Water pervious concrete pavement blocks: durable structures for an integrated water policy

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Abstract

Water pervious pavement blocks are a durable and ecological solution to prevent water run off, to minimize the risk of flooding and to increase the efficiency of water purification.

The application of water pervious pavement blocks on a permeable base and/or sub base allows buffering of the rainwater in the structure and infiltration or retarded outflow to the ground or infiltration system.

This paper presents the results of a research project, conducted at the BRRC during 4 years. The efficiency of water buffering and infiltration in relation to the choice of material is investigated in the laboratory, on a test parking lot and on site. To allow a good choice of the materials and the application site and to control the efficiency on site, different test methods are optimized. Results for different types of concrete pavement blocks (pervious blocks, blocks with enlarged joints or drainage holes), different types of base layer (hydraulic bounded or unbounded materials) and different types of sand layer and jointing materials are looked at. Finally this paper focuses on several applications in Belgium, where measurements have shown a good behavior of the structure and a good durability of the permeability. Data from newly constructed projects, as well as projects in use for more than eight years are presented.

Key words: water pervious structures, pervious concrete pavement blocks, permeability test methods.

Introduction

Water-permeable paving is used to minimize the far-reaching adverse effects produced by sealing off the natural water balance. The risk of flooding during thunderstorms by water running off the surface or by overflow from sewer pipes is strongly reduced by the immediate absorption and subsequent storage of water in the permeable structure. A research project funded by the Flemish Government (through IWT[1]) was undertaken to model the permeability and storage capacity of water permeable structures and to optimize the preservation of permeability.

[1] IWT[1], the Institute for the Promotion of Innovation by Science and Technology in Flanders.

This project includes laboratory tests on the paving material as well as on the base and sub base materials, and field tests on soils and water-permeable pavings. In addition, a parking area with twelve different sections (each 120 m² in area) was constructed on the premises of the Belgian Road Research Centre to test five different types of water-permeable concrete paving block and two different types of base layer. Furthermore, the water permeability of existing and new permeable pavings in Belgium was measured and monitored over time. The Belgian Road Research Centre, the Laboratory for Soil and Water Management of the Katholieke Universiteit Leuven and the federation of Belgian manufacturers of linear and modular paving elements in concrete (FEBESTRAL) were joint in this project.

The permeable paving concept

The concept of water-permeable block paving differs in at least one important respect from that of conventional paving. Whereas in the case of conventional paving water is banned from the structure as much as possible, it is supposed to enter the structure in the case of permeable blocks. It is retained for a certain time, after which it has to leave the structure by infiltration into the ground or by drainage – preferably into a ditch or rain water sewer. As far as structural design is concerned, the rules for conventional block paving have to be followed, with due allowance for the lower bearing capacity that results from the higher porosity of the base layer and the paving and, consequently, for the lower resistance to traffic.

The working principle of water pervious pavement blocks is as follows: the pavement blocks themselves make the water pass through the surface and prevent water run off. The storage of the water is done at the bottom of the structure in the base or sub base layer. This is in favour for the bearing capacity of the structure since the pumping effect which could occur at the surface of the structure in the presence of water and traffic is as much as possible avoided. The evacuation of the water is done by infiltration or by drainage or by a combination of both. From the environmental point of view, infiltration into the soil is desirable, unless the paving structure is situated in a water collecting area.

The most suitable sites for water-permeable paving are shopping areas, company grounds, car parking areas, footways, squares, etc., where large surface areas are subjected to limited or light traffic. Hydraulically speaking, water-permeable pavements are designed to be able to absorb the rainwater from a shower which occurs only once in thirty years for a duration of ten minutes, Belgium statistics indicate this is a rain shower with an intensity of 270 litres per second per hectare. An initial permeability of $5.4*10^{-5}$ m/s is required (safety factor 2), to compensate for the fact that the permeability of the structure may be reduced by air enclosures or by clogging at the surface.

Carefully chosen materials are a prerequisite for a permeable paving structure to work well. The foundation can be made of unbound materials. Important is to find a good agreement between permeability and stability. Stability can only be obtained by a good compaction of the material on site, which requires more energy and time if a discontinuous aggregate is used. In this case the compaction can be made with a vibration plate. It is also possible to use cement-bounded materials in the base layer – for example porous lean concrete, which combines high permeability ($4*10^{-4}$ m/s) with relatively high strength (13 N/mm² on cores). To ensure the stability of the structure, contamination between layers must be prevented, if necessary by separating them with a geotextile.

To avoid silting of the structure, it is advisable to start with a relatively fine material at the top and to use more porous materials at the bottom. The top layers will then operate as a sort of filter for the bottom layers in the way that if a small particle passes through the surface, it will not be blocked before it reaches the soil.

Design criteria and decision tree

To come to an optimum design, different stages have to be looked at, starting from the soil and the necessary drainage system to the choice of pavement blocks over the material and dimensions of the sub base and base layer.

Following decision tree, figure 1, gives the different steps: first the drainage system is determined in function of the soil permeability [Shackel]. In the next step, the thickness of the base layer and type of material is fixed in relation to the traffic on the structure. Consequently the thickness of the sub base layer is determined or by the resistance of the soil towards freezing, or by the necessity on extra buffering capacity of the structure. The maximum of both thicknesses is taken. Finally, a choice of pavement blocks is made and with this, the choice of joint filling material and base layer material. It is possible that a geotextile has to be added to the structure in order to avoid infiltration of one layer into the other. This is the case if drainage lean concrete is used.

Measurement techniques

The goal of the research project was among others the elaboration of reliable test methods in order to facilitate the choice of materials and to obtain a good control method. Test methods used in the laboratory (column test) as well as on site (open-end test and double ring test) were defined. Furthermore, the buffering and infiltration capacity was determined for different types of unbounded base and sub base layers on a test parking lot.

General design of the test parking area

A detailed description of the test parking area can be found in previous publications [Beeldens, 2007]. Twelve different test sections (of 120 m²) were tested, with 2 different base and sub base layers (porphyry 2/20 on sand stone 7/32 or sand stone 0/32) used. Five types of pavement blocks were applied: classic pavement blocks – pervious pavement blocks – blocks with enlarged joints – blocks with drainage holes and grass tiles. Table 1 gives an overview of the various combinations of sub base layer, base layer, sand bed and joint filling material. Additional demands were made on the amount of fine material and on the quality of the aggregates, the latter to prevent rapid contamination of layers by the abrasion of stones.

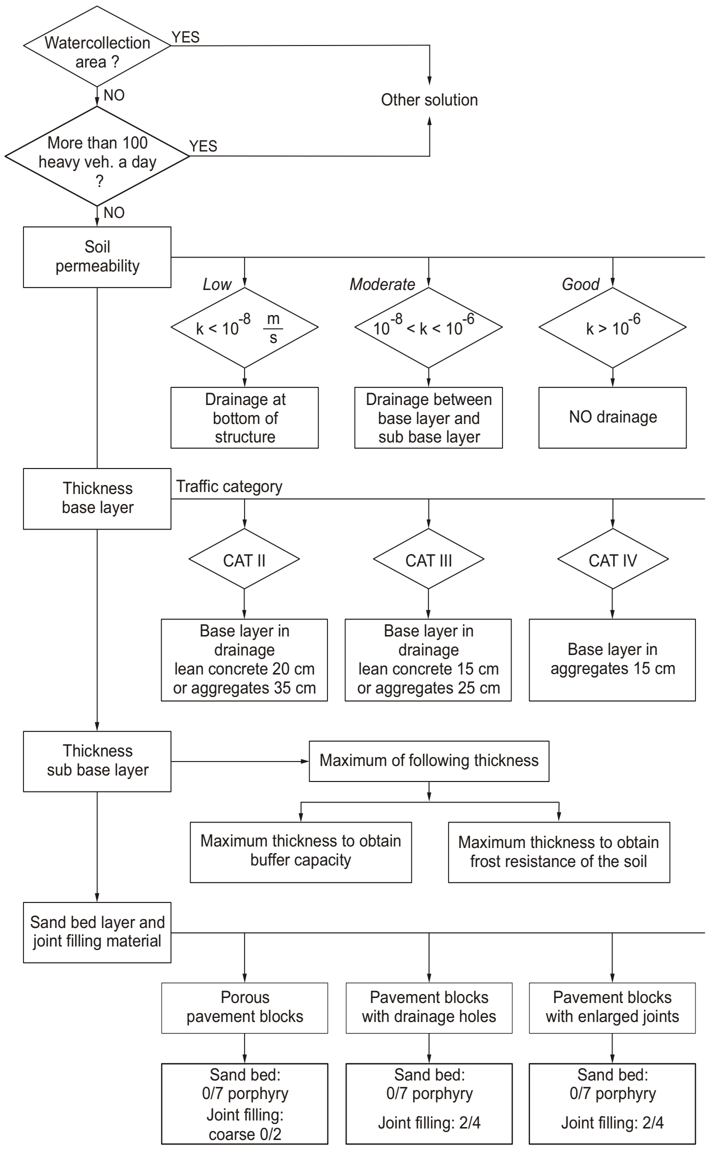

Figure 1 - Decision tree to design the structure of water pervious pavements

Table 1 gives an overview of the different components and the materials used for each of the twelve testing lots.

Table 1. – Overview of the design of each of the testing lots

test site no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
block paving												
conventional	.	.	.	.	.	.	.	.	x	x	.	.
drainage holes	x	.	.	.	.	.	.	x	.	.	.	.
enlarged joints	.	x	.	.	.	.	x	.	.	.	.	.
pervious	.	.	x	x	x	x	.	.	.	.	.	.
grass tiles	.	.	.	.	.	.	.	.	.	.	x	x
joint filling												
0/2 sand of Lustin	.	.	x	x	x	x	.	.	x	.	.	.
white sand	.	.	.	.	.	.	.	.	.	x	.	.
2/4 crushed porphyry	x	x	.	.	.	.	x	x	.	.	.	.
sand & peat	.	.	.	.	.	.	.	.	.	.	x	.
sand & humus	.	.	.	.	.	.	.	.	.	.	.	x
street layer												
2/7 crushed limestone	.	.	.	.	.	.	.	.	x	.	.	.
0/7 crushed porphyry	.	.	x	x	x	x	.	.	.	x	.	.
2/7 crushed porphyry	x	x	.	.	.	.	x	x	.	.	x	x
+ sand & peat	.	.	.	.	.	.	.	.	.	.	x	.
+ sand & humus	.	.	.	.	.	.	.	.	.	.	.	x
Geotextile	.	.	.	x	x	.	.	.	.	x	x	x
base layer												
0/32 crushed limestone	.	.	x	.	.	x	x	x	x	.	.	.
2/20 crushed porphyry	x	x	.	x	x	.	.	.	.	x	x	x
subbase layer												
7/32 crushed limestone	x	x	.	x	x	.	.	.	.	x	x	x
impermeable membrane	x	x	.	.	x	x	x	x	x	x	x	x

The joint filling material and the sand bed were chosen in relation to the type of paving block. With porous paving blocks, water can pass through the block itself; therefore, the joints were filled with a less permeable material (a rough 0/2 (mm) sand) to increase the stability of the paving. The surface through which water can pass is also larger; for that reason, a less permeable aggregate was chosen for the sand bed as well (0/7 mm). In the case of paving blocks with drainage holes and widened joints, the filling material has to be permeable. Since the surface available for water to enter the structure is smaller (min. 10 %), a more permeable sand bed was chosen in this case (2/7 porphyry).

Figure 2 shows the cross sections of the structure with porous concrete blocks, for both types of base layers. The designs with other paving blocks are similar, with adapted paving beds and joint filling materials. An impermeable membrane was applied at the bottom and to the sides, to catch all the water entering the test section and measure its flow rate at the outlet of the drain tube laid on the bottom of the section. The outlet of the tube was arranged by two fine tubes in order to be able to measure also the influence of small rains. These outlets are comparable to an infiltration rate of $1*10^{-7}$ m/s.

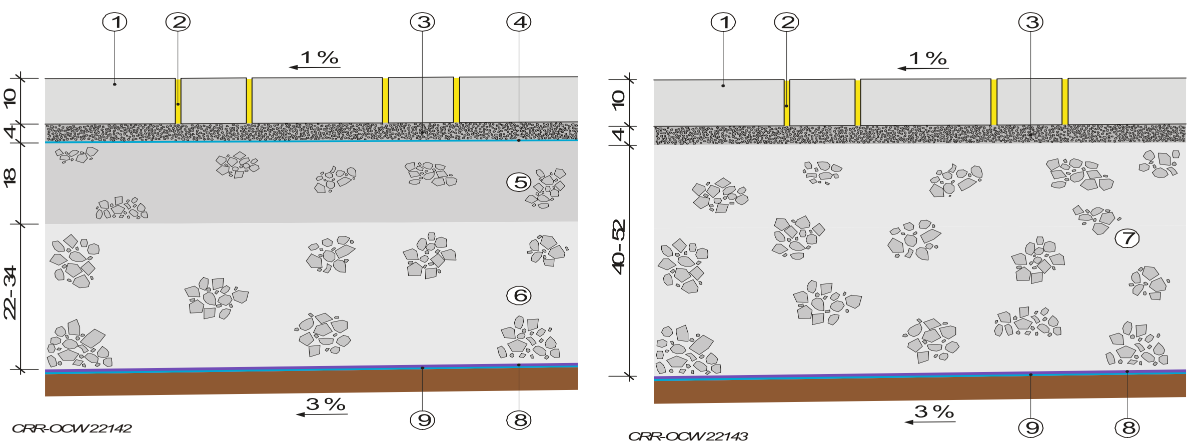

Figure 2 – Cross sections of the structure with porous concrete paving blocks
LEGEND:

1. Porous concrete paving blocks 122 x 100 x 100 mm	100 mm
2. Joint filling material: sand of Lustin 0/2	
3. Sand bed: porphyry 0/7	40 mm
4. Geotextile	
5. Crushed porphyry 2/20	180 mm
6. Crushed limestone 7/32	220-340 mm
7. Crushed limestone 0/32	400-520 mm
8. Protective sheet	
9. Impermeable membrane	(only for test sections)

The height of the structure was calculated in order to prevent frost in the loam soil. The slope at the surface was taken equal to 1 %. This is easier for the contractor to apply than 0 % and gives also a more aesthetic result by avoiding different shadows. At the bottom of the structure, a slope of 3 % was taken to facilitate the water to run off to the drainage pipe. In addition to the ten zones on the main parking, two test sections were constructed with grass grid tiles, to investigate the influence of the amount of humus in the upper layer on the growth of grass. Figure 3 presents an overview of the actual parking area, as well as a view on the outlet at the bottom of the structure.

Figure 3 – Test parking lot and measuring device at the bottom of the structure

The storage capacity of the base layer depends on the thickness of the layer and on the permeability of the material. It is important that fine particles and sand particles are avoided as much as possible to obtain a permeable base layer. On the other hand, the lack of fine material will hamper the compaction of the layer to a large extend. The use of different compaction equipment, such as a vibration plate can lead to good results where a drainable structure is obtained with a good mechanical resistance.

Measurement techniques

In the project, different measurement techniques were used. In the laboratory, the permeability of different types of material (aggregates, porous lean concrete, pavement blocks,…) was tested. This was done in saturated conditions by the column test.

On the test parking area, measurements on the outflow were carried out. The water was collected at the bottom of the structure by an impermeable membrane. A restricted outflow was placed on the drainage tube in order to be able to measure small flows as well as important flows. This also simulates the conditions where no infiltration in the ground is possible and water has to be retarded at the outflow before it is drained away to other infiltration unites. Through these measurements, a good knowledge of the storage capacities of permeable paving structures and of the importance of the different properties of the materials was obtained. A very limited runoff at the surface was detected, even during heavy thunderstorms.

In addition to the measurements performed in the laboratory and on the test sections, field measurements are carried out in various places in Belgium. The sites are mostly parking areas for cars, or pedestrian access roads. The surface areas vary between a few hundred to several thousands of m². To assist the engineer in designing the permeable paving, two different types of measurement are made. First, the permeability of the soil is measured by means of an "open-end" test [US Department, 1963]. An overview of the measuring set is presented in figure 4. Secondly, the permeability of the permeable structure is measured by means of a "double ring" infiltrometer [Borgwardt, 2001]. Measurements with the double ring infiltrometer are made after the structure has been built and can be used as control on the work of the contractor in combination with laboratory measurements on the material itself. During the project, the measurements at the surface are repeated over time, to reveal changes in permeability. Figure 5 shows a double ring infiltrometer set up for measurement.

Figure 4 – Open-end test

Figure 5 – Double ring infiltrometer

Measurement results

Storage capacity

Measurements of the storage capacity by blocking the outflow of the different pavement sections indicated a good correspondence between the porosity of the materials and the height of the water in the structure, figure 6. However, if the water was poured in large quantities on the surface (up to 20 l/s per m²), some air entrapment occurred caused by the fact that no infiltration or drainage at the bottom was possible. This effect was limited under normal thunder storm conditions.

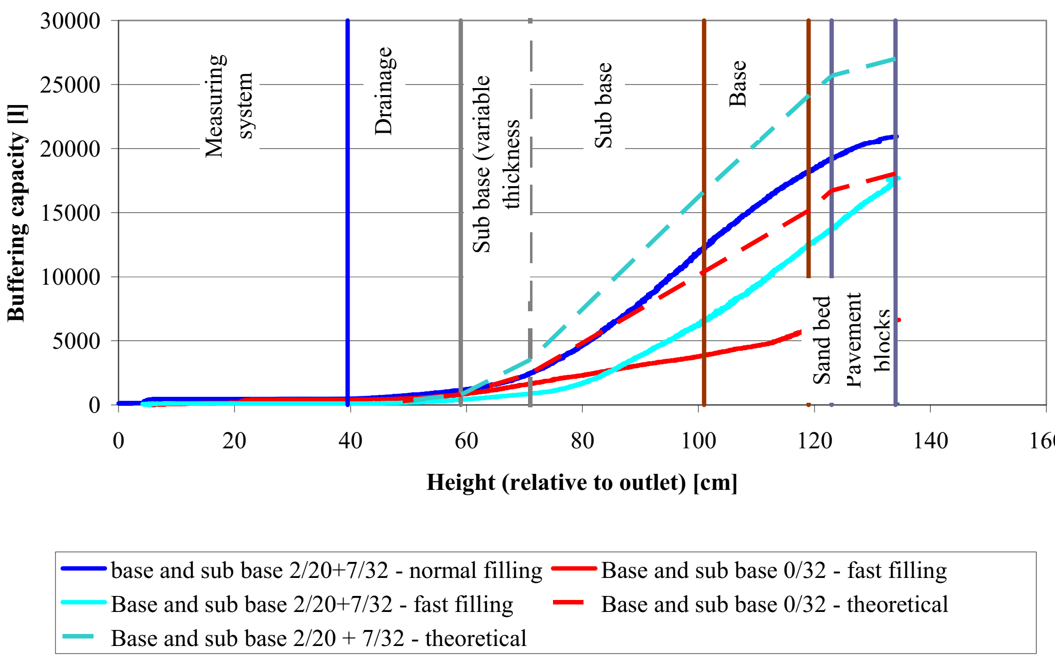

Figure 6 - Storage capacity in the different layers of the pervious structure

The results indicate that the storage capacity is not related to the type of permeable pavement block, but rather to the type and thickness of base and sub base layer. The permeable pavement blocks determine how fast the rain water penetrates into the structure and consequently if any run off of the surface will take place during larger thunder storms.

Figure 7 shows the height of the water in the structure under real conditions, with an outlet limited to 7 l/min for 120 m² (=10 l/s/ha). As can be seen, the water almost never entered the base layer, even with rains up to 260 l/s/ha. Figure 7 also indicates the influence of the intensity of the rain. With heavy rains, the height will be much higher and the infiltration during the rain is less, if the rain falls down over a longer period or if only a small amount of water is falling, the height will be much less and infiltration will take part during the rain.

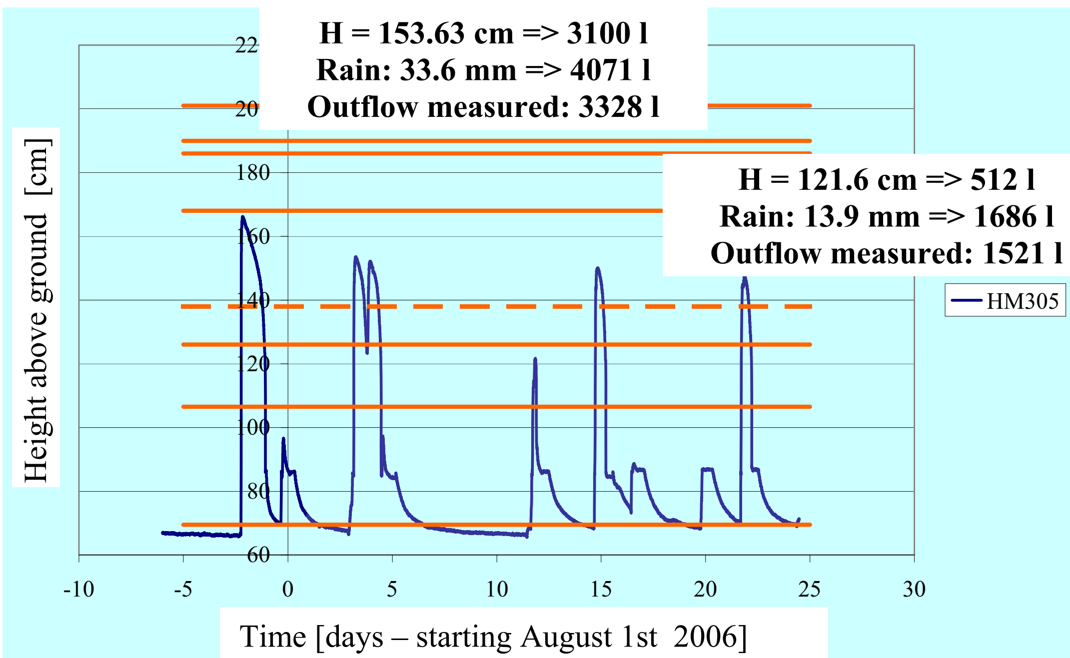

Figure 7 – Actual height of the water in the structure during rainfall

The results also indicated a good retarding capacity by the structure. A small outflow during the thunderstorm itself (around 10 % of the water) was measured, 50 % of the water came out during the 5 to 6 hours following the rain and the other 40 % slowly dropped down in the structure and came out during the following days. The difference in material was visible by the time the water needed to reach the bottom of the structure. This was slightly longer in the case of 0/32 base material.

On the other hand, there are neat differences in surface permeability as measured with the double ring test. The results are shown in table 2. In some cases the quantities to be measured were outside the range of the device. These measurements have been done over a 3 year period. The results of the measurements just after placing and of those done after 3 years in service are given in table 2. As can be seen, little changes in surface permeability of the porous pavement blocks have been noticed. For the pavement blocks with enlarged joints and with drainage holes, a reduction in surface permeability has been noticed, but it still remains more than sufficient to take the design rain.

Table 2: Surface permeability measured by the double-ring test, just after placing the test parking (top) and after three years in service (bottom).

	[7/32-2/20]	[0/32]
Drainage holes [sections 1/8]	> $4*10^{-4}$ m/s $5*10^{-4}$ m/s	*$3*10^{-3}$ m/s* $5*10^{-5}$ m/s
Widened joints [sections 2/7]	> $4*10^{-4}$ m/s $8*10^{-4}$ m/s	*$1.9*10^{-3}$ m/s* $5*10^{-5}$ m/s
Porous paving blocks without membrane [sections 4/3]	$1*10^{-4}$ m/s $3*10^{-4}$ m/s	$1*10^{-4}$ m/s $3*10^{-4}$ m/s
Porous paving blocks with membrane [sections 5/6]	$2.6*10^{-4}$ m/s $5*10^{-4}$ m/s	$8*10^{-5}$ m/s $3*10^{-4}$ m/s
Conventional paving blocks [sections 9/10]	< $2.4*10^{-5}$ m/s	

The obtained retention times and flows are to a large extend function of the geometrical parameters of the structure and the materials used. There is the influence of the size and positioning of the outlet, the height of the different layers in the structure and the porosity and permeability of the materials used in the drainage pipe, the sub base and base layer and in the sand bed. In the case of the test zones, the maximum flow at the outlet is equal to 3.5 l/h/m², which would be similar to a soil with a permeability of $9.7*10^{-7}$ m/s. The total height of the structure is 65 cm. This enlarges the storage capacity significantly but also protects the under laying soil against frost.

Field measurements

Approximately 50 projects are surveyed. The majority were under construction or newly constructed. The permeability of the soil as well as the surface permeability was measured, by the open-end-test and the 'double ring' method respectively. The soil mostly consisted of sand, which has a permeability ranging from $1.2*10^{-5}$ m/s up to $4.5*10^{-4}$ m/s and is, therefore, very suitable for infiltration.

An interesting case study will be highlighted here. It is a parking lot situated in Kortenberg (near Brussels) from a car distributor D'Ieteren (Volkswagen, Audi and Skoda). Over 4000 places are foreseen on 70.000 m². In principle only cars will enter this parking lot. The parking lot was placed in an area sensitive to flooding.

To avoid any risk of flooding, drainage trenches were made into the sand layer beneath the loam soil. To minimize the risk of deformation on the heavy trafficked roads between the parking lots, the roads were realised in coloured concrete. Each section of the parking lot had a specific colour to facilitate the use of the parking lot. An overview is given in figure 8.

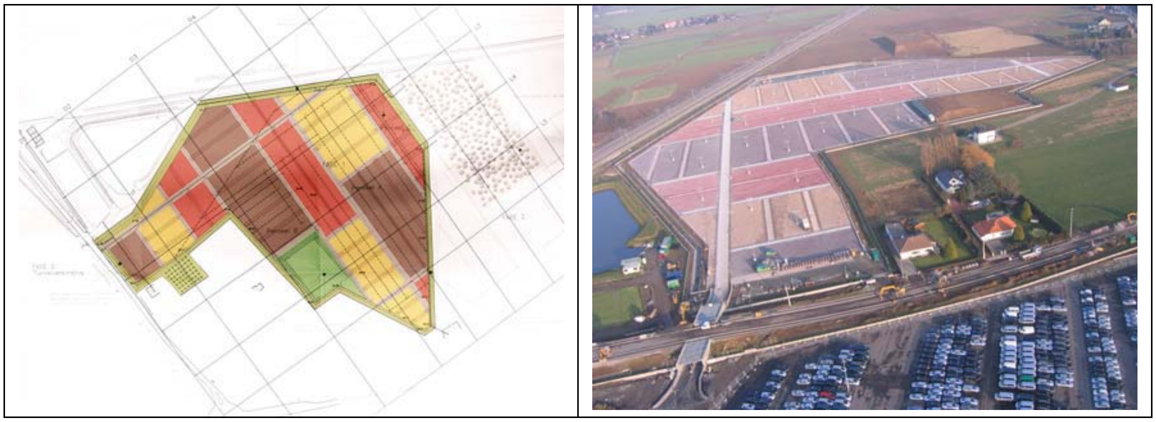

Figure 8 – Map of the parking lot at car distributor D'Ieteren as well as view during construction

Table 3: Field measurements in Belgium

Project	Surface permeability [m/s], measured according to the double ring-method
D'Ieteren parking lot at Kortenberg (2005-2007)	$9.1*10^{-3}$ m/s (soil permeability) $2.7*10^{-4}$ m/s (2005 – surface permeability)
Shopping Centre Waasland, Sint-Niklaas porous pavement block(2003)	$4,3*10^{-4}$ m/s (2003) $7,6*10^{-5}$ m/s (2005 without filling of the joints) $2,5*10^{-5}$ m/s (2005 with filling of the joints)
De Panne – parking zone with porous pavement block (1998)	$1,69*10^{-4}$ m/s (2004)
Zutendaal – parking zone with pavement blocks with enlarged zones (2004)	$1,03*10^{-3}$ m/s (2004)
Heist-op-den-Berg – parking zone (2000)	$4,4*10^{-4}$ m/s (2004)
Evergem – parking zone, metten[2] (2001), flodded by mud and consequently cleaned under high pressure	$2,38*10^{-5}$ m/s (2004)

[2] Type of stone.

For the permeable structure, a sub base layer of limestone 7/32 was used with a base layer porphory 2/20 on top. Since the compaction of the limestone 7/32 was difficult with the normal compaction gears, an additional amount of limestone 0/7 was added. During the second phase of the work however, a new high energy compaction plate was used by which the compaction of the 7/32 was possible.

Besides help to choose the optimal aggregate distributions, the BRRC carried out permeability tests with the double ring infiltrometer on the finished surface. The results are given in table 3.

By measuring the projects over time, a decrease in permeability is determined. The results indicate in most cases a very large permeability, just after construction. This permeability diminishes in time, but stabilizes around 2 to $5*10^{-5}$ m/s.

Conclusions

The results from the project indicate good storage capacity for structures with water-permeable paving blocks. The difference between the various types of concrete paving block lies in the immediate infiltration rate at the surface during rainfall. On the other hand, storage capacity depends mainly on the type and thickness of the base layer and the rate of infiltration into the ground. A compromise between water-accessible porosity (to promote water permeability), compaction properties and bearing capacity (to resist traffic) has to be sought at all times.

Aggregates 0/32 mm with a restricted amount of fines offer a good solution. Porous lean concrete may be used in the case of higher solicitations.

The project comprises laboratory tests, elaborated measurements on the test sections, and field tests on water-permeable paving in various places. The results indicate good permeability, immediately after construction as well as after a longer period; no surface run-off, even during thunderstorms; and long retention times in the structures, depending on restrictions put on the rate of outflow by narrowing the drain tube or by slow infiltration into the ground. Continuous measurements on the test sections and repeated field measurements are made, and indicate a diminishing but sufficient surface permeability over time.

Water pervious structures offer a good alternative as infiltration system. The results indicate a good buffering capacity, infiltration or retarded drainage possibilities, depending on the type of soil. Important is to provide a whole structure, which is permeable. This prevents water run off, allows storage of the water in the base or sub base layer and drainage trough infiltration in the ground or by restricted outflow.

Future research

Following this research project, the BRRC has started a technical support project, in which technical support during design, execution or after construction is offered as well as result dissemination by leaflets, state-of-the-art publications and follow up of the projects is foreseen.

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Experimental Study on Pervious Concrete

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ABSTRACT
Due to its excellent air and water permeability, pervious concrete has become an environmental friendly material in paving application, providing its benefits in reducing the runoff water, enhancing pavement skid resistance by rapid drainage of water, and reducing pavement noise. However, its high porosity and low strength limit its popularity. Based on the concept of pervious concrete, a mix design approach especially for pervious concrete was proposed and an experimental study was undertaken to produce high performance pervious concrete by using gap-graded coarse aggregates and adjusting cement content. The results indicated that pervious concrete with compressive strength up to 33.5 MPa and permeability coefficient of 6 ml/min can be obtained by using this mix design approach. The results also showed that for pervious concrete made with gap-graded aggregates, the strength increases, and the permeability coefficient decreases with the decrease of the aggregate size. There is an optimum content of cement used to coat the coarse aggregates, enhancing the cement-aggregate interface bonding and overall performance of pervious concrete.

Key words: Pervious concrete, gap-graded coarse aggregates, penetration coefficient

Introduction

Pervious concrete began its earliest application in Europe in the 19th century because it uses less cement than conventional concrete. Especially after World War II, cement became scarce and pervious concrete became the best material for housing construction in the world except America. Until the 1970's, pervious concrete was introduced to the United States. Its use began not as a cheaper substitute for conventional concrete, although that was an advantage, but for its permeability characteristics. The problem encountered in America was that of excessive runoff from newly constructed areas. Because of the lack of water permeability and air permeability of the conventional concrete pavement, the rainwater is not filtered underground. This had a negative impact on environment, causing some problem such as the phenomenon of hot island in city, water erosion and degradation in the quality of water.

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Even though pervious concrete is the cost and complexity of it compared to conventional pavements, it is being used more frequently due to its benefits in reducing the runoff water, improving water quality, enhancing pavement skid resistance during storm events by rapid drainage of water, and reducing pavement noise (Chopra et al. 2007, Schaefer et al. 2006, Ghafoori 1995, Haselbach and Freeman 1996).

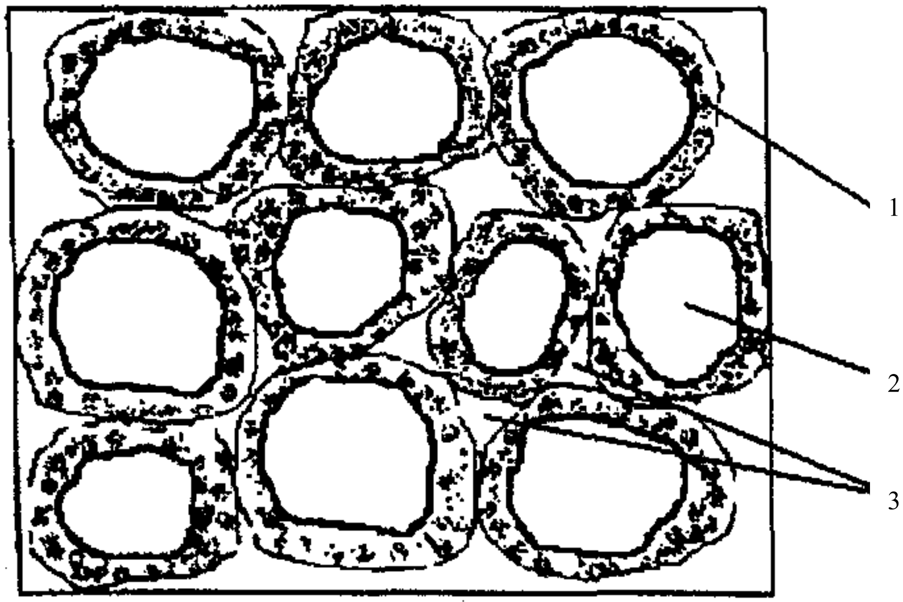
The advantages of pervious concrete relate to its permeability, which depends on the connected voids inside concrete. Since voids are supposed to reduce the strength, many researches have been taken to find a balance between water, aggregate, and cement in order to increase strength and permeability, two characteristic which tend to counteract one another. In 1976, Malhotra (1976) conducted multiple experiments on the effects of various materials properties on the strength of pervious concrete. Later, similar research was conducted by Meininger (1988), apart from the relationship between materials properties and compressive strength of pervious concrete, the relationship between air content and compressive strength was studied. Recently extensive studies were conducted by Ghafoori (1995) and Crouch et al. (2003), focusing on the correlation between compressive strength and compositions of the materials, such as the amount of water, amount of cement, type and size of aggregate. The similar conclusions that the compressive strength of pervious concrete was strongly dependent on the water cement ratio (w/c), the aggregate cement ratio, aggregate size, compaction, and curing were drawn by those researchers in the past 30 years.

Research significance

The strength of pervious concrete made is relatively low, and the pervious concrete can only be applied squares, footpaths, parking lots, and paths in parks. Most of studies are limited on discussing the affecting factors on compressive strength and there were few references on the mix design method by using the normal materials and the strength of pervious concretes, and concrete strength generally limits within 20 MPa. Hence, in this paper, based on the assumption that the single-diameter aggregate forms the concrete strength framework, a mix design approach specifically for pervious concrete was proposed. The effects of unit amount of paste, w/c and aggregate size on the compressive strength and penetration coefficient were discussed based on the experimental results.

Development of mix design approach for pervious concrete

Compared with traditional concrete, pervious concrete has less or no fine aggregates, which provides high porosity of concrete and allows water and air to pass through it. The coarse aggregate usually consists of a single size and is bonded together at its contact points with paste, as shown in Fig. 1 (Yang and Jiang 2003). It results in a concrete with a high percentage of interconnected voids that permits the rapid percolation of water and air through it. Unlike traditional concrete, pervious concrete can have void ratios ranging from 15 to 30% depending on its application. Therefore, pervious concrete has a lower compressive strength, higher permeability, and a lower unit weight (approximately 70% of conventional concrete). In order to produce a pervious concrete with optimum permeability and compressive strength, the amount of paste and aggregate size should be the concerns. On this basis, a mix design approach was proposed as followings:



1-covered coarse aggregate cement paste, 2-coarse aggregate, 3-pore

Fig. 1 Schematic model of pervious concrete

1) Determining the unit amount of aggregate. The first step is to determine the bulk density of coarse aggregate in compacted condition according to ASTM C29. Based on the assumption that coarse aggregate forms the strength framework of pervious concrete, the unit amount of coarse aggregate is the bulk density of aggregate in compacted condition.
2) Calculating the unit amount of cement paste. The unit amount of cement paste has to be optimum. The aggregate can not bind together when there is not adequate cement paste. If the amount of cement paste is too much, the permeability of pervious concrete will be reduced. A 1.0 mm thick of cement paste layer surrounding the aggregate surface is assumed to meet the above requirement. The unit amount of cement paste was calculated according to the equation:

$$M = k\frac{6h\rho_{cp}}{d\rho_g} \quad (1)$$

where,
M − the unit amount of cement paste,
h − the thickness of the cement paste surrounding the coarse aggregate,
ρ_{cp} − the density of cement paste,
ρ_g − the density of coarse aggregate,
d − the average radio of coarse aggregate; and

k − the correction coefficient, which normally ranges in 0.65-0.75 according to the size distribution and surface properties of coarse aggregate.

Experimental methods

Materials The cement used in this study was ordinary portland cement produced by Shanghai cement factory, with a 28-day compressive strength of 58.0 MPa. The fly ash (FA) was provided by Shanghai Wujing power plants. The chemical composition and physical properties of the cement and FA are given in Table 1. Crushed gravel with three size ranges were used as coarse aggregate, as shown in Table 2. A sulphonated naphthalene formaldehyde superplasticizer was used. Its density is 1.2 g/cm^3 and has 35% solid content.

Table 1 Chemical composition of mineral admixture

Chemical composition (%)	OPC	FA
Silicon dioxide (SiO_2)	21.6	54.9
Aluminum oxide (Al_2O_3)	4.13	25.8
Ferric oxide (Fe_2O_3)	4.57	6.9
Calcium oxide (CaO)	64.44	8.7
Magnesium oxide (MgO)	1.06	1.8
Sodium oxide (Na_2O)	0.11	0.3
Potassium oxide (K_2O)	0.56	0.1
Sulfur trioxide (SO_3)	1.74	0.6
Loss on ignition	0.76	0.2

Based on the mix design approach, the unit amount aggregate was determined according to the bulk density of aggregate in compacted condition, and the unit amount of cement paste calculated according to equation 1 ranges from 375 kg/m^3 to 540 kg/m^3. However, the amount of water and the w/c were adjusted according to the workability and strength of pervious concrete. The detailed mix proportion is shown in Table 3.

Table 2 Size ranges of aggregates used

	Sample		
	G_1	G_2	G_3
Size range (mm)	5-10	10-16	16-21
Bulk density in compacted condition (kg/m^3)	1560	1500	1445

Specimens fabrication, curing and testing Instead of following normal mixing sequencing based on ASTM C 192/C, a modified mixing method was applied. Ingredients used to fabricate concretes in Table 3 were mixed in a drum mixer, according to the following steps:

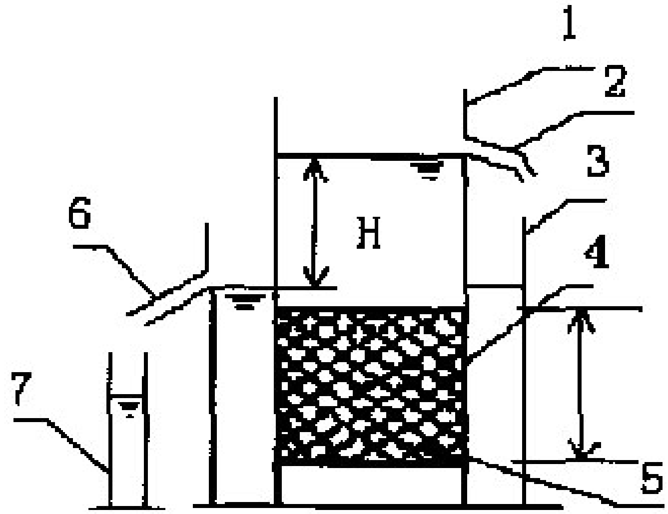
1) Adding coarse aggregates and half of total water to the mixer and mixing for 60 seconds,
2) Adding total cementitious materials to the mixer, and mixing for 90 seconds; and
3) Adding another half of the water and superplasticizer to the mixer, and mixing for another

120 seconds.

Two types of specimens were cast. The cubes with sizes of 150× 150 × 150 mm were used to measure compressive strength. The cylindrical specimens with diameters of 100 mm and heights of 150 mm were used for penetration coefficient test. After molding, specimens were pressed under the 1.0MPa of compressive stress. And the specimens were covered with plastic membrane to hold the moisture in concrete for 24 hours. Then specimens were demolded and keep in the curing room until the testing days. The temperature in the curing room ranged from 20 ^{o}C to 23 ^{o}C and the relative humidity was above 95%. Three specimens were cast for each type of test.

Table 3 Mix Proportion of concrete series

Series	Unit mass (kg/m^3)							Compressive strength /MPa	permeability coefficient cm/s
	Gravel			Cement	Fly ash	water	W/c		
	5~10 mm	10~16 mm	16~21 mm						
1	1560	/	/	270	30	75	0.25	24.0	2.02
2	1560	/	/	270	30	90	0.30	26.0	2.00
3	1560	/	/	270	30	105	0.35	24.5	2.15
4	1560	/	/	315	35	87.5	0.25	26.0	1.75
5	1560	/	/	315	35	87.5	0.30	27.5	1.80
6	1560	/	/	315	35	87.5	0.35	25.0	1.80
7	1560	/	/	360	40	100	0.25	33.5	1.45
8	1560	/	/	360	40	120	0.30	31.0	1.46
9	1560	/	/	360	40	140	0.35	28.6	1.50
10	/	1500	/	270	30	75	0.25	22.0	3.05
11	/	1500	/	270	30	90	0.30	23.0	3.11
12	/	1500	/	270	30	105	0.35	21.0	3.10
13	/	1500	/	315	35	87.5	0.25	24.0	2.72
14	/	1500	/	315	35	87.5	0.30	25.5	2.80
15	/	1500	/	315	35	87.5	0.35	23.5	2.85
16	/	1500	/	360	40	100	0.25	26.5	2.05
17	/	1500	/	360	40	120	0.30	26.0	2.10
18	/	1500	/	360	40	140	0.35	24.0	2.11
19	/	/	1445	270	30	75	0.25	19.0	3.25
20	/	/	1445	270	30	90	0.30	18.5	3.30
21	/	/	1445	270	30	105	0.35	17.0	3.33
22	/	/	1445	315	35	87.5	0.25	22.0	2.9
23	/	/	1445	315	35	87.5	0.30	21.5	2.95
24	/	/	1445	315	35	87.5	0.35	20.5	3.0
25	/	/	1445	360	40	100	0.25	23.0	2.76
26	/	/	1445	360	40	120	0.30	22.0	2.80
27	/	/	1445	360	40	140	0.35	21.5	2.85



1-columnar sheath, 2-overfall pipe, 3-orientation barrel, 4-permeable global barrel, 5-porous concrete, 6-pipe for water out, 7-measuring cylinder

Fig.2 Permeability testing equipment

Compressive strength test was carried out in a testing machine of 2000kN capacity at a loading rate of 2.5 KN/s. The water penetration coefficient (k_r) was measured with the device that was designed by authors. As shown in Fig.2, the cylindrical specimen has a diameter of 100 mm and a height of 150 mm. Above the specimen, the stable water level is kept at 12 cm high and k_r can be calculated by equation 2:

$$K_r = QD \Big/ AH(t_2 - t_1) \tag{2}$$

where,

k_r − the water penetration coefficient (cm/s),

Q − the amount water penetrate the pervious concrete during the time from t_2 to t_1,

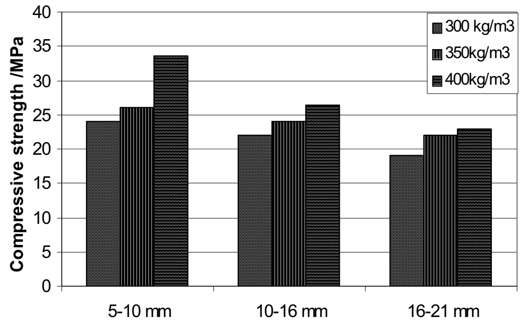
D − the thickness of the sample, and A is the surface area of the specimen,

H − the height of water level determined and here H is 12 cm, and

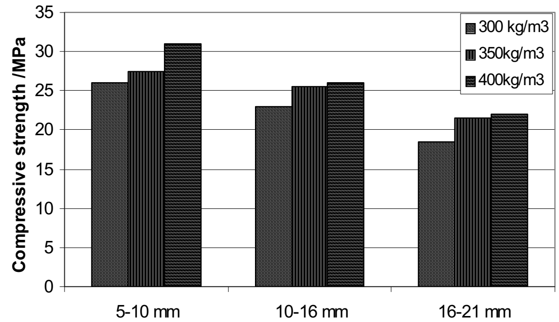
$t_2 - t_1$ − the testing time.

Results and Discussion

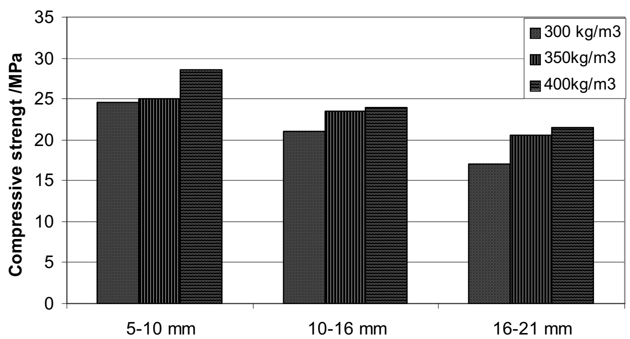
A comprehensive summary of testing results is presented in Table 3. From the table 3, it can be found that it is easy and economic to produce pervious concrete with compressive strength over 20 MPa and permeability coefficient over 2.0 cm/s by the proposed mix design approach, which can meet the requirement of engineering.



(a) w/c =0.25



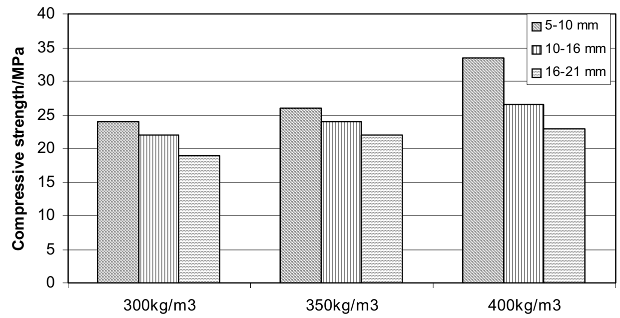
(b) w/c =0.30



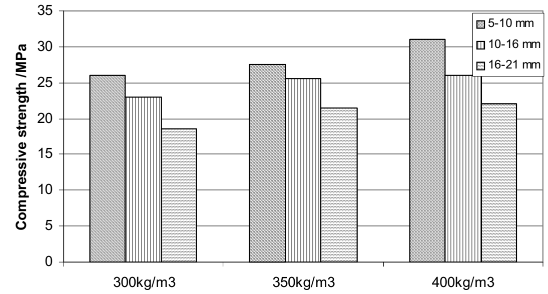
(c) w/c =0.35

Fig. 3 Effect of unit amount cement paste on the compressive strength of pervious concrete

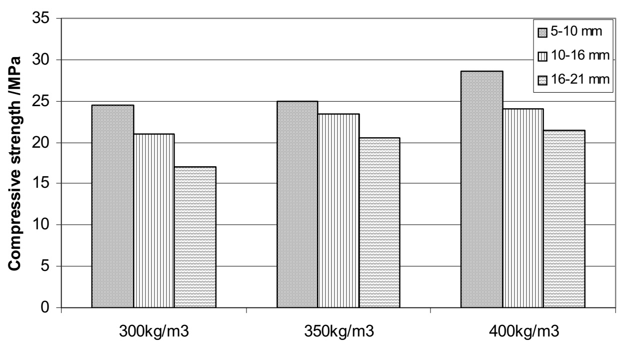
Compressive strength Fig. 3 shows the effect of unit amount of cement paste on the compressive strength of pervious concrete. It can be seen that the compressive strength of pervious concrete increases with the increase of amount of cement paste under the same w/c. The increment becomes small when w/c becomes large. The effect of w/c on compressive strength is related to the aggregate size when the unit amount of cement paste is same. The compressive strength increases with the increase of w/c when the aggregate size ranges in 5~10 mm and the unit amount of cement paste are 300 kg/m^3 and 350 kg/m^3. The compressive strength decreases with the increase of w/c when the amount of cement paste reaches 400kg/m^3. For the pervious concrete with larger coarse aggregate size, the increasing w/c results in the decrease of compressive strength. The main reason is that the total surface area of coarse aggregate is large when the aggregate size is small and it needs more cement paste to coat the aggregate. Therefore, the compressive strength increases with the increase of w/c when the unit amount of cement paste is small. The experimental results indicate that there exists an optimal amount of cement paste for a given w/c. Gap-size coarse aggregate forms strength framework of the pervious concrete and the contribution of cement paste is to bind the coarse aggregate together as an integer. As a consequence, the unit amount of the cement paste needed is the appropriate amount sufficient for coating the coarse aggregate surface.



(a) w/c =0.25



(b) w/c =0.30

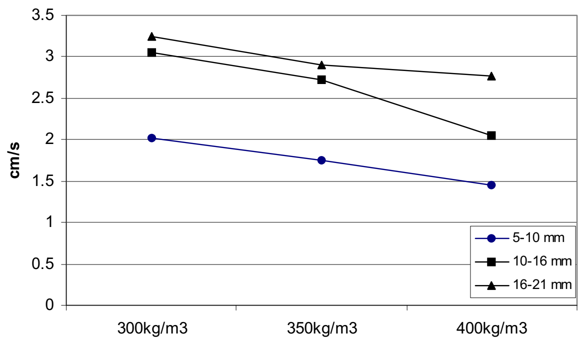


(c) w/c =0.35

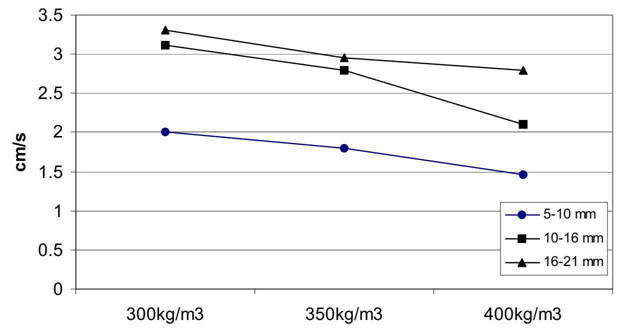
Fig. 4 Effect of aggregate size on the compressive strength of pervious concrete

The effect of aggregate size on the compressive strength of pervious concrete is shown in Fig. 4. It can be seen that the compressive strength of pervious concrete increases with the decrease of aggregate size under the same unit amount of cement paste and w/c. For pervious concrete with 400kg/m^3 of unit amount of cement paste and 0.25 of w/c, the compressive strength of pervious concrete with aggregate size of 5-10 mm is 45% higher than concrete with aggregate size of 16-21 mm. It indicates that the aggregate size has an important effect on the strength of pervious concrete. For pervious concrete, the smaller the aggregate size, the more dense compacted concrete and the higher the compressive strength. Therefore, in order to get high strength pervious concrete, the aggregate size should be controlled in a certain range.

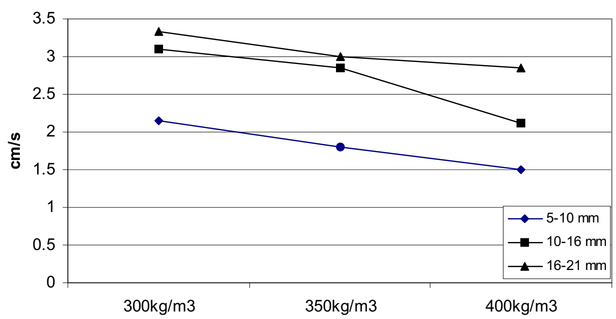
Water penetration coefficient Fig. 5 illustrates the effects of aggregate size and unit amount of cement paste on the water penetration coefficient of pervious concrete. From Fig. 5, it can be seen that the aggregate size affects the water penetration coefficient greatly. When the mix proportion is approximately same, reducing the aggregate size seems to decrease the water penetration coefficient. This may be attributed to the fact that the larger aggregate has



(a) w/c =0.25



(b) w/c =0.30



(c) w/c =0.35

Fig. 5 Effects of aggregate size on the water penetration coefficient

smaller unit surface area and the contact point between each other is less and the pore formed is large. For the concrete with same size of aggregate, the water penetration coefficient decreases greatly with the increase of unit amount of cement paste. When continually increasing the unit amount of cement paste, the rest cement paste will fill the void and block the pores. It is obvious that the water penetration coefficient increases with the increase of w/c, same as normal concrete.

Conclusions

Within the scope of this experimental research, the following conclusions can be drawn:

1) Based on the proposed mix design approach, pervious concrete with 28 days compressive strength 33.5 MPa and 1.45 cm/s of water penetration coefficient can be made by using gap-graded aggregate and common raw materials, which can meet the need of pavement engineering.

2) There exists an optimal unit amount of cement paste for suitable pervious concrete, which is enough for coating coarse aggregate surface with a thin layer of 1.0 mm.

3) For pervious concrete with gap-graded aggregate, using smaller size aggregate can enhance the strength, but reduce the water penetration coefficient. In order to benefit both, an

appropriate aggregate size range should be considered.

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