The Performance of Recycled and Quarry Aggregates and Their Effect on Permeable Concrete

Yan Zhuge[1]
[1]A/Professor of Civil Engineering, University of Southern Queensland

Abstract: In this paper, the results of a series laboratory testing which have been conducted to evaluate the structural strength and permeability/porosity of various mixture designs of permeable concrete basecourse and surface materials have been discussed. In Australia, concrete demolition discharges solid waste to the region in extremely large quantities. To utilise various waste materials in concrete, both low-grade recycled aggregate and four different types of quarry aggregate were used in the research. The tests performed include unconfined compression, porosity and permeability tests. It was found that the compressive strength of low-grade recycled aggregate was much lower than quarry aggregate and the admixtures such as silica fume which could enhance the strength of cement paste binder will have no effect on low-grade recycled aggregate due to failure was dominated by aggregate itself. A mathematical model to predict the compressive strength of permeable concrete made with recycled aggregate was developed and compared with those made with quarry aggregates.

Keywords: permeable concrete material, recycled aggregate, compressive strength, porosity.

1. Introduction

Urbanization converts pervious vegetated areas into impervious roofed and paved surfaces. This increases flooding, damages water quality and threatens the health of natural ecosystems. A sustainable solution to this problem is to use permeable pavement which has become one of the key Water Sensitive Urban Design (WSUD) technologies. Instead of installing rainfall detention ponds or soakaways, permeable pavement system is more cost effective compared to the traditional impervious pavement. Meanwhile, it has been acknowledged by many researchers that permeable pavement system is capable of reducing the sediments and contaminants for lessening the pollutant loads on stormwater, thus it is considered as an economic and environmental-friendly construction as a part of city drainage system. To date, permeable pavement has been developed and applied on small scales such as car-parks but has yet to be widely utilized in Australia (1).

Permeable concrete is relatively porous, providing by the omission of fine aggregates and filled most of volume with coarse aggregate (2), thus, permeable concrete obtains more voids in the structure leading to higher water infiltration and air exchange rates compare to conventional concrete, but the structural strength of it is compromised. Since cement paste in permeable concrete is very thin to bond coarse aggregate together, porous concrete tends to fail at the binder interface between the aggregates and results in the low compressive strength (1). Experimental investigations on compressive and tensile strength, drying shrinkage, permeability and porosity of permeable concrete for paving materials have been conducted by a few researchers in recent years (1), (3), (4). The effect of consolidation techniques, curing types and testing conditions on physical and engineering properties with various mixtures was investigated by (3). They found permeable concrete has a lower modulus of elasticity and compressive strength. However, a higher level of compaction resulted in a higher strength. The curing types (sealed or wet), on the other hand, had no effect on the strength. Similar testing was also carried out by (4), but focused on freeze-thaw durability. Their testing results indicated that use of single sized aggregate could not give concrete adequate strength. Using sand and latex significantly improved the strength and freeze-thaw resistant of the material, but resulted in lower permeability.

The interest in using recycled materials derived from construction and demolition waste is growing all over the world. In general, recycled aggregates (RA) are mostly inhomogeneous, less dense, more porous and weaker as compared to natural aggregates (5). Consistent with sustainable development principles, the use of recycled aggregate was considered to be one of the worthwhile objectives of the current research project.

Permeable concrete has a large volume of air voids which can adversely affect the material's mechanical properties. It is therefore important to determine how its mechanical performance is affected by the presence of pores.

This paper first will present a series of laboratory testing to evaluate the structural strength and permeability/porosity of various mixture designs of permeable concrete material. As the size, type, shape and gradation of aggregate will affect the performance of permeable concrete, these effects will be investigated extensively. The performance of recycled aggregate and four different types of quarry aggregate will be compared. A mathematical model to characterize the relationship between compressive strength and porosity for porous concrete using recycled aggregate will then be developed. The results reported in this paper forms part of a research project aimed at developing a new type of eco-friendly concrete permeable pavement material that has both enhanced structural strength and water quality treatment capabilities to support medium trafficked areas of road.

2. Materials and Mix Design

The materials used in production of the permeable concrete consist of recycled and quarry aggregates, cement, water and water admixtures.

Aggregate is the major component in permeable concrete which covers approximately 80% in weight. The effect of aggregates will be the major factor to the strength of permeable concrete. In general, gradation size for permeable concrete aggregate would be much smaller compared to the conventional concrete aggregate. Only a single sized (open graded) aggregate with small grading gap would be used in permeable concrete to ensure the permeability of the material. The stability of an open-graded aggregate comes from the interlock which occurs along the flat faces of angular particles.

2.1 Recycled aggregates (RA)

Recycled aggregates were supplied by an Adelaide based recycling company. The recycled aggregates are produced from sorted and clean waste concrete and masonry (RCM) typically for road subbase applications. The material contains small quantities of brick, gravel, crushed rock or other forms of stony material as blended material. Asphalt, glass, metal, timber and other vegetation were also found in the aggregate. The shapes and sizes of the aggregates vary and consist of sub-rounded and angular particles with two sizes used in the mixture being 10 mm and 15 mm (Fig 1). All aggregate was placed in the ovens to completely dry out and then was sieved.

As recycled aggregates tend to absorb more water than quarry aggregates, the aggregate's absorption capacity was investigated. The inconsistency of the aggregates was also noticed and this may alter the testing results significantly. During the mix, there were difficulties in controlling the water due to high water absorption of the recycled aggregates. High range superplasticiser was required whining recycled aggregates to maintain a correct workability for sufficient time (6).

Figure 1. Recycled aggregate.

Figure 2 Compressive strength testing rig.

2.2 Quarry aggregates

Four types of quarry aggregates have been used: marble, dolomite, quartzite and limestone. The marble was sourced from Penrice Quarry with 10mm and 20mm in size. The main mineral that constitutes marble is calcium carbonate with white colour. The dry strength tested according to AS1141.22 for 10mm and 20mm marble is 93 kN and 89 kN respectively. The Los Angeles Abrasion Value is 43% for 20mm and

35% for 10mm. This showed that 10mm marble is stronger in strength. The moisture suction of marble is less than 1%.

The mineralogy for dolomite is quite similar to marble which consist of calcium carbonate but some of the calcium carbonate had been replaced by magnesium. Dolomite tends to be flaky in shape with smooth surface and sharp edges. The dry strength tested is 146 kN and the Los Angeles Abrasion value is 25%. The moisture suction of is less than 1%.

Quartzite was a dense, hard metamorphic rock. The quartzite obtained from local quarry was red due to a large amount of iron oxide. The dry strength tested is 163 kN and the Los Angeles Abrasion value is 27%. Limestone was also sedimentary rock. Although some limestones were nearly pure calcite, there were often varying amounts of clay, silt and sand. The dry strength tested is 74 kN and the Los Angeles Abrasion value is 38%.

2.3 Other materials

Adelaide produced Type Premium Cement (GB) with 20% of Fly Ash was used for mix designs using recycled aggregate and General Purpose Cement (GP) was used for quarry aggregate mix designs. Type GB blended cement is commonly used in South Australia roadworks as it is more economical, with improved working time and similar long term strength to Type GP cement, as well as its environmental benefits in terms of the substitution of cement with reactive by-products from coal fired power stations.

Water reducing admixtures, Pozzolith 370C, was used in the mix designs to help reducing the water content. It is a non-retarding strength enhancing admixture. The admixture consequently reduced the amount of water required and hence eliminated the clogging of the specimens from cement fines, resulting in improved cement paste distribution and thus the strength and permeability.

2.4 Mix design

There are two different types of mix design for this paper: type one was for permeable pavement base course material with a lower target unconfined compressive strength (UCS) of 4.0MPa at 28 days moist. The ratio of cement used in the mix designs varied from 5% to 8%. Types two was for permeable concrete surface material with a higher target UCS of 15MPa at 28 days moist. The ratio of cement used in the mix designs varied from 13% to 18% for surface material. Due to the effect of aggregate density, the mix design was based on the volume. The mix designs are shown in Table 1.

3. Testing Results

The preparation of standard concrete test specimens is based on Australian Standards and Guidelines ensuring a consistent and calibrated set of specimen results. Details of sample preparation, compaction and curing can be found in (1).

3.1 Compressive strength

Unconfined compressive strength (UCS) was determined by using an Avery hydraulic testing machine. Compression cylinders were tested according to AS 1012.9-1999. Average dimensions of each specimen were determined for use in subsequent calculations. Once the dimensions were recorded, a rubber cap was placed on top of the specimen and it was then placed in the testing machine and loaded to failure (Fig 2).

3.2 Porosity

Porosity testing is a measurement of water that can be held within the sample volume. Porosity is expressed as a percentage. After 28 days of curing, the specimens were first oven dried at 110°C and then immersed in water for up to 24 hours. They were then removed from the bucket to let the water drain out. A latex membrane was rolled along the boundary of the specimen and petroleum jelly applied on the surface of the latex membrane. The bottom of the specimen was sealed with gaffer tape and the combined weight of the Perspex tube and specimen measured (w_1). Water was added to the top of the specimen until it was filled and the weight measured (w_2). The porosity can then be determined in percentage.

3.3 Permeability

For the permeability test which is a time measurement of water that infiltrates through the soil, samples were cast into 100mm diameter cylinders (as for compressive testing specimens). The height of the specimens was kept constant at 200 mm. As there is no standard for a concrete permeability test, the procedures adopted in this research were similar to that of a permeability test for soil. Both falling head method (AS 1289.6.7.2) and constant head method (AS 1289.6.7.3) were used (Fig. 3). Test apparatus had to be made so that an accurate measurement of the permeability of the samples could be found. This meant that a tube that would tightly seal around the sample was needed so that water would only pass through the sample, and not down the sides. Silicone was used to seal the sample around the base.

Table 1. Summary of mixture proportion and testing results of porous concrete.

Mix No.			Mix volume proportions (%)				Compressive Strength (MPa)	Permeability (mm/s)	Porosity (%)
	Type of aggregate	Size (mm)	Coarse aggregate	Cement	Water	Sand			
Group 1- base course material									
1-1	RA	10-15	85.0	5.0	6.0	4	2.24	20.7	33.7
1-2	RA	10-15	82.5	4.9	8.0	4	0.8	16.8	33.7
1-3	RA	10-15	84.8	7.9	7.3	-	2.55	22.0	31.8
1-4	RA	10-15	83.9	7.9	7.5	-	1.29	22.3	29.9
1-5	RA	10-15	81.5	7.7	9.3	-	0.62	15.6	31.2
Group 2 – surface material									
2-1	Dolomite	6.7-16	78.8	15.7	5.5	-	12.1	33.4	22.5
2-2	Marble	6.7-13.2	78.8	15.7	5.5	-	14.7	14.8	22.1
2-3	Dolomite	6.7-16	81.6	13.6	4.8	-	8.8	23.6	26.0
2-4	Marble	6.7-13.2	81.6	13.6	4.8	-	10.4	35.1	25.4
2-5	Quartzite	6.7-9.5	74.4	18.6	6.7	-	12.0	27.4	21.5
2-6	Quartzite	6.7-9.5	74.4	18.6	6.7	-	12.0	28.3	26.2
2-7	Quartzite	6.7-9.5	74.4	18.6	6.7	-	11.5	26.5	24.8
2-8	Quartzite	4.75-9.5	74.4	18.6	6.7	-	17.5	8.50	19.2
2-9	Quartzite	4.75-9.5	74.4	18.6	6.7	-	14.5	13.7	23.1
2-10	Quartzite	4.75-9.5	74.4	18.6	6.7	-	14.5	13.5	21.1
2-11	Limestone	6.7-9.5	74.4	18.6	6.7	-	15.5	13.3	17.2
2-12	RA	6.7-13.2	81.6	13.6	4.8	-	6.5	23.6	22.3
2-13	RA	6.7-13.2	78.8	15.7	5.5	-	8.4	22.3	22.5

(a) Falling head apparatus.

(b) Constant head apparatus.

Figure 3. Permeability test apparatus.

3.3 Results and discussion

The testing results discussed are based on the 28 day tests. Both hammer compaction and a vibration table were used for the mix designs using quarry aggregate; a vibration table method was used for the mix designs using recycled aggregate. The results are summarized in Table 1.

3.3.1 Effect of aggregate types and sizes

As shown in Table 1, the UCS of recycled aggregate was much lower compared to quarry aggregate. For a mix design of 5% cement and 4% sand for base course material, the compressive strength was below the design target. The testing results also indicated that when the cement ratio increased from 5% to 8% and no sand was used, there is no apparent change of either strength or permeability of the material. Therefore, the first mix design would be more economical. When a higher percentage of cement was used for surface material, the UCS was still 50% lower than quarry aggregate. The testing results also indicated that the density of recycled aggregate was lower than quarry aggregate. Although the same compaction method was used, the mix using recycled aggregate could not be well compacted.

For mix design using quarry aggregate, when a higher A/C ratio was used, the mix design was more economical but normally resulted in less compressive strength. When a better graded aggregate was used (4.75–9.5mm compared to 6.7-9.5mm), the UCS could be improved. There is a concern that well graded aggregate will reduce the permeability. However, as shown in Table 1, all specimens are quite permeable.

The results also indicated that the type of coarse aggregate used in making permeable concrete would influence the strength of permeable concrete even though the aggregates were in the same size and gradation. This can be attributed to the different particle shape and texture of different aggregate, as shown in Fig. 4. It was observed that the more flaky aggregate particles tended to be oriented in one plane under compaction force, which adversely affected the contact area between aggregate and cement, so that the more flaky aggregate did not bond with cement as well as the more rounded aggregate, such as limestone.

(a) Quartzite.

(b) Limestone.

Figure 4. Comparison of different types of aggregate.

3.3.2 Failure mechanism

To obtain a better understanding of the effect of aggregate, the testing specimens were carefully investigated and three failure mechanisms have been observed which are failure through cementing material (type 1 failure), failure through the interface between aggregate and cementing material (type 2 failure) and failure through aggregate (type 3 failure).

Type 1 failure was dominant for mix designs with low cement content. This type of failure could be easily avoided with a proper mix design.

Type 2 failure occurs to the mix designs using quarry aggregate when the surface roughness of aggregate is insufficient for the cement to bond to it. It was observed that porous concrete material using dolomite tends to have more type 2 failure (Fig 5a). Although the dry strength of dolomite is higher than marble and limestone, for the same mix design, the compressive strength of the specimen using dolomite was lower. This was due to a smoother surface and more flaky nature of dolomite compared to other types of aggregate. For the same mix design, the compressive strength of marble is about 20% higher than dolomite due to a better interfacial bonding. In addition, the uneven surface of marble increases the surface area and therefore improves the interfacial bonding strength between the aggregate and cement paste.

It was found that failure of mix designs using recycled aggregate was dominated by type 3 failure as the compressive strength of recycled aggregate was much lower than quarry aggregate (Fig 5b). The microstructure analysis indicated that the interfacial bonding for recycled aggregate is stronger than quarry aggregate due to its rough and porous surface. Therefore, type 2 failure was uncommon. In addition, a higher cement ratio or admixtures such as silica fume which could enhance the strength of cement paste binder will not increase the compressive strength of porous concrete using recycled aggregate due to type 3 failure.

(a) Type 2 failure in dolomite. (b) Type 3 failure in recycled aggregate.

Figure 5. Failure mechanism of porous concrete.

4. Development of Porosity and Compressive Strength Model for Porous Concrete Using Recycled Aggregate

As discussed earlier, porous concrete was designed having a large volume of interconnected voids and leading to higher water infiltration. As a building material, porous concrete also needs to withstand loads. It is therefore important to determine how the presence of pores affects its mechanical properties. The pore structure of a porous material can be characterized by a number of parameters including pore size, pore connectivity, pore surface roughness and pore volume fraction (porosity). Of these, the porosity is regarded as the primary parameter of porous material microstructures. Thus, it’s important to establish a quantitative relationship between porosity and compressive strength of porous concrete.

4.1 Effective and total porosity

The porosity determined under section 3.2 was effective porosity. However, the strength of porous concrete is affected by the volume of its overall voids. In the complex microstructure of concrete, the pores can be present from the nano-scale to the macro-scale. The difficulty of accurately testing the total porosity of porous concrete arises from its unique microstructure. Compared with the pores within cement paste, the interconnected voids between coarse aggregate are larger by several millimetres. Although it is well known that the method of mercury intrusion porosimetry (MIP) is effective for observing the pore configuration in normal concrete, the large amount of connected voids within porous concrete will cause dripping and leakage of mercury if pressure is applied. Thus, the method of MIP is not feasible for porous concrete. Vacuum sealing apparatus is more appropriate to test a relatively accurate porosity for porous concrete in laboratory research (7). However, in practice, setting up such a delicate apparatus is challenging for concrete manufacturers and a simpler method is preferred. In the literature, Kearsley and Wainwright (8) have successfully used the Hoff equation (9) to estimate the total porosity of foam concrete. Similarly, Zheng (10) has presented an equation to estimate the total porosity of porous concrete, which was analogous to the Hoff equation, but incorporated the aggregate proportions for porous concrete. This is shown in Equation (1):

$$\rho_t = \frac{100 + P_c + 0.25P_c}{\frac{100}{\rho} + \frac{P_c}{\rho_c} + (0.25P_c \times 0.75)} \times \rho_w \tag{1}$$

where ρ_t is the theoretical density, P_c is the cement to aggregate ratio by weight, ρ_c is the specific gravity of cement, ρ_w is the unit weight of water and ρ is the aggregate apparent density.

The total porosity can be calculated as:

$$p = 1 - \frac{\rho_b}{\rho_t} \tag{2}$$

where p is the total porosity and ρ_b is the bulk density of the sample.

However, in practice, it will be difficult to evaluate the total porosity using equations (1) and (2). Therefore, the relationship between effective porosity (determined from simple laboratory testing) and total porosity (determined from Equation (2)) was analysed through a regression analysis by our previous research (11) and a formula was derived as follows:

$$p = 0.78p_e + 14.1 \tag{3}$$

Based on Equation (3), the total porosity could be easily determined.

4.2 Proposed model for porous concrete using recycled aggregate

In order to establish a mathematical model to describe the relationship between the compressive strength and porosity of porous concrete, existing models for porous material have been investigated (11). It was found that Griffith's model of fracture (12) has been commonly used. Griffith found that the critical stress incurs crack propagation within a brittle material and can be expressed by:

$$\sigma = \sqrt{\frac{2E\gamma}{\pi a}} \tag{4}$$

where σ is the stress at the fracture (Pa), E is the elasticity modulus (Pa), γ is the fracture surface energy (J/m^2) and *a* is the half length of an internal crack (m).

The presence of pores affects both elasticity and fracture energy, both properties are reduced compared to the pore-free solid material. Therefore, the effective values of *E* and γ need to be determined. Various equations have been developed to describe the influence of pore content on Young's Modulus and surface energy for different materials (13, 14). In our previous study (11), a formula was proposed for porous concrete using quarry aggregate (Equation 5):

$$\sigma = \sqrt{\frac{2E_0(1-p)^m\gamma_0 e^{-np}}{\pi a}} \tag{5}$$

where *m* and *n* are new material constants for porous concrete and can be determined based on experimental data.

A regression analysis was performed on Eq. 5 based on available experimental data. In order to utilise a linear least-squares regression technique, Equation 5 has been re-arranged as a linear equation of the form:

$$Y = mx_1 + nx_2 + c \tag{6}$$

with Y=2lnσ, x_1=ln(1-p), x_2=p, c=lnA and $A = \frac{2E_0\gamma_0}{\pi a}$.

The multiple linear regression run by least square method generates the best fitted plane and parameters, as shown in Fig. 6. The regression results are: m=5.96 and n= -10.01 when c=10.61 for Eq. (6). The coefficient of determination R^2 for this equation was estimated to be 0.99 and the standard error of estimated Y was 0.306. This indicates that the model could describe the correlation between compressive strength and porosity for porous concrete with acceptable accuracy.

In this paper, both recycled aggregate and quarry aggregate have been used in the mix design and their mechanical properties and hydraulic conductivities were compared in the earlier sections. As Eq. 6 was derived for porous concrete using quarry aggregate, the testing results using quarry aggregates are compared with Eq. 6 first. The results are shown in Fig. 7. It can be seen from this Figure that the testing data fits Eq. 6 well which proves again that Eq. 6 can be used to describe the relationship between the compressive strength and porosity of porous concrete using quarry aggregate.

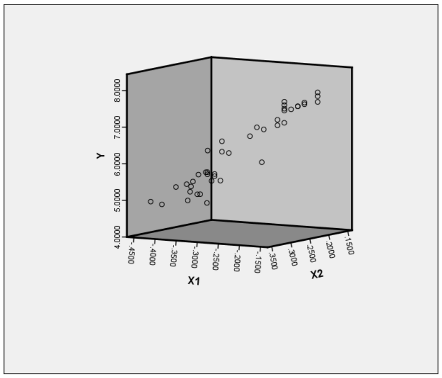

Figure 6. Relationship between Y and x_1, x_2 (11)

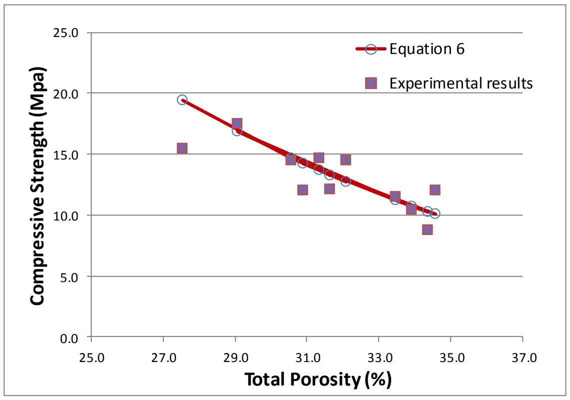

Figure 7. Results for quarry aggregates

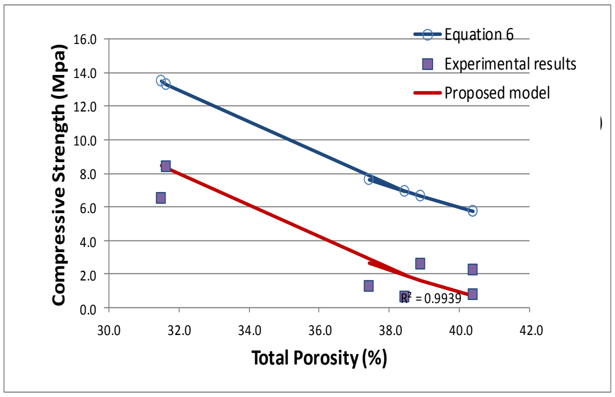

Figure 8. Results for recycled aggregate

The testing results using recycled aggregate are then compared with Eq. 6 and the results are shown in Fig. 8. As indicated in the figure, Eq. 6 overestimates the compressive strength of porous concrete using recycled aggregate. This is due to the fact that the failure mechanism and water absorption rate for porous concrete using recycled aggregate are quite different to that using quarry aggregate. The results from this turn out to be a factor (Z) could be introduced into Eq. (5) to account for these effects. This factor (Z) is further analysed by comparing Eq. (5) with the testing data and the regression analysis. It has been found that Z=1- 5/σ produced the best result with the coefficient of determination $R^2 = 0.9939$ as indicated in Fig. 8.

5. Conclusions

The laboratory testing has been carried out to develop a new type of porous concrete material using both quarry and recycled aggregates. Four types of quarry aggregate and recycled aggregate from sorted and clean waste concrete and masonry (RCM) were used and their performance was compared. It has been found that the dominate failure pattern using recycled aggregate (RA) was type 3 failure which was through aggregate. A higher cement ratio or admixtures will not increase the compressive strength of porous concrete using RA due to this type of failure. Therefore, RA may only be used as a base course material. The results also indicated that a higher compressive strength could be achieved using quarry aggregate with proper grading while still maintaining a good permeability. In addition, the type of coarse aggregate used in making porous concrete would influence the strength of porous concrete due to different particle shape and texture; the more flaky aggregate did not bond well with cement and result in lower compressive strength.

The relationship of compressive strength and porosity for porous concrete using recycled aggregate was also investigated. It is found that the existing model for porous concrete using quarry aggregate overestimated the compressive strength of porous concrete using recycled aggregate. A new parameter to consider the effect of recycled aggregate was introduced and the modified model could predict the compressive strength of porous concrete using recycled aggregate more accurate.

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