship between the results of the mixes is similar to the results of compressive strength as mixture C shows greatest strength and strength of mixture B is the lowest. Hence, the same reasons that were mentioned earlier can be used to explain these values and it can be assumed that grading and size of aggregates influence tensile strength in the same way as compressive strength.

3.5 Stiffness

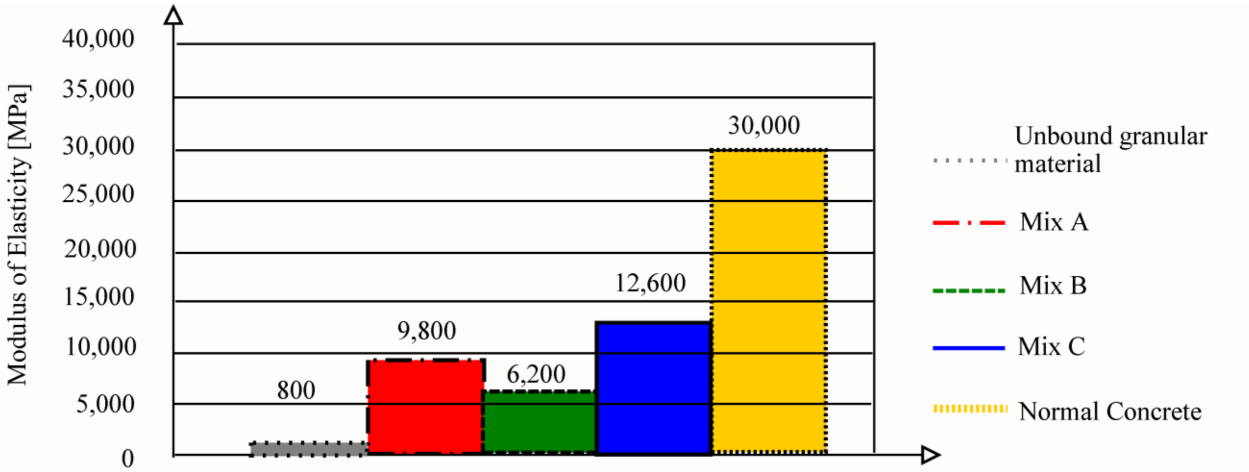

Figure 6. Test Results – Static Modulus of Elasticity.

The modulus of elasticity was determined for each mixture at 7 and 28 days. In Figure 6 the results are compared with typical values for normal concrete and unbound granular materials [Crouch et al, 2007]. The Poisson's ratio ranged between 0.09 and 0.1. The tests were repeated with different stress regimes. No stress dependency of the modulus of elasticity and the Poissons ratio was observed.

In order to determine the tensile modulus the load and deflection were measured 28 days after casting in dry and wet condition using an indirect tensile test. The results of the tests of the three mixtures are displayed in Figure 7. It can easily be seen that the Resilient Modulus decreases in wet condition, because the water has an impact on the stiffness of the binder of the material and an impact on the friction that can be transferred via the grain skeleton.

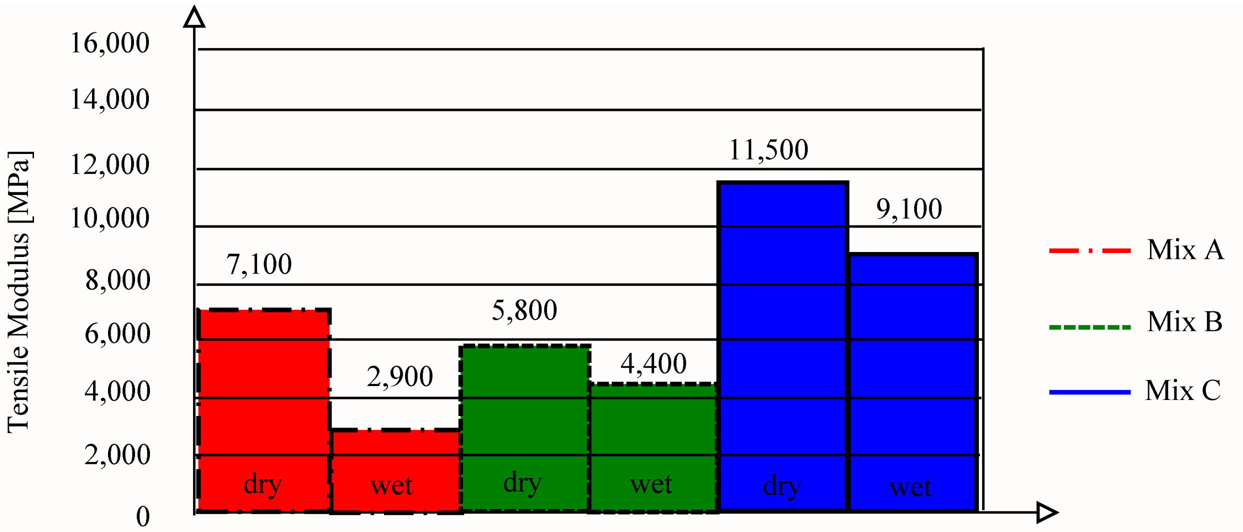

Figure 7. Test Results – Modulus from Repeated Indirect Tension Tests.

The differences between the results of the three mixtures are similar to those already mentioned in the evaluation of the strength and the compressive modulus. The Resilient Tensile Modulus increased as the density increases and the void ration decreased.

4. CONCLUSIONS AND FURTHER RESEARCH

This study aimed to determine the key parameters of a series of pervious cement-bound granular materials which could be used as basecourse for PICP and thereby contribute to sustainable road construction. Although the starting point of the study was a German recommendation for pervious concrete base, the materials generally had mechanical properties intermediate between bound and unbound base in terms of strength and stiffness (modulus). In particular the tensile strengths were extremely low and, in practice, could be disregarded in structural design calculations i.e the materials would not be seen a performing like conventional concrete.

In respect of the hydraulic properties, the trial mixes showed considerable potential. Both the voids ratios and the permeabilities were much higher than would normally be expected for concrete base and, indeed, compared favourably with open graded granular mixes having significantly inferior mechanical properties.

Cement-bound bases of the type described here are likely to be more expensive to produce than permeable granular base. Nevertheless, quarries are often reluctant to produce the non-standard granular materials that are needed for PICPs carrying heavy traffic. By contrast, it is relatively easy to procure lean concretes in most urban areas. In other words, the problem of obtaining permeable granular base may be overcome by selecting cement-bound materials, albeit at greater cost. However, more work is needed to define what this cost differential may be.

Identifying the advantageous properties of pervious cement-bound base will lead to better acceptance and easier construction of permeable pavements. The paper has shown that the tested pervious materials were an adequate substitute for unbound base layers that are currently used in permeable pavements. The permeability and void ratio of the material clearly met the requirements of permeable pavements. The experimental results concerning the strength and stiffness of the material also showed that the material would be able to withstand the loads that basecourses experience due to traffic.

Higher cement contents would not further enhance the hydraulic performance of the material and is probably not warranted in terms of the mechanical properties as these are already adequate for carrying traffic. Moreover, higher cement contents are undesirable in view of ecological requirements, as the production of cement is energy intensive and triggers high carbon dioxide emissions.

Fatigue of the materials is yet to be evaluated and needs further research. To delineate the fatigue characteristics, the authors intend to conduct beam fatigue tests on the different mixtures.

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