

FATIGUE AND STABILITY CHARACTERISTICS OF OPEN POROUS CEMENT BASE MATERIAL

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ABSTRACT

As large cities experience rapid growth, greater pressure is placed on existing infrastructure, in particular the construction and maintenance of roads and highways. 'Permeable pavements' are an economical and sustainable alternative to mitigate problems associated with current road structures. They allow water to percolate through the road structure reducing the impact of rainfall events, filtering of the stormwater, and provide a method of harvesting water whilst withstanding low to medium traffic volumes. Permeable pavements have become well established in the past thirty years in many countries around the world. However, its development and application has been limited in Australia as no national guideline from Austroads exists. The objective of the research summarised in this paper is to determine the structural and hydraulic performance of open porous cement stabilised materials. It is concerned with understanding the fatigue properties of cement stabilised permeable materials under real traffic conditions. In an attempt to fully understand the properties of the material, laboratory testing has been carried out to determine structural and hydraulic properties. These included the tensile and compressive strength, permeability, grading, effective void ratio, flexural stiffness and Young's modulus. These tests were carried out on a group of samples with different aggregate sizes and shape to understand the relationship between the strength of the permeable material and the hydraulic parameters. Based on the results achieved, in obtaining optimum structural outcomes a balance needs to be established between structural and hydraulic properties. Further, based on fatigue characteristic of the samples, it was concluded that permeable stabilised material can withstand five million fatigue cycles without excessive cracking and deformation to the pavement structure. Hence, for low to medium traffic conditions, permeable pavements are a practical alternative to current impermeable design.

1 INTRODUCTION

The principle of 'permeable pavements' is to allow water to flow through the system resulting in flood mitigation, water quality improvement by filtration within the cavities, storage of water within the structure while having the ability to withstand everyday traffic conditions. The growing trend towards Low Impact Development (LID), with distinct goals to increase infiltration, protect water quality and reduce costs for stormwater management, has resulted in a rapid increase in the use of permeable pavements with the greatest potential being porous asphalt or pervious concrete pavement.

With the introduction of porous material, the runoff created by the impervious area can be absorbed thus improving water quality. By allowing water to percolate through the pavement structure, it allows the contaminants and sediments to be filtered and also for the naturally occurring bacteria to form and breakdown these contaminants. Up to 90% of the contaminants are trapped within these pavements (Shackel, 2008).

Porous concrete pavements are limited to certain applications and environments. Restricted use of porous concrete pavements includes cold regions, arid regions or regions with high wind erosion (Pratt 1997). The impact of water freezing from surface infiltration, which occurs through cracks and joints within impermeable pavements causes the voids to expand and induces frost heaving and thawing. This problem is not apparent for permeable pavements since the voids are designed to be larger, consequently leading to a greater capacity to withstand water freezing without any frost induced deformation. Another consideration, which is susceptible to all pavements, is frost heave and thawing, which is induced from subsurface water supplies. Groundwater moisture drawn from capillaries from the surrounding natural soils and aquifers can all contribute to the deformation of the pavement. As the water freezes in large void space within the pavement structure, it produces a negative charge that attracts freshwater and causes them to freeze on contact resulting in larger ice crystals forming. These crystals continue to grow and join, fed mostly by capillary water forming ice lenses. As a result, the vertical and horizontal pressures exerted by the ice lens cause the surface to heave. One of the major concerns during construction and throughout its life is the level of erosion by the nearby environment and the risks it imposes on the porous pavement. In particular, regions near the coast lines which are susceptible to high winds and loose sands and soil can potentially infiltrate the porous layer and affect the permeability as fines are being introduced to the cement.

Porous concrete pavements are predominately used as a base layer. However, they can be adopted for use as a top layer, but due to the large voids and the sizing of the aggregate, durability can be a major issue. Ideally, a thin porous asphalt layer can be placed above to solve this problem.

2 SPECIMEN

To design a successful permeable pavement (open porous cement stabilised materials), the structural and hydraulic requirements must be satisfied. The structural requirements relate to the strength capacities, including adequate compressive strength and flexural strength (fatigue). Hydraulic requirements are determined by factors such as flood mitigation, water quality and water reuse, including the rate of seepage throughout the structure which is important as it determines the volume of water stored and the quality of water leaving the pavement.

To test these requirements, open porous cement stabilised cylinders and beams were developed and cured in accordance to AS1012.8.1. The cylinders were used to determine permeable pavement void ratio, permeability, tensile strength (indirect) and compressive strength. The beams were created to conduct the four point bending test (fatigue). The dimensions of each beam were based on the beam specifications described in the IPC Global beam fatigue apparatus manual (50x63x400 mm).

The mix designs were based on readily available material throughout Australia with different aggregate size and shapes. To obtain the desired hydraulic and mechanical properties, the grain size distribution needs to be gap graded, with the majority of the grains being uniform in size and shape. This was achieved by combining metric and imperial sieve sizes with diameters ranging from 4.75 mm to 9.75 mm. Grain sizes above 9.75 mm were not considered as the particles were too large and bonds created by the cement between the aggregate particles become too weak.

Table 1: Mix design

Sieve Sizes (mm)	4.75-5.613	5.613-6.75	6.75-8.00
River Gravel	Mixture 1	Mixture 2	Mixture 3
Basalt	Mixture 4	Mixture 5	Mixture 6

The scope of this research includes the investigation of two different materials; river gravel and basalt, with the size of the aggregates ranging from 4.75 mm-5.613 mm, 5.613 mm-6.75 mm and 6.75 mm-8.00 mm. In total six mixes was investigated: three for river gravel and three for basalt. River gravel consists of rounded particles while basalt consists of angular particles, and it was expected that each one would exhibit differing fatigue characteristics. All fines were sieved out in order to obtain a uniform grading.

The table below summarises the corresponding physical properties and portioning of all the mixtures for river gravel and basalt.

Table 2: Results of open porous cement stabilised material (M.Oeser, 2009)

	River Gravel	Basalt
Mineral density (t/m ³)	2.66	3.00
Particle shape	Round	Angular
Aggregate content (kg/m ³)	1300	
Cement content (kg/m ³)	300	
Aggregate: cement ratio	4.34	
Water: cement ratio	0.28	
Super-plasticisers	none	

3 HYDRAULIC REQUIREMENTS

3.1 VOID RATIO

The void ratio influences the permeability, strength and the stiffness of the material. In terms of the hydraulic design process, the void ratio determines the storage capacity of the pavement layer. However, the void ratio for cement stabilised material does not fully describe its storage capacity as some of the void is inaccessible. To account for these inaccessible voids, the effective void ratio (e_{eff}) needs to be calculated as follows,

$$V_{eff} = V_T - V_w$$

Where:

V_T is the total volume of water and the volume of grains (without cement)

V_w is the volume of the displaced water

Hence, the hydraulically effective void ratio is calculated as,

$$e_{eff} = \frac{V_{vesff}}{V_T}$$

In general, with the introduction of cement within the mixtures the specimens exhibited greater strength but a reduced water storage capacity. Within the bound specimens there are regions mainly in the centre where voids are completely inaccessible for water to penetrate through. Known as the ‘ineffective voids’, it needs to be taken into consideration in determining the true void ratio for a bound specimen. The figure below summarises the effective void ratio of all the mixtures for river gravel and basalt.

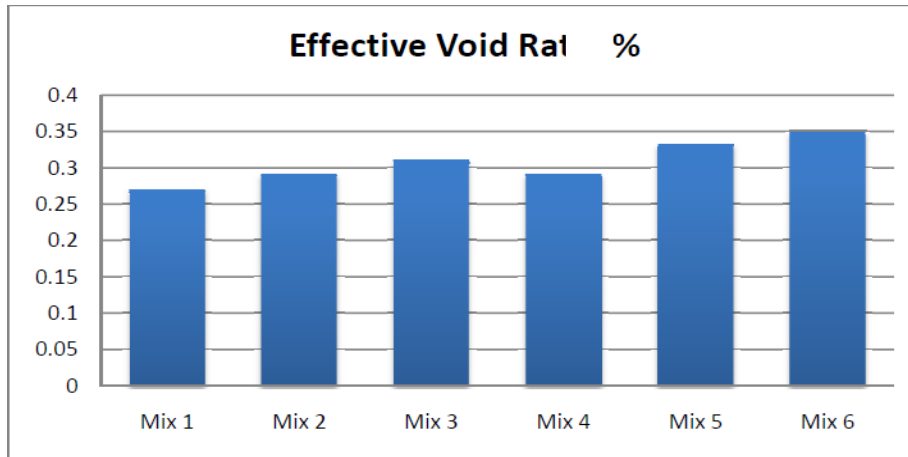


Figure 1: Effective void ratio for Mixtures 1–6

The results suggest that the basalt mixtures had the greatest overall effective void ratio. Comparing the same grain size mixture between river gravel and basalt suggests that the difference in effective void ratio between the two increases as the sizes of the grain increases. This suggests the shape of the individual grain sizes are greatly affected by the storage capacity of the specimens.

3.2 PERMEABILITY

The rate of water flowing through the permeable pavement structure, referred to as the permeability, is of great significance. The permeability, *k*, of each mixture is determined using the falling head permeameter, where,

$$k = 2.303 \log \left(\frac{h_1}{h_2} \right) \left(\frac{t_1 - t_2}{L} \right)$$

In the above equation, *t*₁ refers to the point in time where the water level is at *h*₁ and *t*₂ represents the point in time with the water level is at *h*₂.

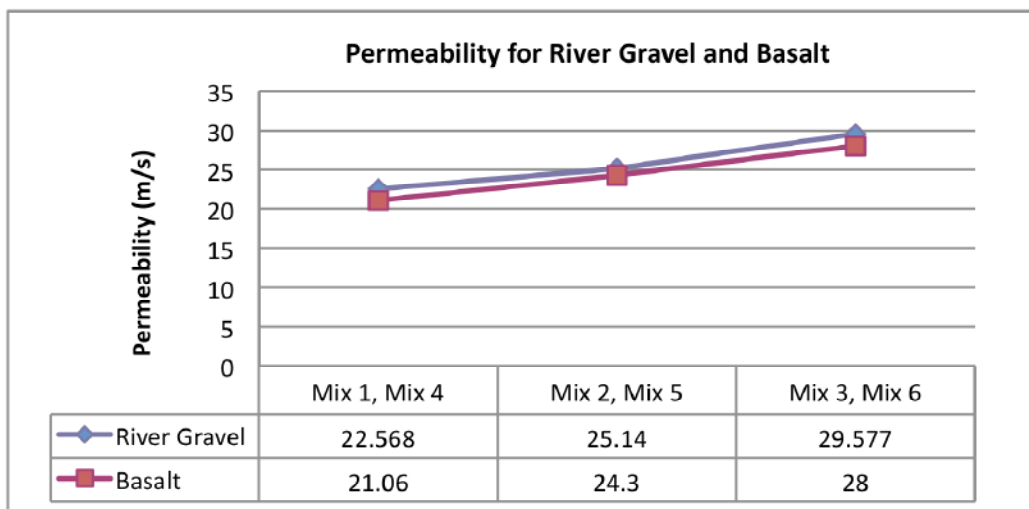


Figure 2: Permeability of river gravel and basalt

It is also expected that the entire sample will not be fully saturated and that there will be regions with pockets of air. The presence of air within these voids will create a suction force that will repel the flow of water. The smaller grain size particles will have a greater suction force as the volume diameter of an individual void is smaller.

Figure 2 summarises the permeability of bound river gravel and basalt. In this case, the coarsest grain sizes (Mixture 3 and Mixture 6) were the most permeable out of all the mixtures. The results confirm that permeability increases with an increase of the void ratio as mentioned earlier. The effect of ineffective voids has also impacted on the permeability of the mixtures. From the results obtained earlier, the greatest percentage of ineffective voids is in the mixtures containing the smallest grain sizes.

4 STRUCTURAL REQUIREMENTS

4.1 TENSILE STRENGTH (INDIRECT)

The procedure and the preparation of the porous cement specimens for tensile testing were based on AS1012.10-2000. The objective of the tensile strength test was to measure how much stress can be applied to the specimen before it cracks. In order to produce accurate results and avoid problems with clamping of the specimen, an indirect tensile test (Brazilian test) was used.

The specimens were tested (Class A 80kN) on the 28th day after casting and the results were compared to ordinary Portland cement. In total, three specimens from each mixture were tested and the average value was taken with the testing performed in dry conditions.

The figure below summarises the tensile indirect strength of the specimens containing river gravel and basalt.

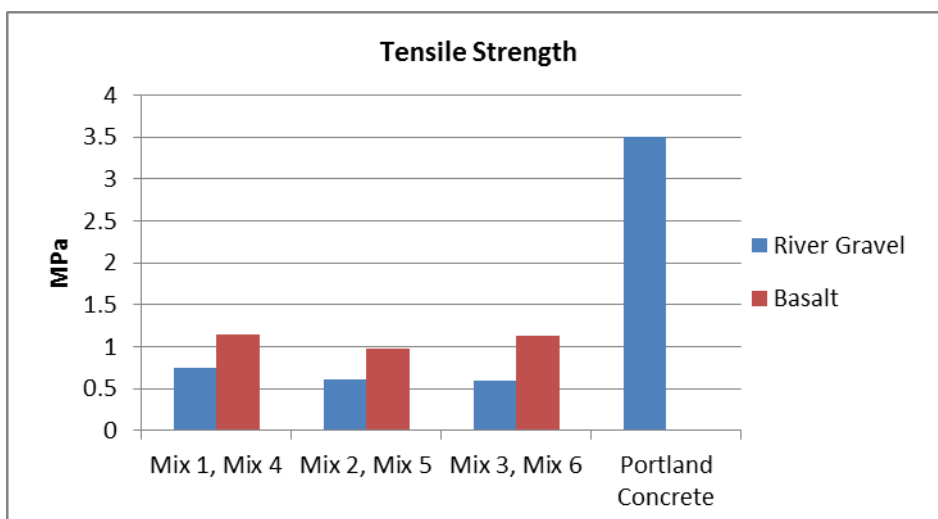


Figure 3: Test results for tensile strength (indirect) of river gravel and basalt

The most noticeable finding was the tensile values for the mixes, where the basalt was observed to be significantly higher than those for the river gravel. This may be due to the configuration of particles within the river gravel and basalt specimens. The fact that river gravel grains consist of rounded particles and basalt grains are of an angular nature affects the transfer of stress through the specimen. As the basalt specimens are being compressed, the angular grains interlock within one another and are more likely to withstand greater loads.

As the particles increased in size, such as Mixture 2 to Mixture 3, the surface area of the mixture decreased and less cement was required to cover the grain. Even though the same cement content is used for all the mixtures, the size of the individual grain particles did not greatly affect the overall strength of the specimen.

4.2 COMPRESSIVE STRENGTH

The procedure and the preparation of the porous cement specimens for compression testing were based on AS1012.9-1999. The objective of the compressive strength test is to measure how much stress can be applied to the specimen before it crushes. This stress can be obtained by placing the specimen upright between two loading plates and applying a uniformly distributed load from each end. The loading gradually increases (Class A 80kN) at a constant rate of 20 MPa per minute until no increase in force can be sustained, and it begins to crush. The maximum force before crushing is recorded and then used to calculate the compressive strength of the specimen. Sulphur capping is also required due to the rough and irregular nature of the specimens. The sulphur cap prevents the concentration of loading on certain areas

of the specimen but rather it spreads out the load evenly. The compressive strength results of the mixes were compared to ordinary Portland cement, which has a compressive strength of 35 MPa.

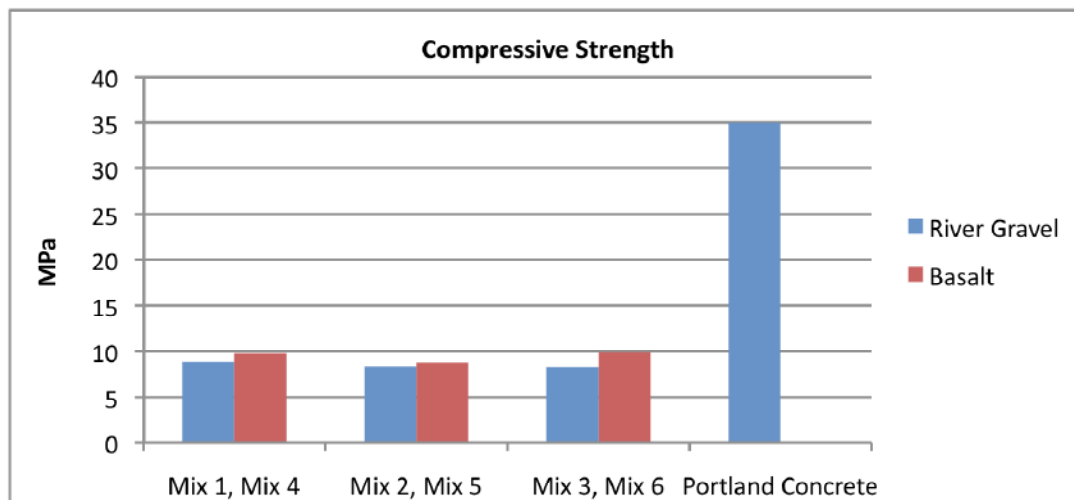


Figure 4: Test results for uniform compressive strength of River Gravel and Basalt

From the indirect tensile test results it was expected that the compressive strength observed would be the greatest for Mixture 1 and Mixture 4, which contains the smallest grain particles and hence the smallest volume of individual voids. From the test, the results suggest the compressive strength was the highest in Mixture 1 for river gravel and Mixture 4 for basalt but overall all the mixtures had a similar compressive strength range. Despite using the same cement content and aggregate shape between the mixtures, the influence of the interface thickness by the cement-binding agent had little impact on the overall results. From observations, the interface thickness decreased as the size of the grain particles decreased due to an increasing surface area. However, with all the mix sizes ranging between 4.75 mm to 8.00 mm, the impact of interface thickness is negligible.

A factor that may have caused discrepancy among the mixes is the aggregate-to-aggregate contact point. Aggregate-to-aggregate contact point refers to how many adjoining grains are attached to one another. As more grains are attached together, it allows an even distribution of force between grain particles and reduces the stress placed on the cement binder.

It was predicted that the basalt mixtures would have a far greater compressive strength than the river gravel due to the density and shape of the basalt grain. However, the results suggest that even though the same compactive effort was applied to all the mixtures, the angular basalt grains did not compact so well, consequently leading to a similar compressive strength as river gravel.

From observing the samples after they had undergone experimental testing, it could be seen that the cement interface between the aggregates failed but that there were also evidence of the aggregate particles splitting for both river gravel and basalt. A high aggregate-to-aggregate contact point, in particular among the smaller grain sizes, caused a gradually increasing load from the uniform compression machine to be directly transferred to the grain particles until they began to crush.

4.3 FATIGUE STRENGTH

It is understood that the amount of strain experienced by the porous material is relative to the thickness of the material. Therefore, the determination of these strains is crucial for calculating an appropriate thickness.

By establishing the traffic and materials properties to be constant and only varying the thickness of the permeable layer, it was possible to determine the bending strain through a finite element program (APADS) at various locations. The areas of interest included locations of high compressive stress, concentrations on the top of the subgrade and the high tensile stresses on the bottom of the asphalt layer, but also the stresses caused by bending as the traffic moves over the surface. By designing the pavement to withstand these stresses, it will prevent fatigue cracking from developing on the surface of the pavement and prevent rutting along the wheel paths due to inadequate compressive tolerance at the top of the subgrade.

The design of the pavement structure was based on typical application of permeable pavements for low traffic volumes conditions with readily available materials. The top asphalt layer is thin enough to act as a seal layer and does not contribute to the bearing capacity.

The porous concrete base thickness was increased in increments of 100 mm, beginning from 100 mm to a final thickness of 500 mm. These thicknesses were based on ideal storage capacities for permeable pavements, but also on design and economic constraints.

The results suggest that as the thickness of the pavement increases, the bending strain experienced decreases. With such small strains experienced at thicknesses from 200 mm onwards, it is suggested that under constant traffic conditions, the porous concrete structure is more than capable of sustaining these loadings without any deformation or cracking. As the main objective of the beam fatigue test is to find the amount of cycles experienced on the beam just as it begins to crack, in order to best utilise this test, the starting bending strain must be at a minimum of 50 micro-strains and increased gradually to 100 micro-strains.

To conduct fatigue strength experiments, the specimens were loaded into a Pneumatic Standalone four point bending Apparatus as can be seen in Figure 5.

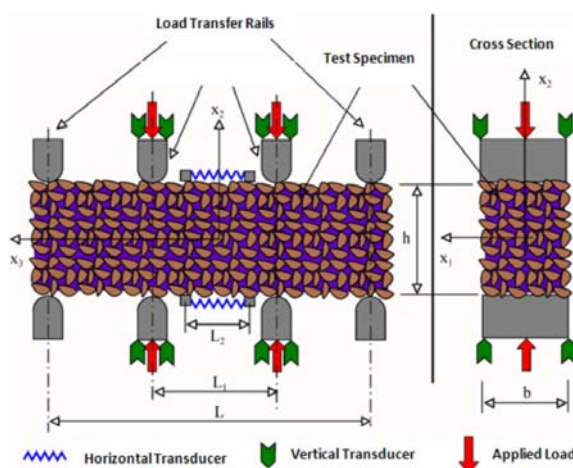


Figure 5: Loading characteristics of the beam fatigue apparatus (IPC Global, 2010)

As shown above, the specimen is placed in a cradle in which it experiences four point bending with free rotation and horizontal translation of all load and reaction points (IPC Global, 2010). The spacing between the loading points is 355.5 mm.

Strain control mode was selected with a range from 50 $\mu\epsilon$ to 100 $\mu\epsilon$. With a known strain value, the load was automatically adjusted so that the specimen experienced a constant level of strain on each load cycle and the modulus of elasticity was continuously back-calculated. The test was stopped as soon as the stiffness modulus fell below 20% of its peak strength or if the specimen reached 5 million cycles without any cracking. The results are presented as the number of cycles multiplied by the elasticity modulus against the elasticity modulus to observe the behaviour of the material as the fatigue test was conducted. Mixture 3 was unable to produce any results.

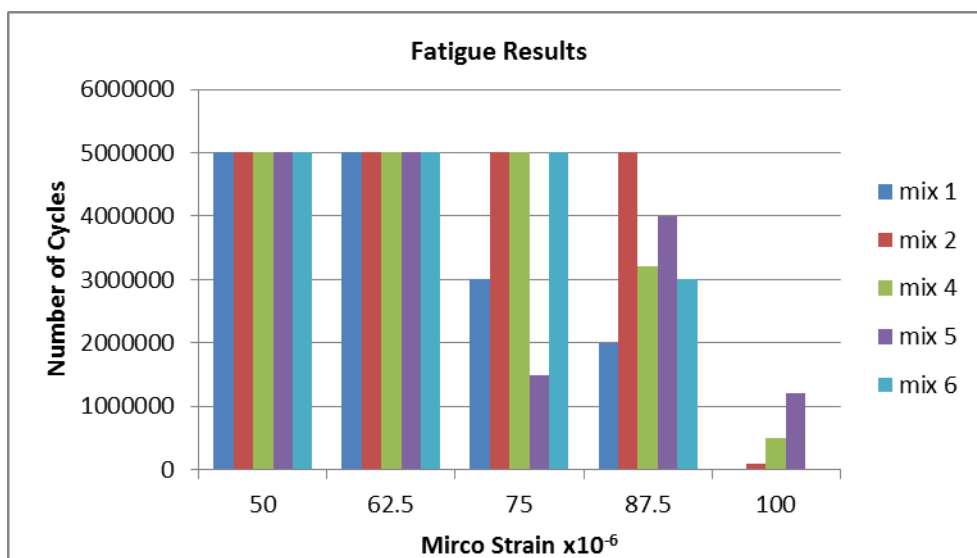


Figure 6: Fatigue result of River Gravel and Basalt

The results suggest that at 50 and 62.5 micro-strains, the cement stabilised material can withstand five million cycles without any deformation to the structure. Observations of the specimen after the test suggests the specimens were intact with no signs of cracking and they would be capable of withstanding more substantially greater cycles. From a practical perspective, for low to medium traffic volumes this would be acceptable as the design life is reasonable.

As the strains increase from 62.5 to 87.5 micro-strains, the number of cycles begins to decrease. This becomes apparent for the smaller grain sizes such as Mixture 1. It may be due to the fact that the smaller the grain size, the more surface area exposed and hence more mortar is required in order to cover the individual grains. This results in weaker bonds (bridges) between the grain particles and less contact points. From a practical point of view, this would not be acceptable, as failure would occur immediately leading to high deformation due to a highly porous structure.

As the strain increase to 100 $\mu\epsilon$ all the mixtures failed to produce any sufficient cycles when placed under a bending strain of 100 $\mu\epsilon$. This suggest that between 87.5 $\mu\epsilon$ to 100 $\mu\epsilon$ lies a limit in which the cement stabilised granular material can maintain a sufficient number of cycles without forming any extensive cracking.

One of the indicators in determining whether the specimen is approaching failure is by continually measuring its elasticity modulus. As the elasticity modulus approaches zero it indicates tensile cracks are propagating from the bottom of the structure to the top.

The samples that did not reach the maximum five million cycles had some form of cracking. After observing all the specimens, the common failure among the samples was the cracking of the cement binder between the aggregate particles and there was no evidence of the individual grains being crushed. The nature of the cracks ranged between micro-cracks (hairline) to macro-cracks.

5 FUTURE RECOMMENDATIONS

Although extensive research has been conducted on river gravel and basalt, there is still a requirement to test different types of material. This is crucial as the potential of permeable pavements can span great distances and the availability of materials is one of the great economic challenges.

One of the limitations to the fatigue and strength testing carried out was that it was not performed under wet or saturated conditions. The influence of water will affect the structural and the fatigue characteristics of the permeable pavement and have an impact in reducing its capacities.

Although a variety of test procedures were conducted, it still does not entirely represent how a permeable pavement behaves in practice. A drawback of the four point bending apparatus is that the bending of the actuator simulates a stationary load on the pavement. The effects of a moving load and the full impact of inertia were not examined due to machinery limitations and hence an accelerated loading facility is required. The accelerated loading facility is a large scale testing procedure and it simulates how truck wheels pass over the pavement thus measuring the effects of inertia and simulating rotating principle stresses in the pavement. In a practical sense design interfaces needs to be examined more carefully, especially between the pavement and kerbs, utilities and drainage pits.

It should also be that even though the same cement content and compactive effort was applied to all the mixtures, this may have not produce optimum results. Further research is required to determine what would be the ideal cement content and compactive effort for the individual mixtures in order to produce the best results.

6 CONCLUSION

After conducting extensive investigation on the properties of porous cement stabilised base material, many parameters and characteristics have been determined. By thoroughly understanding all aspects of permeable pavements, it can be realised that its application can be an economic and green solution if adopted on an industrial scale. The results suggest that porous cement stabilised base material at certain strains can be suitable as a base layer for permeable pavements while having good hydraulic properties.

The hydraulic test results suggest that the grain size influences the effective void ratio and the permeability. The relationship between hydraulic and mechanical characteristics of open porous cement stabilised material is a balancing act as one characteristic affects the other. It was interesting to note that the increasing grain size leads to a greater effective void ratio but its reduction in compressive and tensile strength was only minor. The experimental results concerning the strength of the material also prove that the material is able to withstand the loads that the base course experiences due to traffic.

After analysing all the fatigue results it is clear that the majority of the samples are capable of withstanding low end bending strains, with greater potential to withstand greater cycles if the testing is continued. As the strains are increased

the results become inconsistent among the mixtures and therefore it is not recommended to design for these strains in practice.

7 REFERENCES

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