Investigation of the Effect of Various Additives on the Strength of Environmentally Friendly Permeable Concrete

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Abstract— **Over recent years the development of one Water Sensitive Urban Design technology, known as permeable pavement has been researched to potentially eliminate the majority of runoff issues associated with road surfaces. Permeable pavements perform the dual functions of supporting traffic and of stormwater management. This paper aims to develop a new type of permeable concrete pavement material with enhanced compressive strength while maintaining its permeability. A series of laboratory testing have been conducted to evaluate the structural strength and permeability of various mixture designs of permeable concrete. The effects of adding different supplementary additives as well as applying two different layers have been discussed in details. The additives used in this project are silica fume, fly ash, and polymers. The associated failure pattern with each different mix design has also been discussed.**

Keywords-permeable concrete; compressive strength; additives; silica fume; fly ash; environmental friendly; pavement

I. INTRODUCTION

Urban development in many countries is increasing at an exponential rate due to increasing growth of population and economy. This increase of urban development has led to an increase in impervious surfaces as more available land areas get paved. Permeable concrete pavement is an effective means to minimize the environmental issues caused by stormwater runoff. Permeable concrete is made up of narrowly graded coarse aggregate, cement, additives (optional) and water with little or no fines. A system of permeable and interconnected voids is created by binding the coarse aggregates together with just enough cement to coat aggregates. The voids allow stormwater to infiltrate through the pavement into the underlying soil and play a significant role in mitigating the impacts of stormwater.

The research on permeable concrete pavement has begun in developed countries such as the US and Japan since 1980s [1]. However, the strength of the permeable concrete is relatively low due to its high porosity compared to the conventional concrete [2].

At the moment, permeable concrete can only be applied to areas of light traffic and low loads of vehicles due to its low strength. However, as the demand for the permeable concrete increases in many applications as an environmental friendly sustainable solution, there is an urgent need to produce the high strength permeable concretes. However, research in this area is very limited [2, 3, 4]. The concrete strength can be improved by adjusting the concrete mix proportion, using smaller aggregates and different placement techniques such as installing two different sized aggregate layers and using supplementary cementitious materials such as silica fume, fly ash, and polymers.

Polymers have been introduced as an additive to minimize some disadvantages of concrete such as: delayed hardening, low tensile strength and large dry shrinkage cracking [5]. Polymers altered concrete can be put into two categories: Polymer Modified Concrete (PMC) and Polymer Cement Concrete (PCC). Reference [6] found that the addition of an acrylic polymer additive resulted in a higher compressive strength in comparison with conventional no-fines concrete. When adding 5% of acrylic polymer, the compressive strength increased from 10.6 MPa to 12.3 MPa in high cement mixes and from 6.9 MPa to 7.7 MPa in low cement mixes.

Reference [7] revealed that fly ash required longer periods of time to develop strength. Compressive strength of fly ash concrete is contributed by hydration reaction, pozzolanic reaction, and packing effect that is a proper arrangement of small particles which fill the voids and contribute to the increment of compressive strength.

The addition of silica fume produced the highest increase in strength compared to other supplementary cementitious materials [8]. With the addition of 8% of silica fume, the compressive strength increased by 33%. The increase in strength could be attributed to the improvement in the bond between the hydrated cement matrix and the aggregate.

This paper aims to develop a new type of permeable concrete pavement material with enhanced compressive strength while maintaining its permeability. The paper presents some important findings from a series of laboratory testing.

The effects of adding different supplementary additives and applying two different layers have been discussed in details. The additives used in this project are silica fume, fly ash, and polymers.

II. MATERIALS AND MIX DESIGN

A. Materials

The materials used in production of permeable concrete consist of quarry aggregates, cement, water and admixtures (optional). Aggregate is the major component in porous concrete which covers approximately 80% in weight. The effect of aggregates is the major factor to the strength of porous concrete [4].

The aggregate used was the dolomite from the McLaren Vale Quarry which has a mineral makeup of calcium carbonate and magnesium, with a tested dry density of 2.66 t/m^3 and a moisture absorption characteristic of 0.8%. The aggregate sizes used were 10mm and 3-5mm (Figure 1). Dolomite was selected as our previous research indicated that dolomite yielded the highest compressive strength [9]. A 3-5mm small sized dolomite aggregate was used to incorporate with 10 mm large sized dolomite aggregate to form a two layered mix design as it is believed that the compressive strength of permeable concrete will be increased with such an innovative two layered design.

Adelaide produced General Purpose Cement (GP) was used. Some additives were also used aimed at improving the compressive strength of permeable concrete. Silica fume, namely Microsilica 600 with 80% S_iO_2 in amorphous state, was used. It is a highly reactive pozzolan and very fine amorphous silica conforming to Australian Standard AS 3582.3. This additive was used in mix design 2 with a quantity of 10% in weight.

Fly ash used was a medium grade fly ash from Leight Creek coal in the power station at Port Augusta, South Australia. Port Augusta fly ash conforms to AS 3582.1 as a supplementary cementitious materials for use with Portland cement. This additive was used in mix design 3 with a quantity of 10% in weight.

Hydrocryl 307, a white liquid pure acrylic polymer from Acquos in Victoria was used in mix design 4. It has a specific gravity of 1.04g/cm^3 and a glass transition temperature (Tg) of 7°C. This polymer was used with a quantity of 10% in weight.

Figure 1.   Dolomite aggregate

B. Mix Design

The optimal Aggregate to Cement (A/C) and Water to Cement (W/C) ratios were obtained through our previous researches [3]. A/C and W/C ratios used in this investigation are 4.5 and 0.36 respectively. The percentage of additive added into each mix was about 1.7% of the total volume. There are two mix designs for control mix and a layered mix with no additives.

III. SAMPLE PREPARATION AND TESTING PROCEDURES

A. Sample Preparation

Aggregates are sieved to separate into 10 mm and 3 -5 mm and then the separated aggregates are washed to remove any particles that may interfere with the binding capacity of cement. The washed aggregates are dried in the oven. The required amount of materials is weighted and aggregates and cement are then poured into the rotating concrete mixer. Water is then slowly added while the mixer is still rotating and continues until the mix become homogeneous. Fresh concrete is then filled into the steel cylinder moulds in three equal layers. Each layer is rammed 20 times with a drop hammer. Lids are placed on the moulds to allow them to settle for 24 hours during which concrete are hardened. Specimens are removed from the moulds and labelled, wrapped with plastic wrapping and put into the lime bath for curing. The samples were cured at 23±2°C according to AS 1012.8.1.

B. Testing Method

For each batch, two samples were prepared for permeability testing and others were for compression, three tested at 7 days and 28 days respectively. The results showing up in this paper were all average values. The testing conducted include: unconfined compressive strength (UCS), water permeability and porosity.

The unconfined compressive strength (UCS) testing of concrete specimens was carried out in the lab according to AS1012.9. Prior to loading process, caps were placed on the ends of samples. Type of capping used depended on surface condition of the concrete samples. Rubber capping was usually used for conventional concrete with smooth top and bottom surface; and sulphur capping was used for samples with rough surface like porous concrete. The testing results indicated that the compressive strength of the porous concrete would increase dramatically through by use of the sulphur capping [3], as this capping restrained the aggregates on the top effectively (Fig.2). Thus, sulphur capping was adopted for all samples in this study.

Figure 2.   Compressive strength testing rig.

Permeability as a unique ability for water to penetrate through porous concrete was expressed in millimetres per second (mm/s). Since porous concrete generally owns a much higher permeability compared to the normal dense concrete, the permeability test method for the latter one was not suitable for testing porous concrete. As there is no Australian Standards for such testing, a testing method which was similar to the falling head test method for soil (AS 1289.6.7.2 2001) was adopted in this research.

The testing apparatus has been gradually improved from our previous research [3]. Instead of using a rigid perspex tube as previous testing, the cylindrical plastic pipe was used in this test. With inline steel wire and adjustable steel tie, the pipe was tight to inhibit water leakage along the sides of the sample (Fig.3). Moreover, the tiny gap between the specimen and the pipe at the bottom was sealed with processed plasticines to prevent water infiltration through the edge of pipe, which will affect the accuracy of the permeability coefficient. Subsequently, the water permeability rate of porous concrete was calculated by equation (1).

$$k = \frac{aL}{At} \times \ln\frac{h_1}{h_2} \qquad (1)$$

Where k is the permeability coefficient (mm/s), a is the area of the cylindrical pipe (mm^2), A is the area of specimen (mm^2), L is the Length of specimen (mm), t is the time for water to pass from level h_1 to h_2 (s) through the pipe.

Figure 3.   Permeability testing rig.

The porosity test was carried out at 28 day of age. The open porosity was measured as the percentage of pore volume or void space within the concrete that can contain water. The sample was oven dried at 110°C firstly and was left to cool for measurement. The dimensions of the sample were measured in dry condition and the total volume of sample (V_T) including the solid and void component was determined. Then the sample was sunk into a bucket filled with sufficient water to cover the whole sample and the water level was marked. After 24 hours, the sample was moved out from the bucket and the water was refilled up to the marked level. The weight of water added was read by the scale and the magnitude of this reading was equal to the changed volume (V_C), using the concept of 1 gram=1cm^3 for water. The open porosity of the concrete sample was calculated with equation (2):

$$P(\%) = \frac{v_T - v_C}{v_T} \times 100\% \qquad (2)$$

Where P is the open porosity (%), V_T is the total volume of specimen (mm^3), "V_T-V_C" is the volume of void space (mm^3).

IV.   RESULTS AND DISCUSSIONS

A.   Control mix with no additives

The compaction method for making permeable concrete is one of the most influential factors in the sample preparation. Through different compaction methods and as the compaction energy increased, the density of the concrete also increased and therefore resulted in a higher compressive strength. However, this greater compaction efficiency has effectively caused a reduction in air voids within the permeable concrete.

The testing results of average density, average 28 days compressive strength, permeability and porosity are shown in Table 1. Three different kinds of compaction methods were used and compared. As indicated in Table 1, the hammer compaction was favoured, not just because it yielded the highest compressive strength, but also it simulated actual road construction methods in the form of heavy rollers and rammers. Optimum compaction method would have seen both hammer and roller methods used, but unfortunately it was not achievable due to the instruments which were available and the cylinder casting method. The hammer compaction method was selected for all the remaining mix designs where different types of additives were used.

TABLE I.   EFFECT OF COMPACTION METHODS

Compaction method	Results			
	Density (kg/m^3)	Compressive strength (MPa)	Permeability (mm/s)	Porosity (%)
Hand rod	1938	15.2	18.7	31
Vibration Table	1785	11.2	29.2	40
Drop hammer	2063	18.0	9.15	23

The major disadvantage of hammer compaction method is the loss of permeability. In addition, as the impaction strength of a falling hammer was so strong, it crushed the weak aggregate and created weak layers (this will be further discussed under the section of failure mechanism).

B.   Effects of additives

A/C and W/C ratios used for mix designs with additives are the same as the control mix. The additives were added at the 10% by weight. The testing results for 7 and 28 days compressive strength for each mix design were shown in Table 2. There is a small increment in compressive strength for the mixes using silica fume and fly ash compared to the control mix as shown in Table 2. These increments could be attributed to the improvement in the bond strength between the hydrated cement and the aggregates and the filling effects of silica fume and fly ash. However, the polymer mixes produced lower compressive strength than the control mix.

TABLE II.   EFFECT OF ADDITIVES

Mix	Density (kg/m^3)		Compressive strength (MPa)	
	7 days	*28 days*	*7 days*	*28 days*
Control mix	2982	2063	16.0	18.0
Silica Fume	2090	2066	17.0	21.4
Fly Ash	2128	2083	18.2	21.6
Polymer	2065	2006	14.8	17.8
Layered	2073	1979	17.2	19.8

The use of polymer additive material can increase the mechanical properties of concrete; the use of Vinylidene chloride can increase the bond strength of ordinary concrete by five times [10]. It is believed that the polymer mixes did not improve the compressive strength of permeable concrete was due to two reasons: the water cement (W/C) ratio was not adjusted properly when the liquid polymer was added and resulted in higher ratio than the control mix; the volume percentage of polymers was too low (1.68%) which reduced the bonding effect of polymers. Therefore, when adding liquid polymers to porous concrete, the mix design must be investigated carefully to achieve an optimal result.

C. Two layered mix design

A double layered porous concrete cylinder comprising of two different aggregate sizes was tested. The objective of this two layered design is to increase the load carrying capacity and not to decrease the permeability by having smaller sized aggregate at the top and larger sized aggregate at the bottom. The smaller aggregate will create a lower porosity ratio where the aggregate will be tightly positioned next to each other allowing more efficient stress transfer, and effectively increasing the compressive strength. The two layered mix design is shown in Fig. 4.
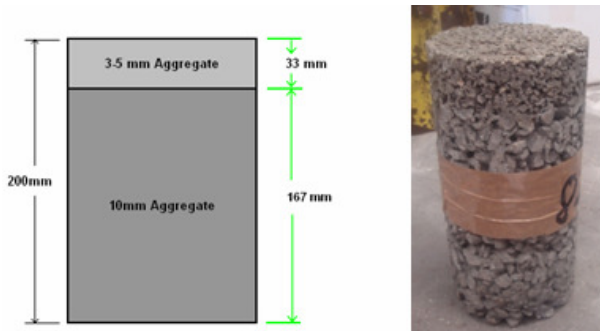

Figure 4.   Layered mix design

The two layers were mixed in separate concrete mixers and then casted as one. The cylinder mould was filled in the standard 3 layer (two bottom layers 10mm aggregate and the third top layer 3-5mm aggregate) and compacted in the same manner as for other mixes.

No additive was added for the layered mix design. As shown in Table 2, a layered mix design produced a higher compressive strength than that of the control mix. Using smaller aggregates increased the compressive strength of the permeable concrete at the top layer. This mix design indicated

that the strength of permeable concrete can also be improved without adding additives.

D. Permeability and porosity

The permeability and porosity tests conducted after 28 days of curing time. The results are presented in Table 3.

TABLE III.   PERMEABILITY AND POROSITY

Mix	Density (kg/m^3)	Permeability (mm/s)	Porosity (%)
Hand rod	1938	18.7	31
Vibration Table	1785	29.2	40
Control mix	2063	9.15	23
Silica Fume	2066	6.47	18
Fly Ash	2083	6.75	17
Polymer	2006	7.72	16
Layered	1979	5.47	18

The permeability and porosity of the mix designs compacted with hand rod and vibration table were very high due to the low density of the specimens. The addition of additives in the mixes compacted with drop hammer achieved lower permeability and porosity than that of the control mix. As the acceptable flow rates for water through porous concrete are typically from 2 mm/s 5.4 mm/s [11], the mix designs in Table 3 could be further adjusted, such as to reduce the W/C ratio, to increase the percentage of additives and therefore to reduce the permeability and increase the strength. Using smaller aggregates sized 3 to 5 mm at the top layer in the layered mix resulted in the reduction of the average pore size and it led to a reduced permeability.

The porosity-permeability relationship is important to the optimum performance of permeable concrete. Previous research indicated that the relationship between the coefficient of permeability and the porosity can be derived in Equation (3) [12]:

$$K = 0.00091(\frac{P+5.52}{1.17})^{3.72} \tag{3}$$

Where *k* is the permeability coefficient (mm/s), P is the porosity (%).

It is shown that permeability increases with an increase in porosity and follows an exponential trend line. The testing results of the permeability and porosity for each mix design are plotted in Fig. 5 together with equation 3. As shown in Fig 5, the testing results follow a similar trend of equation 3. However, further research is required in this area as permeable concrete is a porous material and understanding its transport properties is therefore important. In general, permeability depends on the total porosity but more importantly, it depends on the way in which the total porosity is distributed and connected.

In order to investigate the transport properties of permeable concrete, a few specimens were cut in vertical directions as shown in figure 6 and examined. It was found that the

specimens compacted with vibration table generally tended to have uniform structures with more pore spaces connected. It led to a higher permeability and porosity. Specimens compacted with hammer did not have a uniform microstructure because of not evenly compacted during the compaction. However, it had a tendency to have less pore spaces as aggregates were more closely compacted. It resulted in a lower permeability and porosity.
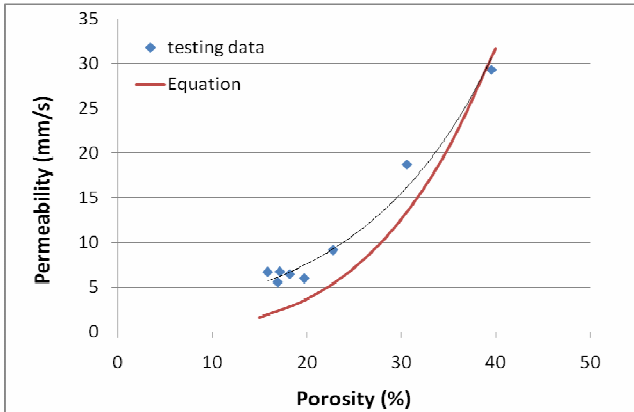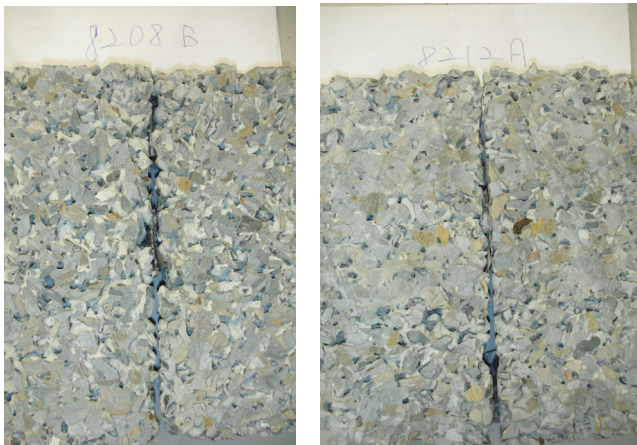

Figure 5.   Permeability versus porosity

(a) compacted with vibration table   (b). compacted with hammer

Figure 6.   Comparison of the transport properties

Figure 7.   Microstructure of layered mix design

For the layered mix as shown in Fig. 7, the microstructure for the top layer was relatively uniform and densely compacted, which led to smaller pore spaces and well connected with one another. However, smaller pore spaces resulted in lower permeability and porosity. The bottom layer had more pores but randomly distributed.

A percolation type model will be developed at the next stage of the research where the microstructure can be built up using randomly or regularly deposited shapes.

E.   Failure mechanism

There are three possible failure mechanisms could occur to permeable concrete [3]:

    1) Cement failure

    2) Cement and aggregate interface (bond) failure

    3) Aggregate failure

Although all three failure mechanisms have been observed, only type 2 failure is dominate in all testing specimens. As discussed in our previous research [3], type 3 failure was only dominate when recycled aggregate was used and type 1 failure could be prevented with a proper mix design.

As shown in Fig. 8, the cement coating has been sheared off due to the compressive load which indicated a type 2 failure. However, when the W/C ratio was too high, for example, when liquid polymer was added to the mix design, the failure mechanism changed to type 1 failure (Fig. 9). This probably explained why the compressive strength was not increased when adding polymer to the mix design. Although polymers could increase the bond strength of concrete, the failure mechanism of the specimens was due to cement failure, not bonding failure.

Figure 8.   Type 2 failure

Figure 9.   Type 1 failure (polymer mix)

Another interesting observation was that the majority of the failures of the testing specimens did not occur through the centre of the specimens. This type of failure indicated that the hammer compaction method is unreliable due to its non uniform compaction. The hammer compaction was conducted by blowing the specimens in a circular path inside the cylinder. The centre of the specimens became significantly compacted while the edges of the specimens were less compacted during the compaction.

The non-uniform compaction resulted in the centre of the specimens having a higher density, which led to a higher compressive strength at the centre. The edges of the specimens were less compacted, which resulted in a lower density and lower compressive strength. The failure pattern in Fig. 10 shows that the failure has occurred on the sides of the specimen due to less compaction.

Figure 10. Failure due to non-uniform compaction

For the layered mix, the failure was observed to have occurred in the bottom layer where the larger aggregate was used. The dominate failure mechanism was still type 2 failure. The failure did not occur in the top layer due to the efficient stress transfer between the small aggregate, see Fig. 11. Therefore, enhancing the cement binder is a major problem in porous concrete design.

Figure 11. Failure patten for layered mix design

V. CONCLUSIONS

The laboratory testing has been carried out to develop a new type of porous concrete material. From the results obtained, the following conclusions may be drawn:

1. Adding a small amount of additives does not have significant effects on the compressive strength. It is required further research on the optimal percentage of each additive.

2. The permeability and porosity testing revealed that adding a small amount of additives will not significantly affect the permeability and porosity. The amount of additives could be increased for the further mix design.

3. Layered mix has produced a slightly higher compress strength, which indicates that the strength of permeable concrete can also be improved without adding any additives.

4. The hammer compaction method produced non-uniform internal structures. Specimens were not evenly compacted and resulted in a lower density around edges of the specimen. Most failures occurred on the sides of the specimens rather than through the centre of the specimen. It is suggested that a combined compaction method should be adopted in the future, to incorporate a static compactor in the consequent vibrating procedure.

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