THE DEVELOPMENT OF A ROTATIONAL SHEAR DEVICE FOR EVALUATING ERODIBILITY OF STABILISED SUBBASES

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ABSTRACT

Soil properties and climatic effects all contribute to erosion of subbase material, which leads to rigid pavement failure. The erosion takes the form of pumping of material and water, subsequently creating voids. The formation of voids can lead to a rapid decline in the durability and serviceability of the pavement. At present there is not a single laboratory test, which could identify materials resistant to pumping.

Thus there is a need to develop a laboratory test, which could predict erosion of material in a pavement. The aim of this paper is to present the initial results of a Rotational Shear Device (RSD) constructed to simulate erosion of subbase layers under a concrete slab. A review is given of existing tests, which are used to test for erosion. Motivation for the adoption of the RSD is given. Details of the device as well as pilot laboratory tests are also presented.

Pilot laboratory tests were preformed on a G2 material stabilised with 2% and 4% Cem I 42.5 cement. Duplicate samples were tested at the CSIR with the mechanical wet-dry brushing test. As expected, the 4% stabilised samples eroded less than the 2% stabilised samples under the conditions in the RSD and thus was confirmed by results from the mechanical wet-dry brushing tests.

1. INTRODUCTION

Soil properties and climatic effects contribute to erosion of subbase material, which leads to rigid pavement failure.

Erosion under a rigid pavement can be described as pumping. Pumping is defined as:

- The ejection of water and subgrade, subbase or shoulder material through pavement joints, cracks, and edges; or
- The redistribution of material under the slab (Van Wijk *et al*., 1989).

Pumping takes place when the following three conditions occur:

- The presence of water in the pavement.
- High slab deflections, as a result of heavy wheel loads, thin slabs, or both, or a slight curl of the slab, with the individual slab ends raised slightly off the underlying layer, caused by thermal gradients or differential drying within the slab.
- Materials that are susceptible to pumping, for example untreated shoulder subbase material, or the surface of stabilised subbase.

The water retained between the slab and the subbase layer is pumped back and forth at high velocities under the pressure caused by the wheel load passing over the area. Dempsey (1982) found that under a wheel load, water velocity under the slab is 2 m/s at a pressure of 2.1 kPa, and can be as high as 6.4 m/s under a pressure of 20.7 kPa. Water pressures can also be linked to the vehicle speeds. Research has indicated that pressures were higher at speeds of 20 – 40 km/h and lower at 60 km/h (Van Wijk, quoted by Hansen *et al*., 1991). However, further research by Hansen *et al*. (1991), indicated that the water pressure increases with vehicle speed, using a three-axle truck, passing at 40, 72 and 97 km/h.

The maximum shear stress at the top of the upper subbase layer caused by the passing truck was calculated as 14 Pa (Hansen *et al.,* 1991). When the shear strength of a material is smaller than the shear stresses applied, the material will start to erode. The critical shear stresses at which a material will start to erode vary, according to Van Wijk and Lovell (1986), because of the influences of Cem I 42.5 content and curing time. The critical shear stress at which material will erode, the pressure build-up and water velocity all play a role in how much pumping of material will take place and thus how much material will collect under the leave slab. Larger material remains under the leave slab and is redistributed by pumping. Fine, loose material is transported out, with water, through the cracks or by drains (Hansen *et al.,* 1991).

Thus a need to develop a laboratory test, which could predict erosion of material under a rigid pavement, was evident. The aim of this paper is to present the initial results of a Rotational Shear Device (RSD) constructed to simulate erosion of subbase layers under a concrete slab. A review is given of existing tests, which are used to test for erosion. Motivation for the adoption of the RSD is given. Details of the device as well as pilot laboratory tests are also presented.

2. REVIEW OF EXISTING EROSION TESTS

The most commonly used erosion test on subbase samples is the Wet-Dry Brush Test (Method A19) in the TMH1:1994. Samples are compacted using the Standard Proctor effort and cured for seven days at a relative humidity of 95 to 100 %, at a temperature of 22 to 25°C in a curing room. Specimens are then soaked in water at room temperature for five hours. Thereafter the specimens are removed from the water and placed in an oven at 71°C for 42 hours. The specimens are then brushed manually with a wire scratch brush with a force of approximately 13.5 N. This is the first of 12 cycles. Although the test is simple and inexpensive to be performed, it is difficult to ensure that the applied force remains constant. Although the method is flawed, it is considered as the best test method currently available.

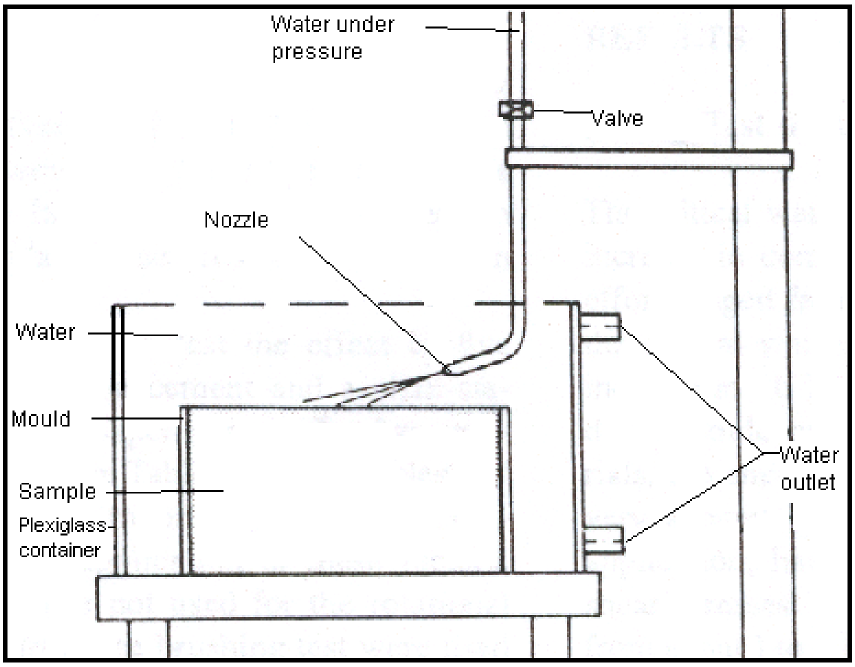

Figure 1. The jetting device (Van Wijk *et al.,* 1985).

Other tests methods have been explored. One of these is the jetting test, as described by Van Wijk *et al*. (1986) and illustrated by Figure 1. It consists of a jet placed at an angle of about 20 degrees with the sample. A pressure vessel provides water pressures of up to 345 kPa. The sample is placed in a Plexiglas container with water outlets at two different levels. Erosion of the samples can be measured in the submerged or unsubmerged conditions by changing the water outlet level in the sample container. Samples can also be tested in or out of the moulds. Eight different spray nozzles with different orifices and spray angles can be used. Shear stresses on the sample surface are approximated. A uniform distribution of shear forces is assumed over the contact area. The shear stress is calculated by dividing the shear forces by the contact area (Van Wijk *et al*., 1986).

Another erosion test device, a Rotational Shear Device (RSD), which has only been used experimentally, also exists. The RSD consists of a sample, which is placed inside a Perspex cylinder. The sample is surrounded by water in the annular space. The cylinder encapsulated by top and bottom discs, is then rotated. A motor of 560 W generated rotational speeds of between 300 and 3000 rpm. The top cap of the sample was connected to a shaft that transferred the rotation due to shear stress on the sample to a lever arm that pressed against a torque-measuring device. The amount of eroded material is weighed after completion of the test (Van Wijk, 1985). This set-up, as it was used by Van Wijk (1985), can be seen in Figure 2.

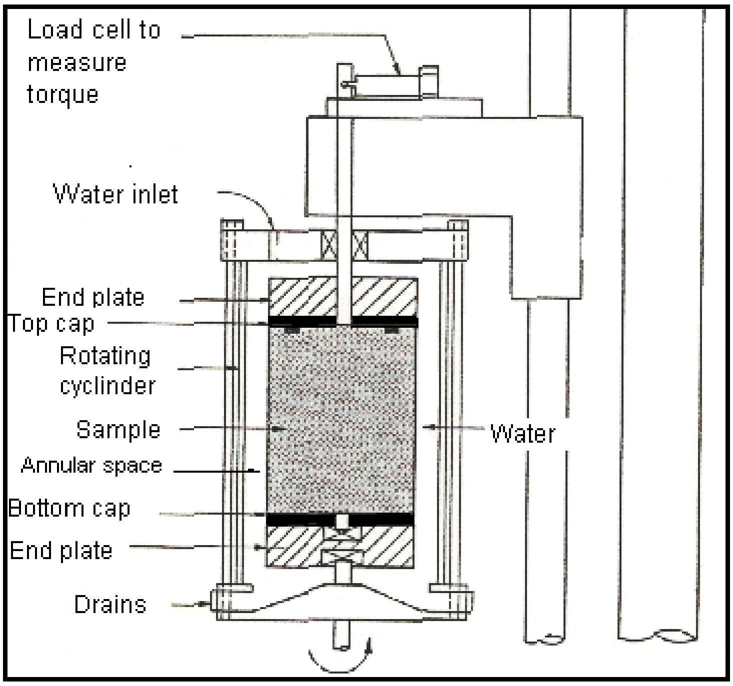

Figure 2. The rotational shear device (RSD), as used by Van Wijk (1985).

With the RSD, uniform shear forces on the lateral surface of the samples are developed. These forces can be adjusted in magnitude, meaning that the shear stress that causes erosion when the stress is greater than the shear strength of the material, can be determined. Clays and stabilised materials can be tested, but the test is not suited for non-cohesive materials like sand.

It was decided to investigate the RSD further, due to the fact that it simulates the mechanisms of erosion under a rigid pavement and not just a contact area as compared to other erosion tests. This test was also strongly recommended by Van Wijk (1985) as simulating field conditions the best.

3. ROTATIONAL SHEAR DEVICE

3.1 Background and Design Principles of the RSD

Moore, Masch and Espey at the University of Texas developed a RSD in the 1960s (Van Wijk, 1985). The device was used in experimental work done by them. Their aim was to apply a constant shear stress to the sample, unlike the variable shear stress on an area of contact on the sample, as was developed in other test methods like the jetting device. Thereafter other researchers modified the device for their specific projects. The device was used in three main research projects namely, the University of Texas at Austin study, the University of California at Davis study and the Mon-terval study, which are all described by Van Wijk (1985).

The design principles of the device are the following:

- The RSD is based on hydraulic principles. The device consists of a transparent cylinder that rotates around a soil sample that is kept stationary. The space between the cylinder and the sample is filled with water. Shear forces will be developed between the water and the sample.
- Laminar flow is assumed (Van Wijk, 1985), which means that the water has the same velocity as the rotating cylinder on the outside, but that the velocity is zero at the surface of the sample.
- At a critical value the condition changes from laminar to turbulent, when the velocity at the sample surface increases. With increasing speed, shear stresses are developed at the surface of the soil sample. When the shear forces that are developed exceed the shear strength of the material, erosion takes place.
- These design principles of the device correlate with the mechanism of erosion under a rigid pavement.

3.2 Construction of the RSD

Based on the literature review and for practical reasons, it was decided that the RSD would have approximately the same dimensions as used by Van Wijk (1985). The device had to be constructed as the original devices were all built in the United States of America and is not commercially available in South Africa.

A large rectangular frame was used. The electric motor with a capacity of 1400W was mounted on the side of the frame. A 25 mm shaft, connected to the rotating Perspex cylinder, was connected through a pulley and belt system to the motor. A hand-held digital tachometer was used to determine the rotational speed of the rotating cylinder. Two flanges kept the shaft in position.

The rotating cylinder is sealed by means of a bottom and top disc. The top disc rests on spacer bolts. The bottom disc was connected to the bottom cap, on which the sample rests, through a small shaft, which fits into a 10 mm inner diameter bearing. A top cap is placed on top of the sample and the top cap has a screwed-in shaft, passing through two sealed bearings through the top disc. The Perspex cylinder is sealed at both ends with o-rings, which fit into grooves in the bottom and top discs. There are two inlets for water in the top disc and two outlets in the bottom disc. The bottom disc was cone shaped with an angle of 30° within the diameter enclosed by the Perspex cylinder.

Connected to the shaft protruding through the top disc, which is also connected to the top cap, is a lever arm. The lever arm is made of spring steel and presses against a steel rod stopper welded to the frame. Strain gauges were attached on the lever arm and the strain was measured at a distance of 342.5 mm from were the arm is connected to the axis.

The final set-up of the RSD can be seen in Figure 3, as well as the location of the main components.

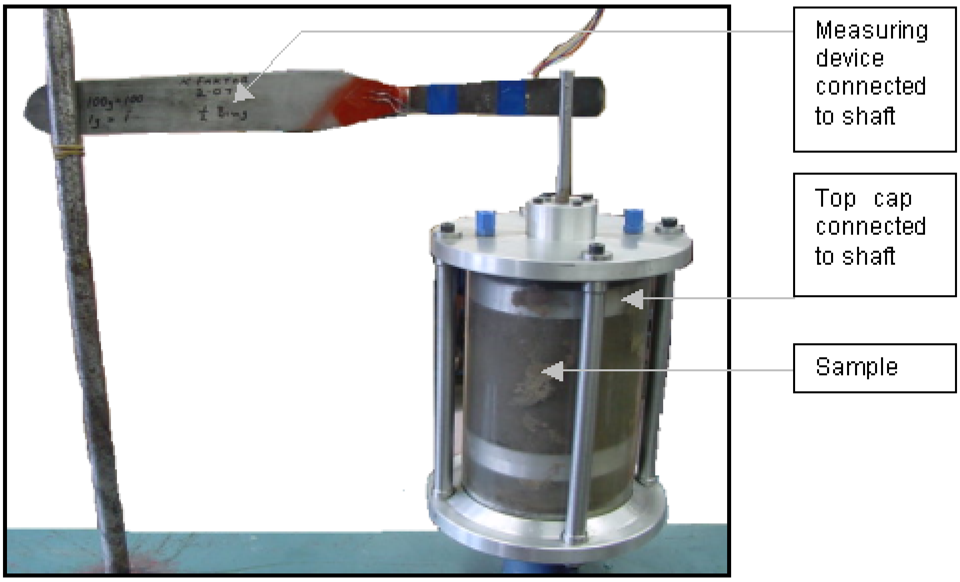

Figure 3. Final set-up of the RSD.

4. EXPERIMENTAL PROGRAMME

4.1 Preparation and Set-up of the Specimens and RSD

After construction of the RSD, it was important to determine if the equipment worked as expected, and whether reasonable results are obtained. Laboratory samples 102 mm in diameter and 117 mm high were prepared with a single quartzitic gravel. The only variable was the cement content. The samples were stabilised with Portland cement (Cem I 42.5), at cement content of 2 % and 4 %, to ensure that any changes in material characteristics could be clearly seen, as it is known that the samples with the higher cement content will be stronger and more erosion resistant. Samples were tested in the RSD and also with the wet-dry brushing test.

Eight samples of G2 material were stabilised with 2% and 4% Cem I 42.5. They were prepared according to Method A19 (Wet-Dry Brush Test) in TMH1:1994. They were then cured in a moisture room at 21°C. Two samples of each Cem I 42.5 content were tested at 28 days and at 4 months. The samples were soaked in a water bath for 12 hours at approximately 20°C prior to testing. The samples were weighed before and after soaking.

The samples were then placed in the RSD without any water in the device. Strain readings were taken at different rotational speeds, namely at 500, 700, 1000, 1200, 1500 and 1700 rpm. This was done to determine the internal friction of the device, with the sample in position, as a function of speed. The internal friction values were used in calculations.

4.2 Test Procedure

The RSD was then filled with water and rotated at the various rotational speeds. Strain readings were taken at these revolutions to determine the influence of the water on the internal friction of the device. The difference between these readings and the internal friction values determined when rotated without water, was used in the calculations of force, torque and shear stress.

The sample was then rotated at 1000 rpm for 10 minutes, taking strain readings every 2½ minutes. The same was done at 1250, 1500 and 1700 rpm. The device was not stopped with an increase in revolutions, but continued rotating as the speed of rotation was increased. The rotational speed was then decreased in the same manner, taking strain readings every 2½ minutes.

Although previous researchers had rotated the RSD at speeds between 300 and 3000 rpm, 1700 rpm was used as a maximum in this case. This maximum rotation was used due to safety concerns, as the device was not perfectly balanced and not enclosed.

After the rotational cycle was completed, the device was drained. The drained water and eroded material was then oven dried at 105 to 110°C. The dried eroded material was weighed.

4.3 Comparison Test

Duplicate samples were taken to the CSIR for mechanical wet-dry brush testing. The test method is in principle the same as described in Method A19 (Wet-Dry Brush Test) in TMH1:1994, except that the brush process is done mechanically. The force applied to the sample remains constant by using a brush load of 2.25 kg. The sample is rotated for 50 revolutions. The test results are expressed as percentage mass loss and will be compared with the results from the RSD.

4.4 Preliminary Observations

Visual observations could be made while testing the 2% stabilised material. Discolouration of the water in the device could be clearly seen with each increase in rotational speed indicating increased erosion. Loose particles could be heard striking the Perspex. Rotation of the sample in the cylinder could, however, be observed and was found to be a problem.

While testing the 2% stabilised material, the digital strain meter readings stayed in close proximity of the same value, but increased when the rotational speed was increased. The readings did not indicate when the sample rotated, although it could be visually observed.

Visual observation of tests on the 4% stabilised material were not so clear as with tests on the 2% stabilised material. Discolouration of the water in the device was visible, but not to the same extent as with the 2% stabilised material. No definite discolouration occurred with increase in rotational speed as with the 2% stabilised material.

While testing the 4% stabilised material, the reading on the digital strain meter varied considerably, in such a way that it was difficult to obtain an average value. The readings did not indicate clearly when the sample rotated, although it could be observed to rotate.

5. RESULTS FROM THE ROTATIONAL SHEAR DEVICE

5.1 Percentage Mass Loss

The wet-dry brushing test was performed on duplicate samples to indicate whether the loss of mass, which resulted from tests with the RSD were reasonable.

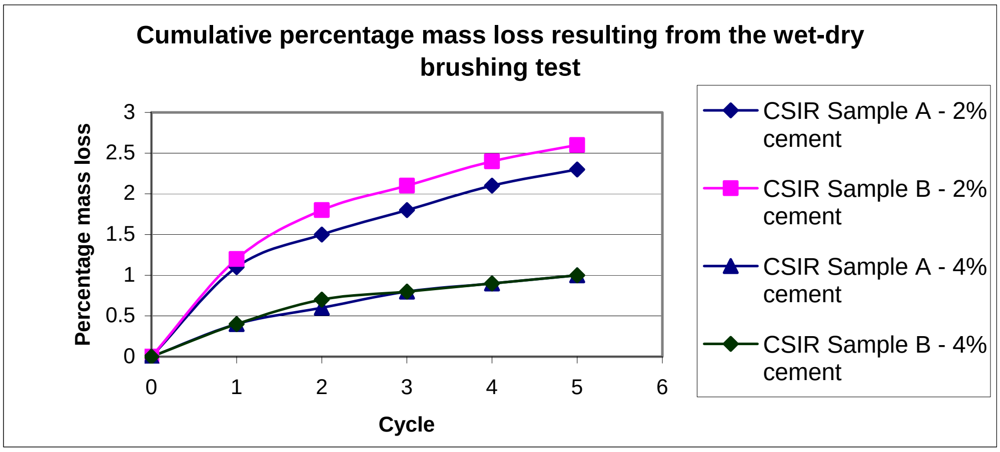

Figure 4. Cumulative percentage mass loss resulting from the wet-dry brushing test.

Figure 4 illustrates the cumulative percentage of mass loss from the wet-dry brushing test. Table 1 summarises the percentage mass loss resulting from tests with the RSD after testing for 10 minutes at four rotational speeds, in increasing and decreasing speed order, in other words a total of 70 minutes.

Table 1. Percentage mass loss resulting from tests with the RSD.

	2 % Cemented material		4 % Cemented material	
	Sample 1	Sample 2	Sample 1	Sample 2
% Mass loss (28 days)	4.8	2.2	1.3	1.1
% Mass loss (4 months)	2.5	2.2	0.6	1.0

From the results of the Wet-Dry Brushing tests it can be seen that the 2% stabilised samples' cumulative percentage mass loss is greater than the 4% stabilised samples, as was expected. The percentage mass loss calculated from results from the RSD is in the same range as the percentage mass loss calculated from the wet-dry brushing test after 5 cycles, namely 2.5% for the 2% and 1% for the 4% stabilised samples. Sample 1 of the 2% cemented material tested at 28 days was damaged during demoulding and tested in the RSD in that condition this accentuated the erosion and explains the considerable percentage mass loss recorded. The sample is rotated at various rotational speeds for 70 minutes continuously in the presence of water, while the sample is dry when brushed during the wet-dry brush test. Mass loss is also measured at different stages during testing in the respective test methods.

5.2 Calculations

Strain gauges were attached to the lever arm, which pressed against the vertical rod. The strain gauges were calibrated so that 1-gram load = 1, is shown as output reading and from this the force with which the lever arm pressed against the vertical rod stopper could be calculated. The following equation was used to calculate the force:

$$F = m.\,a \qquad (1)$$

With F = force (N)
m = mass (g)
a = gravitational acceleration (10 m/s^2)

The torque each sample exerted on the lever arm was calculated by the following equation:

$$T = F.\,s \qquad (2)$$

With T = torque (Nm)
F = force (N)
s = length of lever arm (m)

The length of the lever arm was taken from where it was attached to the shaft to where it pressed against the vertical rod. This distance was measured as 0.342 m.

The shear stress (τ) on the sample was calculated by using equation 3.

$$T = 2\,\pi r^2\,l\,\tau \qquad (3)$$

With: T = Difference in torque calculated with and without water in the device
r = inner cylinder radius of 0.128 m
l = the length of the sample 0.117 m

Force, torque and shear stress were calculated using equations 1 to 3 for the increase of revolutions, as well as for the decrease of revolutions, of the RSD. An illustration of the shear stress calculated with increase, as well as decrease in rotational speed, can be seen in Figures 5 and 6. The measurement of 28 days were superimposed, hence only one curve. Slight variations were found on the samples tested at 4 months. These results show that the order of testing does not affect the applied shear stress.

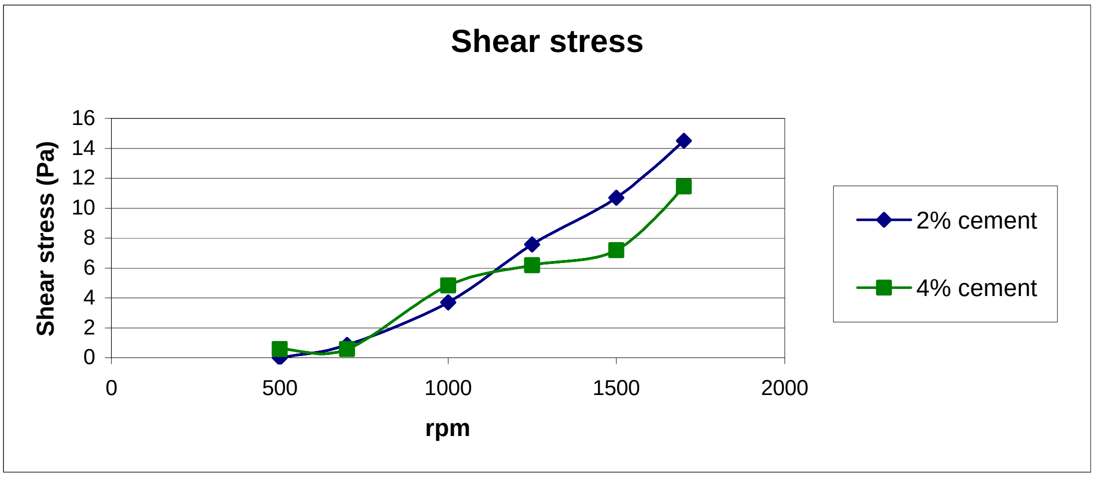

Figure 5. Shear stress (28 days).

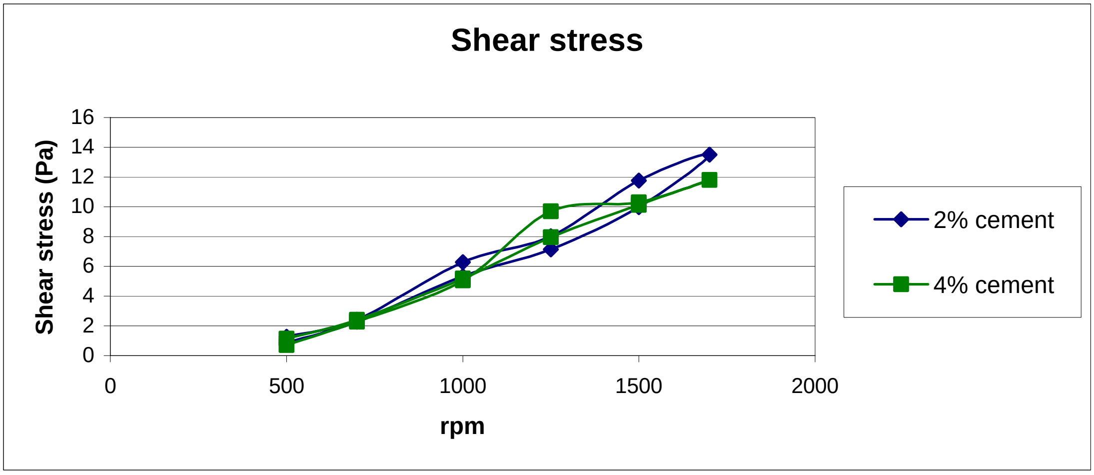

Figure 6. Shear stress (4 months).

In both sets of samples, tested at 28 days and 4 months, the shear stress values are in the same range. The shear stress on the various samples is small in comparison to other stresses encountered in engineering. In the literature review, stresses between 2.3 Pa and 35 Pa were calculated during previous studies. It is, however, doubtful if this was the true shear stress on the sample, and not just a reflection of the stress on some component of the device. The shear stress increases as the rotational speed increases. Figures 5 and 6 illustrate this. It can be concluded that force, torque and shear stress is a function of the rotational speed and not of the roughness of the sample caused by erosion of material. This aspect needs further investigation, as it would be expected that the erosion would affect the shear stress, if the rotation were sufficiently high.

6. CONCLUSIONS

As expected, the 4% stabilised samples eroded less than the 2% stabilised samples under the conditions in the RSD. This indicated that assumptions made as to the simulated conditions in the device, that of water eroding stabilised material, were reasonable.

Results from wet-dry brushing tests performed on duplicate samples of those tested in the RSD, confirmed that, the 2% stabilised samples eroded more than the 4% samples. The resulting cumulative percentage mass loss from the wet-dry brushing test after five cycles, and the percentage eroded material from the RSD after a complete test cycle, were in the same range.

The calculated force, torque and shear stress from the measured values are quite small in comparison to what engineers are used to. The small values can be explained when one considers that it should reflect what is happening to the sample. The sample stays still while the water in the annular space is rotating around it and eroding the sample. The erosion of material causes surface roughness of the sample to increase, which results in the sample rotating. This aspect of the design has to be revisited. It can be concluded that with the amount of material eroded the shear stress can be expected to be small. From a review of the literature on the background of the device, previous researchers calculated shear stresses of 2.3 to 35 Pa, as well as Hansen *et al* (1991) who calculated the maximum shear stress at the top of the upper subbase layer caused by the passing truck as 14 Pa. Thus the calculated values of the experiments seem plausible.

It is recommended that this pilot study be extended, and that the RSD be calibrated against field samples taken from roads which are known to have both good and poor erosion resistance of the subbase.

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Elsabé Ras completed a B.Eng. (Civil) degree at the University of Pretoria in 2003, during which she conducted a final year research project, titled "The development of a Rotational Shear Device for evaluating erodibility of stabilised subbases", which is the topic of this paper. Currently she is enrolled as a full-time honours student in the field of Transportation Engineering at the University of Pretoria.

She gained some experience in the field of engineering during holidays. The most recent include: Admin. Officer (November 2002 – January 2003) at The City of Tshwane Metropolitan Municipality in the departments City Planning and Mapping, as well as Roads and Stormwater: Project Managing. She was also employed by Africon: Contract Management and Materials Division as Assistant Lab Manager at KMIA (Kruger Mpumalanga International Airport) site from November 2001 – January 2002.