ADVANTAGES AND DISADVANTAGES IN USING PERMEABLE CONCRETE PAVEMENT AS A PAVEMENT CONSTRUCTION MATERIAL

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The management of environmental sustainability is of increasing importance to the construction industry and its management. One of the issues with respect to sustainability is the impact of urbanization, which results in the conversion of pervious spaces to areas of impervious (paved) surfaces, leading to a range of related problems. A solution is to use permeable concrete pavements, which can be an effective means of addressing a number of environmental issues and supporting sustainable development. Permeable pavements can facilitate biodegradation of oils from cars and trucks, help rainwater infiltrate into soil, decrease urban heating, replenish groundwater, allow tree roots to breathe, and reduce flash flooding. However, the long term behaviour of permeable pavement is still not well understood. Permeable concrete is a special structural concrete with the fine particles removed. This creates 15 to 20% voids. Thus, permeable concrete obtains more voids in the structure leading to higher water infiltration and air exchange rates compared with conventional concrete. However, a current constraint to the development of permeable pavements is their perceived lack of structural strength. This is caused mainly by the need for greater porosity for treatment purposes. This paper demonstrates that this material is not only an important contributor to sustainable practice, but that also it can, with proper mix design and targeted use of admixtures, achieve reasonable strength for use as a pavement construction material.

Keywords: asset management, civil engineering, material management, risk, sustainability.

INTRODUCTION

Environmental sustainability is a topic of increasing importance in the construction industry and its management. This growth of the importance of environmental sustainability in the industry is reflected, for example, in the increasing discussion of environmental issues in both academic and practitioner-oriented circles, and also in changing regulations and building codes (Department of Trade and Industry 2006). It is also taught in a number of engineering degree programmes. For example, the University of Southern Queensland teaches the "Technology, Sustainability and Society" course, which has a strong sustainability focus underpinning a range of environmental, economic and societal matters of importance to engineering practice, to all degree level engineering students (Thorpe 2009).

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Thus, there is a strong awareness of sustainable engineering and construction practices in both the construction industry and the engineering profession. While this awareness has translated into a strong focus by government on sustainable building and development (for example, Australian Building Codes Board 2005), it has not fully translated into certainty about its benefits within the construction industry. For example, there can be negative impacts of sustainable initiatives. They can be relatively expensive compared with traditional materials, and their life-cycle performance has not yet been fully tested. In addition, there can be environmental risks with some sustainable materials, such as potential leaching of contaminants from residual Portland cement binder in recycled concrete aggregate in road construction (Apul *et al.* 2003, Petkovic *et al.* 2004). Similarly, it has been found that while there is a trend towards sustainable construction practices, their role as a driver for innovation within at least the small and medium enterprise (SME) sector of the industry is not fully established (Thorpe *et al.* 2008).

It is against this backdrop of the recognition of the need for sustainable practices in design and construction management, and yet uncertainty within the construction industry about the degree to which sustainability is a significant issue, that the effective management of storm water runoff, particularly in urbanized areas, is considered. Permeable concrete pavements can be an effective means of addressing such issues (Balogh 2005). While permeable pavements can facilitate biodegradation of oils from cars and trucks, help rainwater infiltrate into soil, decrease urban heating, replenish groundwater, allow tree roots to breathe, and reduce flash flooding, their long term behaviour is still not well understood. One particular matter is the importance of good mix design and careful planning and execution of construction details (Tennis *et al.* 2004).

ISSUES IN SUSTAINABLE CONSTRUCTION

A common definition of “sustainable development” is that proposed by the author of the 1987 report of the World Commission on Environment and Development, which defines this term as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland 1987: 54). Such a definition represents a significant challenge for construction management in its endeavours to sustainably develop the world for the benefit of human beings, and reduce the impact of construction activities that as noted by Wallace (2005: 82) can significantly impact on waste, energy use and greenhouse gas emissions.

The importance of sustainable practices in construction is also being recognized by regulatory authorities. For example, the United Kingdom has implemented strategies for more sustainable construction (Department of the Environment, Transport and the Regions 2000: 8, 14-16, Department of Trade and Industry 2006: 100-103). Similarly, Australia has implemented new energy-efficiency measures for buildings (Australian Building Codes Board 2005). Sustainable practices and processes can also feature in contract selection, being claimed to reduce risk and increase the probability of obtaining value for money (Adjetunji *et al.* 2003).

When considering the impact of environmental sustainability on construction management, it is important to understand that the generally positive outlook discussed above should be tempered with uncertainty and potential risk. For example, the previously noted environmental risks with the potential threat of contaminants leaching from recycled aggregate used in road construction need to be managed.

LIFE CYCLE CONSIDERATIONS IN ROAD PAVEMENTS

Road pavements, which are a significant area of construction activity, are a particular class of engineering physical assets. According to the Australian Austroads peak road management organization, the life cycle of an asset may be broken down into the following components:

- identification of need for the asset, in the light of community requirements
- provision of the asset, including its ongoing maintenance and rehabilitation
- operation of the asset
- disposal of the asset at the end of its useful life (Austroads 2010).

Austroads (2010) also states that the elements of asset management are focused on facilitating the delivery of community benefits such as accessibility, mobility, economic development and social justice.

It has also been identified that engineering assets tend to serve a number of communities of interest (or stakeholders), and are usually closely linked with the environment of which they are part. Thorpe (1998) states that physical infrastructure assets (such as road pavements) are founded on the natural environment and support the economic environment and social environment. Such assets should meet the requirements of a number of stakeholders, such as the road owner, its users, and the community external to the road such as owners of properties that abut the road.

These communities, or stakeholders in the road, each have different requirements, which require optimization of a number of asset performance goals, such as the level of service at the required level of demand, functional serviceability (for example, ride standard), optimum service life consistent with balancing the maximum benefit over the life of the road and the minimum whole of life cost, and overall whole of life performance (Thorpe 1998). Meeting such requirements, along with delivering community benefits of the road in a sustainable manner, requires innovative approaches to pavement development that aids construction management through minimizing environmental and project risks while delivering a quality product.

USE OF PERMEABLE CONCRETE IN ROAD PAVEMENTS

One innovative approach to sustainable road pavement design and construction is the use of permeable concrete pavements. It has been observed that the growth and spread of impervious surfaces within urbanizing watersheds pose significant threats to the quality of natural and built environments. Such threats include increased storm water runoff, reduced water quality, higher maximum summer temperatures, degraded and destroyed aquatic and terrestrial habitats, and the diminished aesthetic appeal of streams and landscapes. The materials used to cover such impervious surfaces may effectively seal surfaces, repel water and prevent precipitation and other water from infiltrating soils. They also allow storm water to wash over them, thus generating large volumes of runoff followed by relatively dry conditions a short time later. Pollutants would also accumulate over such impervious surfaces (Barnes *et al.* 2000).

Permeable concrete pavement systems are claimed to help control the amount of contaminants in waterways, through reducing or eliminating runoff, and allowing treatment of pollution. Such treatment occurs as a result of capturing initial rainfall and allowing it to percolate into the ground, thus allowing soil chemistry and biology to "treat" the polluted water naturally. It is also claimed that through collecting rainfall and allowing it to infiltrate, permeable concrete allows increased groundwater and aquifer recharge, reduction of peak water flow through drainage channels, and minimization of flooding. It may also allow credits to be obtained in green rating scales for sustainable construction. Other claimed advantages of this material include less absorption of solar radiation because of the light colour of concrete pavements compared with darker materials, and less storage of heat because of the relatively open pore structure of permeable concrete. It is also claimed to better protect trees than other surfaces (Tennis *et al.* 2004).

It is claimed that the high flow rate of water through a permeable concrete pavement allows the capture of rainfall, thus reducing storm water runoff, recharging groundwater and supporting sustainable construction through controlling rainwater on-site and addressing storm water runoff issues. A permeable concrete pavement and its sub-base may provide enough water storage capacity to eliminate the need for retention ponds, swales, and other precipitation runoff containment strategies, thus leading to more efficient land use. (Tennis *et al.* 2004). It is also lightweight and has low-shrinkage properties. Permeable concrete has been used extensively for the construction of tennis courts in Europe, especially in France (Ghafoori and Dutta 1995). More recently, permeable concrete has been used to reduce noise resulting from the interaction between tyre and pavement (Neithalath *et al.* 2006). It was believed that the porous surface can minimize air pumping, while the pores inside the material also absorb sound energy through internal friction.

On the other hand, there are potential issues with permeable concrete pavement such as its potential to clog under certain circumstances with muddy runoff (Delatte *et al.* 2007: 15), and the importance of planning and executing with care their mix design and construction details (Tennis *et al.* 2004). This last factor, which is particularly important if permeable concrete is to be used for durable road pavements, is the focus of the research described in this paper.

ANALYSIS OF THE PROPERTIES OF PERMEABLE CONCRETE PAVEMENTS

The basic permeable concrete pavement system consists of a top layer of porous concrete covering a layer of gravel that covers a layer of uniformly sized aggregate, which is placed on top of the existing soil sub-base (Figure 1). Storm water penetrates the porous concrete and is filtered through the first layer of gravel. The voids in the lower level of large aggregate are filled with runoff. The stored runoff gradually infiltrates into the underlying soil.

The factors determining the design thickness of permeable concrete include its desired hydraulic (e.g. permeability and voids contents) and mechanical properties (e.g.

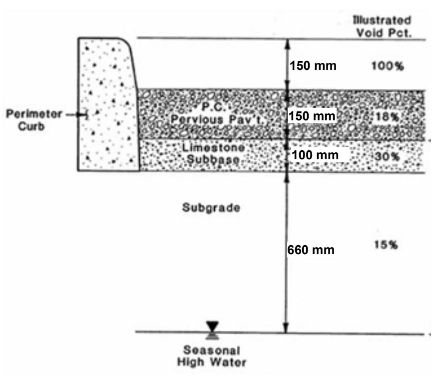

Figure 1. Schematic of a typical pervious concrete pavement section (Balogh 2005)

strength and stiffness). All of these have been extensively investigated through a series of laboratory testing and the major results are reported here (Zhuge 2008, Zhuge and Lian 2009). As it is noticed that not only the size of aggregate, but also the gradation and amount of aggregate will affect the compressive strength and static modulus of elasticity on porous concrete, the effect of various types of aggregate has been studied to establish the best local resource and then proceed to the design of optimal mix with various additives.

Materials

Aggregate is the major component in permeable concrete which covers approximately 80% in weight. The effect of aggregates will be the major factor in the strength of porous concrete. In general, gradation size for porous concrete aggregate would be much smaller compared with conventional concrete aggregate. In our research, recycled aggregates and three different kinds of quarry aggregate were used without fine aggregate and other admixtures in stage one. Sands and silica fume were applied to enhance the strength of porous concrete at the second stage.

Three types of coarse aggregate were obtained from local quarry: quartzite, dolomite and limestone. In order to explore the optimum aggregate for making porous concrete, these three types of coarse aggregate were investigated and compared at the first stage.

The recycled aggregates were produced primarily from demolition concrete, but also contain small amounts of crushed brick and tile. 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.

The results of previous research indicated that mineral additives could lead to the improvement of concrete properties such as mechanical strength and concrete durability, since the mineral composite reduced the thickness of the interfacial transition zone (ITZ) between the aggregate and the cement matrix. Therefore, silica fume, namely Microsilica 920-u, was tried to seek adequate strength of porous concrete at the second stage of testing. Besides, a new generation superplasticizer was incorporated as the chemical intensifier.

Testing procedures

The casted cylinders were demoulded after 24 hours, labelled and weighted for various testing. Then the samples were cured in a lime bath at 23±2°C, according to AS 1012.8.1-2000. 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 testing conducted include: unconfined compressive strength (UCS), water permeability and porosity.

The UCS testing of concrete specimens was carried out in the laboratory according to AS1012.9-1999. Prior to loading process, caps were placed on the ends of samples. The type of capping used depended on the 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. It was found that the compressive strength of the porous concrete would increase dramatically by use of the sulphur capping, as this capping restrained the aggregates on the top effectively (Figure 2).

Permeability as a unique ability for water to penetrate through porous concrete was expressed in millimetres per second (mm/s). Since porous concrete generally has 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 Standard 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 was developed as shown in Figure 3, where a cylindrical plastic pipe was used. With inline steel wire and adjustable steel tie, the pipe was tight to inhibit water leakage along the sides of the sample. 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.

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 in the concrete that can contain water.

Summary of testing results

The testing results on compressive strength at 28 days for different kinds of aggregate were obtained. On average of all test specimens, the compressive strength of recycled aggregate was much lower than quarry aggregate, around 2 MPa (Table 1). As indicated in Table 1, the testing results also show 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, a mix design with a small percentage of sand would be more economical.

For permeable concrete using single-sized quarry aggregate, the compressive strength could reach around 15 MPa while the samples were still having excellent permeability (Table 2), which was much higher than the minimum requirement of around 3 mm/s. Dolomite yielded the highest compressive strength, followed by limestone, and quartzite achieved the lowest strength. This indicated that the type of coarse aggregate affects the strength of porous concrete even though the aggregates were in the same size and gradation. This may be attributed to the difference of dry strength, particle shapes and textures of aggregate. Quartzite particles absorbed more water compared to other types of aggregates, which would make the cement paste around it less viscous to develop and showed the worst compressive strength. Dolomite would be regarded as the best aggregate for making permeable concrete.

As all samples showed a good permeability, some filler materials could be used to further enhance the strength of porous concrete.

Figure 2. Compressive strength testing rig

Figure 3. Permeability testing rig

Table 1: Mix design and testing results for recycled aggregate

Mix No	Aggregate (%)	Cement (%)	Water (%)	Sand (%)	UCS* (MPa)	Permeability (mm/s)	Void (%)
1A	85.0	5.0	6.0	4	2.24	20.7	33.7
1B	82.5	4.9	8.0	4	0.8	16.8	33.7
1C	84.2	5.0	5.2	4	**	15.7	31.8
2A	84.8	7.9	7.3	-	2.55	22.0	29.9
2B	83.9	7.9	7.5	-	1.29	22.3	31.2
2C	81.5	7.7	9.3	-	0.62	15.6	29.9

**UCS: unconfined compressive strength. **All specimens were too weak to be tested.*

Effect of Admixtures

The second stage of the research involved using chemical additives and fine aggregates to improve the strength of porous concrete. Dolomite was collected as coarse aggregate based on the testing results at stage one.

As indicated in Table 3, the testing results showed that samples made with additives exhibited higher strengths than the one without. Silica fume exerted a positive influence on compressive strength of porous concrete similarly to normal concrete. Technically speaking, when the silica fume is added, more water is demanded for wetting the large specific surface area of silica fume particles in a concrete mixture to keep its workability. Thus, if the same water/cement ratio was used for samples with and without silica fume, the one with silica fume normally experienced problem. As it was observed during the testing, some silica fume particles concentrated over a small region where the sediment and segregation were easily seen. Therefore, the benefit of using silica fume was not achieved without other chemical admixtures.

Through a series of trial and error exercises, it was found that by adding a small amount of superplasticizer (0.8%) to the mixtures containing silica fume, both the workmanship and the compressive strength of the samples were improved extensively.

With the assistance of silica fume and superplasticizer simultaneously, fine aggregate could be utilized to achieve a higher strength. The quarry sand (S2) could promote the development of cement hydration product, which would reduce the capillary pores in cement matrix during the 28-day curing and then achieved a dense microstructure, showing a higher compressive strength of 33.2 MPa. In contrast, the smaller sized dolomite particles (S1) could not bridge the crystallized hydrated cement to form more paste to increase the bonding strength. Therefore, the use of quarry sand was more effective than that of fine dolomite particles.

Failure mechanism

To obtain a better understanding of permeable concrete, the testing specimens were carefully investigated and three failure mechanisms have been observed. They 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).

Table 2: Testing results for quarry aggregate

	A1	Quartzite A2	B1	Dolomite B2	B3	C1	Limestone C2
Compressive Strength (MPa)	11.8	15.5	15.8	19.0	15.5	15.5	14.0
Permeability (mm/s)	27.5	13.7	19.9	8.51	14.8	13.3	16.0

Table 3: Testing results for quarry aggregate with various additives

Batch No	W/C	Fine aggregate	SF (%)	SP (%)	Density (kg/m3)	UCS (MPa)	Permeability (mm/s)	Porosity (%)
B2	0.36	0	0	0	1926	19.0	8.51	16.6
B4	0.36	0	10	0	2012	22.0	6.13	13.2
B5	0.28	0	7	0.8	2079	24.3	12.64	16.0
B6	0.32	S1	7	0.8	2140	30.0	5.39	9.0
B7	0.36	S2	7	0.8	2248	33.2	3.98	7.50

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 permeable concrete material using dolomite tends to have more type 2 failures. Although the dry strength of dolomite is high, the smooth surface of dolomite decreased the interfacial bonding. Using additives as discussed in the previous section will improve 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. 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 failures. Therefore, recycled aggregate may only be used as a base course material for permeable pavements.

DISCUSSION

Permeable concrete pavements have a number of advantages with respect to sustainable construction and its management. In particular, they have considerable potential to manage runoff from urban landscapes, treat through natural biological processes runoff water, manage heat, facilitate the growth of trees and manage pollution. They also have the potential to reduce noise resulting from the impact of tyre and pavement, and may allow credits to be obtained in green rating scales. These advantages mean that they are able to facilitate sustainable construction processes, and so assist the construction industry better respond to global sustainability challenges.

One important construction management issue is the need to ensure quality of the finished product through careful concrete mix design and the construction process. This paper has addressed one aspect of this quality management process – the strength of permeable concrete pavement material. Testing of this material has demonstrated that with good mix design, good aggregate selection, addition of selected mineral and chemical additives that increase bonding strength within the material, that permeable concrete pavement of compressive strength up to 30 MPa with acceptable permeability can be obtained.

From the construction management point of view, disadvantages include the need to design the pavement, mix and construction process well to ensure maximum strength and bonding; and, because of their lower strength compared with other aggregates, to limit recycled aggregates to at best a base course material.

Apart from the need to undertake tightly specified and well quality controlled mix design and placement, and close attention to placement of materials used in permeable concrete pavements, a potential disadvantage with permeable concrete pavements is their ability to being able to manage clogging issues like muddy water. This potential disadvantage requires further research. In addition, given the risks previously identified in this paper with potential leaching from binder material in recycled concrete aggregate with respect to normal road pavements, further research in minimizing this risk is required.

CONCLUSION

Overall, through its ability to minimize risk to the natural environment on which roads are constructed, particularly in urban areas, permeable concrete has good potential to make a positive contribution to sustainable road construction and life cycle management. It can meet stakeholder requirements through less impact on the environment on which roads are constructed, and therefore can assist the construction industry to move closer to sustainable construction management. The major issue that needs attention is the need to closely apply quality management to pavement and mix design, and concrete placement. More research is required to better manage its disadvantages, such as the possible potential to clog under certain circumstances and to minimize any leaching effects into the environment from binder material.

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