HYDRAULIC CONDUCTIVITY AND MATERIAL PROPERTIES OF
PERVIOUS PAVERS WITH SPECIAL UPPER LAYER

By

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And approved by

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Pervious pavement is a new type of pavement made of porous material. There are a lot of connected pores inside the pervious pavement material. Permeability of the pervious pavement is much higher than conventional, impervious pavement. The higher permeability of pervious pavement can effectively improve urban drainage as well as water environment. Rain water falling on the permeable pavement can penetrate down into ground to reduce volume of runoff as well as filter out contaminants in the runoff. But most of the ordinary pervious pavement has some drawbacks. Compressive strength of the ordinary pervious pavement is typically lower than that of the impervious pavement. The pores within the ordinary permeable pavement are easily blocked by particulate matter and then the infiltration capability will be reduced. There is a special pervious pavement whose upper surface has a low porosity, dense layer. The advantages of this permeable pavement are: (1) the upper
layer, though dense, still has a relatively high permeability, and (2) the dense upper layer can prevent or minimize the amount of sediment entering the pavement. The hydraulic conductivity of the pervious paver samples were tested in this thesis research. The porosity of the pervious paver samples and the strength of the samples were also tested in this research. The results of these laboratory tests were subsequently analyzed. The advantages and disadvantages of the special pervious pavement were evaluated, and the implications for field applications were discussed.
Acknowledgements

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# Table of Contents

ABSTRACT OF THE THESIS .............................................................................................................. ii
Acknowledgements ....................................................................................................................... iv
Introduction ...................................................................................................................................... 1
Objective ......................................................................................................................................... 8
Hydraulic Conductivity Tests ........................................................................................................ 10
  Experiment Set-up for Hydraulic Conductivity Tests ................................................................. 10
  Methods of Hydraulic Conductivity Tests ................................................................................. 16
  Results of Hydraulic Conductivity Tests ................................................................................... 17
Porosity Measurements .................................................................................................................. 25
  Methods of Porosity Measurements ......................................................................................... 25
  Results of Porosity Measurements ......................................................................................... 26
Porous Bricks Strength Tests ......................................................................................................... 33
  Methods and Results of Bending Strength Tests ..................................................................... 33
  Methods and Results of Compression Strength Tests ............................................................... 41
Infiltration Capacity Recovery Tests ............................................................................................ 47
  Measurements of Decrease in Infiltration Rate with Time ....................................................... 47
  Measurements of Infiltration Capacity’s Full Recovery Time .................................................... 52
Discussion ...................................................................................................................................... 55
Conclusion ...................................................................................................................................... 57
Further Research ............................................................................................................................ 58
References ...................................................................................................................................... 59
List of Figures

Figure 1: Porous Pavement Systems ................................................................. 2
Figure 2: Grass Driveways with Permeable Pavers ........................................ 3
Figure 3: Permeable Pavement ...................................................................... 3
Figure 4: Permeable Pavement with a Dense Layer ...................................... 7
Figure 5: Normal Permeable Pavement Sample ............................................ 8
Figure 6: Another Normal Permeable Pavement Sample ............................... 8
Figure 7: Constant-head Permeability Test ..................................................... 11
Figure 8: Five Brick Sample 1 Together ......................................................... 13
Figure 9: Hydraulic Conductivity Experiment Device .................................... 15
Figure 10: Hydraulic Conductivity Result for Sample 1 ................................. 19
Figure 11: Permeable Brick Sample 1 ............................................................. 20
Figure 12: Hydraulic Conductivity Result for Sample 1 without Dense Layer .... 21
Figure 13: Sample 2 Hydraulic Conductivity Experiment .............................. 22
Figure 14: Hydraulic Conductivity for Sample 2 ............................................ 23
Figure 15: Sample 3 Hydraulic Conductivity Experiment ............................... 24
Figure 16: Hydraulic Conductivity for Sample 3 ............................................ 25
Figure 17: Diondo D5 Scan Machine ............................................................... 26
Figure 18: Diondo D2 Scan Machine ............................................................... 26
Figure 19: Three-Dimensional Brick ............................................................. 27
Figure 20: Main View of Brick Sample 1 ......................................................... 27
Figure 21: Brick Sample 1 from Bottom View .............................................. 27
Figure 22: Side View of Brick Sample 1 .......................................................... 28
Figure 23: Extract Pore from Loose Part of Brick ......................................... 28
Figure 24: Pore Quantity of a Specific Volume .............................................. 29
Figure 25: Dense Layer Sample .................................................................. 30
Figure 26: Three-Dimensional Dense Layer Sample .................................... 31
Figure 27: Main View of Dense Layer Sample .............................................. 31
Figure 28: Top View of Dense Layer Sample .............................................. 31
Figure 29: Side View of Dense Layer Sample .............................................. 32
Figure 30: Top View and Side View of Extracted Pore from Dense Layer of Brick .. 32
Figure 31: Main View and Three Dimensional View of Extracted Pore from dense layer of Brick ................................................................. 32
Figure 32: Pore Volume of Each Pore .............................................. 33
Figure 33: Bending Test Equipment .................................................. 35
Figure 34: Bending Test Equipment with Brick Sample 1 ................. 35
Figure 35: Brick Sample 1 before Bending Test ............................. 36
Figure 36: Brick Sample 1 during Bending Test ............................ 36
Figure 37: Brick Sample 1 after Bending Test ............................... 37
Figure 38: Bending Pressure Data for a Sample 1 Brick .................. 37
Figure 39: Bending Pressure Data for another Sample 1 Brick ........ 38
Figure 40: Bending Pressure Data for a Sample 2 Brick ................. 38
Figure 41: Bending Pressure Data for another Sample 2 Brick ....... 39
Figure 42: Bending Pressure Data for a Sample 3 Brick ................. 39
Figure 43: Bending Pressure Data for another Sample 3 Brick ....... 40
Figure 44: Compression Test Equipment ........................................ 42
Figure 45: Brick Sample 3 before Compression Test ..................... 43
Figure 46: Brick Sample 3 during Compression Test ...................... 43
Figure 47: Brick Sample 3 after Compression Test ......................... 44
Figure 48: Compression Pressure Data for a Sample 2 Brick .......... 44
Figure 49: Compression Pressure Data for another Sample 2 Brick ... 45
Figure 50: Compression Pressure Data for a Sample 3 Brick ........... 45
Figure 51: Compression Pressure Data for another Sample 3 Brick ... 46
Figure 52: Permeable Brick with Organic Glass Surrounding .......... 47
Figure 53: Water Level Control Device ........................................... 48
Figure 54: Hydraulic Conductivity of the Brick Sample with Different Hydraulic Gradient ............................................................. 49
Figure 55: Hydraulic Conductivity when Dry the Brick Sample Each Day .................. 50
Figure 56: Hydraulic Conductivity when Heat the Brick Sample Each Day ........ 51
Figure 57: Water Weight Variation ................................................... 53
Figure 58: Hydraulic Conductivity Variation .................................... 54
Figure 59: Relationship between Water Content and Suction ............ 56
List of Tables

Table 1: Results of Hydraulic Conductivity Test of Sample 1 ............................................. 18
Table 2: Results of Hydraulic Conductivity Test of Vertical Sample 1 ............................... 20
Table 3: Results of Initial Hydraulic Conductivity Test of Sample 2 ................................. 22
Table 4: Results of Initial Hydraulic Conductivity Test of Sample 3 ................................. 24
Table 5: Results of Bending Strength Test ........................................................................... 41
Table 6: Results of Compressive Strength Test ................................................................... 46
Table 7: Water Weight of Each Hydraulic Conductivity Test (kg) ...................................... 53
Table 8: Hydraulic Conductivity for Brick 1 ....................................................................... 53
Introduction:

The process of urbanization has produced a large number of impervious pavements, which has a great impact on storm water runoff. Urbanization increases runoff and increases flood intensity (Bouwer, H. 2002). Low Impact Development (LID) refers to a technique that can be used in cities to reduce the impact of impervious surfaces on storm water runoff (Semple, A., Blick, S., Kelly, F. and Skupien, J. 2004). LID can reduce the amount of runoff generated during rain storms and reduce contaminants by treating runoff (Santamouris, M. 2013). LID includes a variety of technologies such as permeable sidewalk, permeable parking lot, permeable driveway, planter box, rain garden, swales, vegetated filter strips, amended soil, rain barrel and green roof. To reduce the area occupied by impermeable pavement, engineers have tried to use pervious pavement instead of impervious pavement (Bear, J. 1972).

Porous pavement (Figure 1) is a kind of pavement with a lot of connected holes inside. It is a kind of green infrastructure. Nowadays porous pavement has been widely used in the world. For example, we can see porous pavement system (Figure 2) in some parking lots. Also, there are some permeable driveways (Figure 3). Porous pavement has some advantages. Porous pavement can be a rainfall collection device. It is beneficial to recycle and reuse rainfall water. In addition, some kind of porous brick can be made of waste building material. It increases the building material utilization rate. On the other hand, nowadays city has a lot of building and impermeable
pavement so it has a lot of difference from natural environment. Normal impermeable pavement does not have connected holes so rainfall water cannot infiltrate into the ground and become surface runoff (Dullien, F.A.L. 1979). It causes a lot of city environmental problems. First, surface soil has low moisture content so the plant in the city grows slowly. Second, most cities have overexploited groundwater without rainfall water replenishment that results in groundwater level decline (Jones, G. and Dole, M. 1929). Third, impermeable pavement cut off the moisture and heat of the ground surface. So the big city cannot adjust moisture and temperature automatically. It creates heat island effect (Wood, B.D. and Valdes-Parada F.J. 2013). Heat island effect can significantly increase the city cooling energy consumption during the summer. Lastly, rainfall water cannot infiltrate into the ground so that the risk of flood increase. It is easy to cause city waterlogging. There is a lot of water above the pavement so the roughness of the pavement decreases, and driving becomes very dangerous.

Figure 1: Permeable Pavement
Figure 2: Porous Pavement Systems

Figure 3: Grass Driveways with Permeable Pavers
One of the primary advantages of permeable brick is that urban rainfall water can infiltrate into the surface through the pores of the brick body. Thus it can effectively reduce the undesirable effects of the impermeable pavement (Adler, P.M. and Berkowitz, B. 2000). Pervious bricks also have other environmental benefits, such as reducing road noise, improving water quality and reducing the amount of contaminants infiltrated into the soil to protect groundwater from contamination. However, in order to produce the above-mentioned environmental benefits, the permeability of the brick body must meet the design requirements, that is, to achieve the design value of the permeability coefficient (Wang, M. and Pan, N. 2008).

The permeable brick is a typical porous medium. In the field of porous media seepage research, some scholars have found that the fluid migration in porous media is affected by pore structure through a large number of seepage experiments and numerical simulations (Dullien, F.A.L. 1979). Pore structure includes porosity, pore size distribution, connectivity and tortuosity and so on. However, the scale of industrial attention is several orders of magnitude larger than the pore microstructure scale that actually affects seepage. The key issue is to figure out the relationship between the flow rate, viscosity and pressure drop in the porous media during seepage. Therefore, the permeability coefficient as a parameter to evaluate the average seepage capacity of porous materials is very important.

There is an effective method to overcome the problem of unequal scale to solve the
empirical relationship between the contact porosity morphological parameters and the average permeability coefficient. Previous studies have shown that this method is very effective, such as reservoir sandstone leakage prediction and fluid movement in the particle-filled reactor.

Porous media can be seen as a static or flowing fluid (air, water, oil, blood and etc.) filled with pore space. It has universal significance in the natural world (Chen, Z.Q., Cheng, P. and Zhao, T.S. 2000). In addition to the above-mentioned porous pavement, groundwater, oil and gas development, plant nutrient transport and so on are all porous media seepage problem. Porous media seepage research is the theoretical basis of the above areas (Zhang, B., Yu, B.M., Wang, H.X. and Yun, M.J. 2006). Due to the complexity of the pore structure in the porous media, the heat and mass transfer problem of the pore scale is very complicated and becomes the research difficulty of each discipline.

Therefore, the study of the permeable characteristics of the typical porous media of the permeable bricks and the development of the corresponding prediction model can not only contribute to the understanding of the permeability of the permeable bricks (Tong, D.K. and Zhang, H.Q. 2001), but also can provide reference for the study of porous media in other engineering fields (Hicks, R.E. 1970). At the same time, it will help expand the basic theory of porous media penetration. The most important characteristics of the porous media is hydraulic conductivity that should be measured.
Some countries, including the United States, research on the use of porous brick occurred earlier (Whitaker, S. 1996). The technology is mature. A large proportion is permeable pavement, but the proportion of pervious bricks is not too high. Due to the large number of pores inside the permeable bricks, the compressive strength is low, so the permeable bricks can only be used in light traffic roads such as public squares, sidewalks, parking lots and parks. Taking into account of the strength of the porous brick, cost and other issues, those countries also use permeable asphalt, fine gravel, pebbles, porous concrete; these constitute a comprehensive pavement system.

Ordinary permeable pavement has the problem of being easily clogged with particulate matter (Ji, X., Chan, S.Y.N. and Feng, N. 1997). After a period of use, the permeability of ordinary pervious pavement will decline. In practical applications, road management staff usually will use from time to time a vacuum truck for the pavement cleaning (Wu, J.S., Yu, B.M. and Yun, M.J. 2008), sucking out particles inside the pavement that block the infiltrating water, so as to restore the water permeability of the pavement (Center for Watershed Protection. 2006). The maintenance cost for permeable pavement is high. Engineers are also trying to prevent this kind of particulate matter from clogging (Karacan, C.O. and Halleck, P.M. 2003).

One way is to add a layer of dense layer with smaller holes to the surface of the pavement so that the particles cannot pass through this layer.
In our experiments we used a permeable paver produced by a company that has a very dense layer of pores on its upper surface. We tested the infiltration rate in the experiments, but in the course of the tests, we found that its penetration capacity declined, thus we also analyzed the reasons for the decline (Latief, F.D.E. and Fauzi, U. 2012). For comparison, we experimented with two other ordinary tiles without dense layer surfaces (Wang, T.J., Wu, C.H. and Lee, L.J. 1994). In addition, we tested the compressive strength of these bricks, and CT-scanned the company's brick to observe its internal structure. During the experiments we used three different types of pavement sample. Sample 1 (Figure 4) is Permeable Pavement with a Dense Upper Layer. Sample 2 (Figure 5) is a kind of normal permeable pavement sample. Sample 3 (Figure 6) is another kind of normal permeable pavement sample.

![Figure 4: Permeable Pavement with a Dense Layer](image)
The objective of this study was to measure the hydraulic conductivity of the permeable bricks with a dense layer, compared to the hydraulic conductivity of the
permeable bricks without the dense layer. An experimental device was established so that water could permeate through the permeable bricks and allow infiltrated water to flow into the container. The hydraulic conductivity of the permeable bricks was quantified by measuring the time during which the volume of water flowed through, or the weight of water flowing out per unit time.

We also used the material-testing machine in the laboratory. This test machine can give the pressure that is applied on the permeable brick sample. Then till the sample become failure we can measure the maximum applied pressure. This test machine has replacement parts, we can press the upper and lower sides of the sample, and we can also replace the part of the sample after the focus of a line of force (Wilson, M. 2002). This can be used to measure the compressive and flexural strength of the sample by using this test machine. After that, we also used the means of CT scanning to analyze the internal structure of the permeable bricks with dense layer (Martin III, W.D., Kaye, N.B. and Putman, B.J. 2014).

In the experiment, we found that with the increase in penetration time, penetration capacity of the permeable brick with a dense layer gradually declined. We analyzed the causes of the decline in suction capacity by theory and tried to find a way to restore the permeability of the permeable bricks. We then dried permeable bricks over different periods of time and subsequently measured the infiltration rates. The time required for the recovery of the permeability of the permeable bricks was quantified,
and the practicality of the permeable pavement in practical applications was analyzed.

**Hydraulic Conductivity Tests**

*Experiment Set-up for Hydraulic Conductivity Tests*

We have known that different types of porous bricks have different internal structure and different permeability. We set up an apparatus to do the infiltration test. We measured the different hydraulic conductivity of different types of porous bricks. We also measured the hydraulic conductivity over different time periods. This experiment used constant-head method which is called permeability test. During the test, the water levels above the brick remain constant, and the volume of water that goes through the brick over a period of time is measured. The experiment principle is shown in Figure 7. We can use equation 1, equation 2 and equation 3 below to calculate the hydraulic conductivity.

\[ V = QT = vAT \]  

where

- \( V \) = Volume
- \( Q \) = Outflow Rate
- \( v \) = Velocity
- \( A \) = Cross Area
- \( T \) = Time

*Equation 1: Outflow Volume Equation*
\[ K = \frac{v}{i} \quad (2) \]

where \( v = \) Velocity

\( K = \) Hydraulic conductivity

\( i = \) Hydraulic gradient

*Equation 2: Hydraulic conductivity Equation*

\[ i = \frac{\Delta h}{L} \quad (3) \]

where \( \Delta h = \) Infiltration Distance

\( L = \) Height of Permeable Zone

*Equation 3: Hydraulic gradient Equation*
In the initial experiment, we only measured the permeability of three different permeable bricks, using different hydraulic gradients. This kind of experimental method can be used for two permeable bricks with no dense layer on the surface. The permeation rate under different hydraulic gradients can be measured and the several calculated permeation rates can be compared. Five pieces of the same permeable brick were tied together, with the sides coated with waterproof glue and a transparent plastic sheet wrapped around to prevent water from moving out. Using our experimental setup, we can successfully complete the experiment by changing the external water level to achieve the different hydraulic gradients. The water can flow smoothly from below the permeable bricks and then through the overflow device to allow the water overflow into the container.

However, this experimental method is not practical for a permeable brick with a dense layer. Initially we put five pervious brick samples with a dense layer together (Figure 8), surrounded by waterproof glue and wrapped in transparent plastic sheet, into the experimental device, poured water on to the top surface. The water penetrated into the top brick but the flow from the underneath of the bottom brick was very slow, and we were unable to accurately measure the outflow of water through the overflow device. Then we had to give up measuring the penetration rate through the five bricks stacked together under different hydraulic gradients, and ended up using only a single brick
for infiltration experiments. We also only measured the penetration rate under a single hydraulic gradient, that is, the bottom free-flowing condition with the hydraulic gradient equal to one. In this case, the water was able to flow smoothly from the overflow device, thus enabled us to successfully completed the experiments.

After several sets of experiments we had a new discovery, water seepage rate of the permeable brick with dense layer became smaller and smaller. We used the same water container, but the time it took to fill became longer and longer. We also analyzed whether the infiltration rate was getting slower due to the dense layer. We put the permeable brick in the vertical orientation and placed it in the experimental device to do the experiment. Prior to the test, the brick was also coated with waterproof glue on the surrounding sides and was wrapped in transparent plastic sheet, and top of the dense layer was coated with waterproof glue to cover the dense layer. These ensured that the water left only from the bottom of coarse layer. The measured
penetration rate also decreased over time, but the decline was much smaller than the previous experiment, indicating the dense layer was most responsible for the decline of the infiltration rate over time. Then we also designed the experiment to test the recovery time for the penetration rate.

We built a hydraulic conductivity experiment device (Figure 9). Following the experiment principle, we used organic glass to construct a transparent box. We made an organic glass box which can hold water. We placed the bottom of the box on to regular bricks stacked up inside the tall organic glass tank. The bottom of the organic glass tank was drilled with a few holes that were connected to several hoses. The hoses were connected to the small box outside the tall organic glass tank. The small box outside is the overflow device with a vertical separation organic glass panel located in the middle serving as the overflow weir. The small outside box is located on the side of the tall tank and it can be moved up and down along two iron bars with screw. The experimental set-up has water supply system, orifices, spilling water flume, supporting bricks, porous brick samples, volumetric measurement cylinder, etc.
Additional experimental devices include chronograph, thermometer which has measurement range from 0°C to 50°C and resolution of 1°C. An electronic scale which has measurement range from 0 kg to 10 kg and resolution of 1 g. We used a timer to measure the time required for the water to fill the container of fixed volume, or to control the amount of time, and then measure the volume of water in the container. For each experiment we used a thermometer to measure the water temperature to observe whether the different water temperature would have an impact on the experiment. And the weight of the water was measured using an electronic scale, the electronic scale has a peeled function, and the weight of the container can be subtracted to measure the weight of the water in the container.

The experiment samples used were three different types of porous bricks. Sample 1
(Figure 4) is a porous bricks that has a cross sectional area equal to 405 cm$^2$, length equal to 27 cm, width equal to 15 cm, and height equal to 6.6 cm. Sample 2 (Figure 5) is a porous brick that has a cross sectional area equal to 194 cm$^2$ and height equal 5.84 cm. Sample 3 (Figure 6) is a porous brick that has a cross sectional area equal to 194 cm$^2$ and height equal to 6 cm. Sample 1 is the permeable brick with dense layer on the top. Sample 2 and sample 3 are made of ordinary permeable pavement materials without dense layer. The three different tiles are produced from three different companies.

**Methods of Hydraulic Conductivity Tests**

For preventing the water penetrate from the four sides of the porous bricks, use 703 glue to paint surrounds the side of the porous bricks and use transparent tape to wrap the four sides of the porous bricks. After these steps, the water can only infiltrate from the top to the bottom. Put those porous brick sample into the experiment equipment. Prepare tap water and use rubber tube to drain water into the experiment equipment. Adjust the faucet tap to control the out flow rate of the rubber tube to make the water above the porous brick remain constant. Waiting for the water continuously going out of the equipment, measure the outflow volume in a certain period of time.

First we pour the water to the upper surface of the permeable brick, the water will continue to deep into the brick body. We constantly pour water on the upper surface of
the brick to ensure that the water level on the surface of the brick does not change. The amount of water above the brick is kept at only a thin layer. After a period of time the water began to seep from the bottom of the brick. After adjusting the water level, inside part of the overflow device on the outside of the experimental device is filled with water and no water on the other side. After the water begins to leak from the bottom of the brick, the overflow device begins to seep water and the water can flow out of the hose connected to the overflow device. And so the water out of the more stable after the container can be used to flow out of the water, at the same time start the timer. After the container was full of water, you can press the timer and record it. After the water in the container is drained, reconnect the water again.

The ordinary permeable brick Sample which was used to do the experiment is to put five pieces of water in a pile, with waterproof glue and transparent glue into the experimental device. We changed the water level so that we can change the different hydraulic gradient. Three of the hydraulic gradients are submerged outflow and one of the situations is a free flow situation. In the experimental device to adjust the water level at the same time, the outside of the overflow device water level also follows the device within the water level adjustment. The water level of the overflow device is flush with the water level in the large box.

**Results of Hydraulic Conductivity Tests**
We only use one sample 1 porous brick to do the experiment. This is a dense layer of permeable bricks. Place a separate piece of brick in the experimental setup. The water level in the device is adjusted below the lower surface of the sample. This time we did was free flow experiment. The same experimental method as Sample 2 Sample 3 was used. The volume of the external connection water container is 800 cm³. We measured the time required to fill the container. Then we can infer the penetration rate of permeable bricks. According to the time we recorded, the time required to fill a bottle of water is getting longer. And then calculated the outflow rate is gradually decreased. Hydraulic gradient is the same, approximately equal to one. The calculated hydraulic gradient is also gradually decreasing (Table 1). We have following result (Figure 10).

<table>
<thead>
<tr>
<th>No.</th>
<th>Infiltration Length V (cm³)</th>
<th>Time t (s)</th>
<th>Flow Rate Q (cm³/s)</th>
<th>Velocity V=Q/A (cm/s)</th>
<th>Hydraulic Gradient i</th>
<th>Hydraulic conductivity K=v/i (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.6</td>
<td>800</td>
<td>10</td>
<td>0.025</td>
<td>1</td>
<td>0.025</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>800</td>
<td>92</td>
<td>8.70</td>
<td>0.021</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>800</td>
<td>97</td>
<td>8.25</td>
<td>0.020</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>6.6</td>
<td>800</td>
<td>124</td>
<td>6.45</td>
<td>0.016</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>800</td>
<td>129</td>
<td>6.20</td>
<td>0.015</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>6.6</td>
<td>800</td>
<td>132</td>
<td>6.06</td>
<td>0.015</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>6.6</td>
<td>800</td>
<td>151</td>
<td>5.30</td>
<td>0.013</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>6.6</td>
<td>800</td>
<td>160</td>
<td>5.00</td>
<td>0.012</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>6.6</td>
<td>800</td>
<td>165</td>
<td>4.85</td>
<td>0.012</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
<td>800</td>
<td>177</td>
<td>4.52</td>
<td>0.011</td>
<td>1</td>
</tr>
</tbody>
</table>
The abscissa is the time duration that the container is filled with water. The first time filled with water with the shortest time. And then the time filled with water gradually increased. Then we calculated hydraulic conductivity also decreased obviously.

As a result of the sample 1 permeable brick surface has the grey coating; in order to eliminate the influence by the coating, change the brick to vertical (Figure 11). The cross sectional area equals to 99 cm$^2$, height equals to 27 cm. As the same method we used above, research the change of hydraulic conductivity with time (Figure 12). We can get following results (Table 2).
## Table 2: Results of Hydraulic Conductivity Test of Vertical Sample 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Infiltration Length $\triangle h$ (cm)</th>
<th>Volume $V$ (cm$^3$)</th>
<th>Time $t$ (s)</th>
<th>Flow Rate $Q$ (cm$^3$/s)</th>
<th>Velocity $V=Q/A$ (cm/s)</th>
<th>Hydraulic Gradient $i$</th>
<th>Hydraulic conductivity $K=V/i$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>800</td>
<td>377</td>
<td>2.12</td>
<td>0.021</td>
<td>1</td>
<td>0.021</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>800</td>
<td>407</td>
<td>1.97</td>
<td>0.020</td>
<td>1</td>
<td>0.020</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>800</td>
<td>457</td>
<td>1.75</td>
<td>0.018</td>
<td>1</td>
<td>0.018</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>800</td>
<td>503</td>
<td>1.59</td>
<td>0.016</td>
<td>1</td>
<td>0.016</td>
</tr>
</tbody>
</table>
Figure 12: Hydraulic Conductivity Result for Sample 1 without Dense Layer

The abscissa is the time duration that the container is filled with water. From this point of view, hydraulic conductivity still decrease with the experimental time increase. But because of the vertical brick has a bigger $\Delta h$. Every time it fills the water, it takes longer to become full. For the same time, the decline in hydraulic conductivity is relatively smaller than the experiment of horizontal sample 1 brick.

Sample 2 is five porous bricks (Figure 13) which have a cross sectional area equals to 194 cm$^2$ and total height is 29.2 cm. Serial number 1 through 3 are submerged flow and serial number 4 is free flow which has Infiltration Length equal to total height of five bricks. We used the previously mentioned experimental method, waiting for the effluent water to stabilize. Measure the weight of water flowing out for a certain
period of time. Thus we can calculate the outflow rate. Measure the difference between the upper and lower water levels \( \Delta h \) before each experiment. By outflow rate and cross area, we can calculate velocity. For the five brick \( L \) is the thickness of each brick multiplied by five. The hydraulic gradient is calculated by \( L \) and \( \Delta h \). Calculate the hydraulic conductivity (Table 3) by velocity and hydraulic gradient (Figure 14).

![Figure 13: Sample 2 Hydraulic Conductivity Experiment](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Infiltration Length ( \Delta h ) (cm)</th>
<th>Flow rate ( Q ) (cm(^3)/s)</th>
<th>Velocity ( V=Q/A ) (cm/s)</th>
<th>Hydraulic gradient ( i=\Delta h/L )</th>
<th>Hydraulic conductivity ( K=V/i ) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.5</td>
<td>3.67</td>
<td>0.019</td>
<td>0.39</td>
<td>0.048</td>
</tr>
<tr>
<td>2</td>
<td>18.3</td>
<td>5.23</td>
<td>0.027</td>
<td>0.63</td>
<td>0.047</td>
</tr>
<tr>
<td>3</td>
<td>23.5</td>
<td>7.34</td>
<td>0.038</td>
<td>0.80</td>
<td>0.043</td>
</tr>
<tr>
<td>4</td>
<td>29.2</td>
<td>10.51</td>
<td>0.054</td>
<td>1</td>
<td>0.054</td>
</tr>
</tbody>
</table>
Each hydraulic gradient calculates a hydraulic conductivity. This group of experiments has four different hydraulic gradients. In theory, each group of hydraulic conductivity is equal. As we see from the figure, hydraulic conductivity in sample 2 experiment is stable for different infiltrate length. The average hydraulic conductivity is 0.048 cm/s.

Sample 3 is five porous bricks (Figure 15) which has a cross sectional area equals to 194 cm2, each height equals to 6 cm. Those five bricks connect together so the total height is 30 cm. Serial number 1 through 3 are submerged flow and serial number 4 is free flow which has Infiltration Length equal to total height of five bricks. The experiment method is same as the method we use in sample 2. We used the previously
mentioned experimental method, waiting for the effluent water to stabilize. Measure the weight of water flowing out for a certain period of time. Thus we can calculate the out flow rate. Measure the difference between the upper and lower water levels $\Delta h$ before each experiment. By outflow rate and cross area, we can calculate velocity. For the five brick $L$ is the thickness of each brick multiplied by five. The hydraulic gradient is calculated by $L$ and $\Delta h$. Calculate the hydraulic conductivity (See Table 4) by velocity and hydraulic gradient (Figure 16).

![Figure 15: Sample 3 Hydraulic Conductivity Experiment](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Infiltration Length $\Delta h$ (cm)</th>
<th>Flow rate Q ($cm^3/s$)</th>
<th>Velocity $V=Q/A$ (cm/s)</th>
<th>Hydraulic gradient $i=\Delta h/L$</th>
<th>Hydraulic conductivity $K=v/i$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.0</td>
<td>1.87</td>
<td>0.0096</td>
<td>0.40</td>
<td>0.024</td>
</tr>
<tr>
<td>2</td>
<td>18.5</td>
<td>2.49</td>
<td>0.013</td>
<td>0.62</td>
<td>0.021</td>
</tr>
<tr>
<td>3</td>
<td>22.0</td>
<td>2.96</td>
<td>0.015</td>
<td>0.73</td>
<td>0.021</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>3.82</td>
<td>0.020</td>
<td>1</td>
<td>0.020</td>
</tr>
</tbody>
</table>
As the same as we did for sample 2, each hydraulic gradient calculates a hydraulic conductivity. This group of experiments has four different hydraulic gradients. In theory, each group of hydraulic conductivity is equal. As we see from the figure 13, hydraulic conductivity in sample 3 experiment is stable for different infiltration length. The average hydraulic conductivity is 0.0215 cm/s.

**Porosity Measurements**

**Methods of Porosity Measurements**

We used the CT Scan Machine “Diondo D5” from Germany (Figure 17) to scan the coarse part of the brick sample. We used three dimensions CT method to measure
porosity of the porosity. Put the porous brick sample into the scan zone. Rotate the brick a circle. Each angle creates a two-dimensional photo. Reconstruct those two-dimensional photos to make three-dimensional data.

![Figure 17: Dional D5 Scan Machine](image)

We use another higher distinguishability CT machine “Dional D2” (Figure 18) to scan the dense layer of the brick sample. This machine has higher distinguishability than “Dional D5”. We use this machine to scan the dense layer of the brick sample which has smaller pore size.

![Figure 18: Dional D2 Scan Machine](image)

**Results of Porosity Measurements**
We have the Three-Dimensional Brick sample 1 picture (Figure 19). After we use CT scan method, we can get main view (Figure 20), bottom view (Figure 21) and side view (Figure 22). We can compare those views with the three dimensional picture. Extract Pore from Coarse Part of Brick. We can see the pore distribution in the brick sample (Figure 23).

Figure 19: Three-Dimensional Brick Picture

Figure 20: Main View of Brick Sample 1

Figure 21: Brick Sample 1 from Bottom View
After this test, we can get the pore information in the coarse part. There are more than 70% of pores are smaller than 0.5mm$^3$. More than 90% of pores are smaller than 1.0mm$^3$ (Figure 24).
After we extract pore from the coarse part of brick, we tried to measure the size of those pores. By observing the distribution of porosity in the three-dimensional field of the coarse layer, it can be found that the pores are connected as a whole. After we used the porosity measurement program, we had following results:

1. On the top of the brick, the dense part has porosity 0.04%. However, the “Diondo D5” machine is not accurate enough for measuring the dense part. So this result is not accurate enough. On the bottom part of the brick, the coarse part of the brick has porosity 9.29%. This result is accurate enough.

2. Most of holes are connected. Only a few holes are individual holes.

3. The volume of the biggest hole in the coarse part is 10.69 mm$^3$. The volume of the smallest hole is 0.02 mm$^3$. The main holes volume distribution is from 0.1 mm$^3$ to 1.5 mm$^3$. 

Figure 24: Pore Quantity of a Specific Volume
There is the dense layer material we cut from the permeable brick sample 1 (See Figure 25). The dense layer sample is 8.25mm times 8.25mm times 8.25mm. After we use Diondo D2 CT machine scan the sample, we can get Three-Dimensional Dense Layer Sample (Figure 26), Main View of Dense Layer Sample (Figure 27), Top View of Dense Layer Sample (Figure 28) and Side View of Dense Layer Sample (Figure 29). We also can extract pores. We can get Top View and Side View of Extracted Pore from Dense Layer of Brick (Figure 30) and Main View and Three Dimensional View of Extracted Pore from dense layer of Brick (Figure 31).

![Figure 25: Dense Layer Sample](image)
Figure 26: Three-Dimensional Dense Layer Sample

Figure 27: Main View of Dense Layer Sample

Figure 28: Top View of Dense Layer Sample
After this test, we can get the pore information in the dense layer. There are more than 70% of pores are smaller than 0.05\,mm³. More than 90% of
pores are smaller than 0.1mm$^3$ (Figure 32). The major material of the dense layer is sand.

![Figure 32: Pore Volume of Each Pore](image)

**Porous Bricks Strength Tests**

Porous brick have permeable hole so their bending strength and compression strength are less than normal brick. Here we use strength test equipment to measure the bending strength and the compression strength of the different types of porous bricks.

**Methods and Results of Bending Strength Tests**

We use the bending strength test equipment (Figure 33) to measure the different types of porous bricks. Sample one marked as big and black (Figure 34). Sample two marked as small and red. Sample three marked as small and black.
We put the three different types of bricks into water submerged for 24 hours. Then we put the wet sample 1 brick on the bending test equipment. Sample 1 brick was putted on two metal arms. Another metal arm moved slowly to the brick surface middle (Figure 35). Then operate the bending test equipment. The machine give pressure to the brick middle surface (Figure 36). Increase the pressure until the brick had a bending fail (Figure 37). Then the computer showed us the pressure (Figure 38). We also tested another sample 1 brick and get the strength result (Figure 39). We also tested two sample 2 bricks and get the bending strength (Figure 40 and Figure 41). We also tested two sample 3 bricks and get the bending strength (Figure 42 and Figure 43).
Figure 34: Bending Test Equipment with Brick Sample 1

Figure 35: Brick Sample 1 before Bending Test

Figure 36: Brick Sample 1 during Bending Test
Figure 37: Brick Sample 1 after Bending Test

Figure 38: Bending Pressure Data for a Sample 1 Brick
Figure 39: Bending Pressure Data for another Sample 1 Brick

Figure 40: Bending Pressure Data for a Sample 2 Brick
Figure 41: Bending Pressure Data for another Sample 2 Brick

Figure 42: Bending Pressure Data for a Sample 3 Brick
Because the sample 1 has two layers, the curves in Figure 38 and Figure 39 have two peaks. The coarse layer had failure first and then the dense layer had failure. After we did the bending test, we can use equation (Equation 4) to calculate the bending strength (Table 5).

$$R_f = \frac{3PL}{2HB^2}$$ (4)

Where, $R_f$ = Bending Strength (MPa)

P = Failure Load (N)

l = Distance of two Support Point (mm)

H = Width of the Sample (mm)

B = Thickness of the Sample (mm)

*Equation 4: Bending Strength Equation*
### Table 5: Results of Bending Strength Test

<table>
<thead>
<tr>
<th>Sample</th>
<th>l (mm)</th>
<th>H (mm)</th>
<th>B (mm)</th>
<th>P (N)</th>
<th>$R_f$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>270</td>
<td>150</td>
<td>66</td>
<td>9990</td>
<td>6.192</td>
</tr>
<tr>
<td>Sample 1</td>
<td>270</td>
<td>150</td>
<td>66</td>
<td>10580</td>
<td>6.558</td>
</tr>
<tr>
<td>Sample 2</td>
<td>198</td>
<td>98</td>
<td>58.4</td>
<td>5640</td>
<td>5.012</td>
</tr>
<tr>
<td>Sample 2</td>
<td>198</td>
<td>98</td>
<td>58.4</td>
<td>7080</td>
<td>6.291</td>
</tr>
<tr>
<td>Sample 3</td>
<td>198</td>
<td>98</td>
<td>60</td>
<td>7750</td>
<td>6.524</td>
</tr>
<tr>
<td>Sample 3</td>
<td>198</td>
<td>98</td>
<td>60</td>
<td>9110</td>
<td>7.669</td>
</tr>
</tbody>
</table>

From the results of the calculation, we knew the bending strength of each permeable brick sample. The permeable brick with a dense layer sample 1 has similar bending strength as normal permeable brick sample 2 and sample 3.

**Methods and Results of Compression Strength Tests**

We use the compression strength test equipment (Figure 44) to measure the different types of porous bricks. Sample two marked as small and red. Sample three marked as small and black.

We put the three different types of bricks into water submerged for 24 hours. Then we put the wet sample 2 brick on the compression test equipment. Sample 2 brick was putted on a circular plate. Another metal circular plate moved slowly to the brick top surface (Figure 45). Then operate the compression test equipment. The machine give
pressure to the brick top surface (Figure 46). Increase the pressure until the brick had a compression fail (Figure 47) (Beier, R.A. 1994). Then the computer showed us the pressure (Figure 48). We also tested another sample 2 brick and get the strength result (Figure 49). We also tested two sample 3 bricks and get the compression strength (Figure 50 and Figure 51). However, when we tested the two sample 1 bricks, they were over the range of the equipment. So their compression strengths are higher than the range of the equipment (Table 6).

Figure 44: Compression Test Equipment
Figure 45: Brick Sample 3 before Compression Test

Figure 46: Brick Sample 3 during Compression Test
Figure 47: Brick Sample 3 after Compression Test

Figure 48: Compression Pressure Data for a Sample 2 Brick
Figure 49: Compression Pressure Data for another Sample 2 Brick

Sample 3 (small, black)

Figure 50: Compression Pressure Data for a Sample 3 Brick
Figure 51: Compression Pressure Data for another Sample 3 Brick

Table 6: Results of Compressive Strength Test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Sample 1</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Sample 2</td>
<td>22.9</td>
</tr>
<tr>
<td>Sample 2</td>
<td>27.2</td>
</tr>
<tr>
<td>Sample 3</td>
<td>30.4</td>
</tr>
<tr>
<td>Sample 3</td>
<td>38.4</td>
</tr>
</tbody>
</table>

During the compressive strength test, the sample 1 was over the range of our test machine. The failure did not occur during the test. The failure of sample 2 and sample 3 permeable bricks occurred. The compressive strength of the brick with dense layer
sample 1 is higher than the normal permeable bricks sample 2 and sample 3.

**Infiltration Capacity Recovery Tests**

**Measurements of Decrease in Infiltration Rate with Time**

When we change to different hydraulic gradient, it has similar result. We chose another new sample 1 porous brick. Use 703 glue painted four sides of the porous brick. Air-dry the brick for more than 24 hours. Then paste Plexiglas around the four sides of the brick (Figure 52). Then put the brick into the experiment equipment. We can compare two different hydraulic gradients. After the measurement, we got the higher hydraulic gradient is equal to 2.2 (Figure 53) and the lower hydraulic gradient is approximate equal to 1.

![Figure 52: Permeable Brick with Organic Glass Surrounding](image-url)
After we do the experiment, we measure the hydraulic conductivity of two bricks under different hydraulic gradients. We can see the hydraulic conductivity decrease continuously (Figure 54). The First data is the result for 30 minutes of the test. So it looks much smaller than the first data in Figure 10. The first data in Figure 10 is the result for 80 seconds.
If we dry the brick for 24 hours, the permeability will recover. So we try to measure how the infiltrate ability recovers. We did the same experiment process as number 1 and number porous brick on the first day afternoon. We measured the water weight three times. Then we calculated the hydraulic conductivity. We can see the hydraulic conductivity decrease. After we measured the third time of the water weight, we stop the experiment process and put the brick in a dry and shady place. After 24 hours, we did the same process of the experiment. After we calculated the hydraulic conductivity, we can observe that the infiltrate ability had partially recovered. Then we do the same experiment process for six days. Dry 24 hours first then do the infiltrate experiment. We can see every time the infiltrate ability recovered (Figure 55). But it cannot recover as the first time we do the experiment. It only can recover part of the infiltrate...
ability. The first two hydraulic conductivity data are nearly 0.004 cm/s. The hydraulic conductivity data in last two days are nearly 0.0015 cm/s. For New Jersey 24 Hour Rainfall data (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs141p2_018235.pdf), the rainfall amounts in Inches in Atlantic City the 1 year storm is 2.72. It is equal to 6.9 cm. So for this rainfall intensity, the Paver sample 1 is enough for Atlantic City rainfall.

So we decided to try to dry it quickly. If we use incandescent lamp heat the brick for 3 hours and dry the brick for 18 hours, the permeability will recover more. We did the same experiment for 8 days. In the middle of the experiment every day we have used this dry 18 hours with incandescent drying 3 hours method. In the chart we can see that the infiltrate ability has been greatly restored after drying by the incandescent
lamp. However, with the passage of time, the permeability of the permeable brick can only be partially restored; the final penetration capacity is still less than the first day of the penetration capacity (Figure 56).

![Figure 56: Hydraulic Conductivity when Heat the Brick Sample Each Day](image)

In the actual weather conditions, the middle of the two rains there will be a certain time interval. This time the brick can be dried. We want to know how long it takes for a permeable brick to fully recover. We still use the same experimental method. On the first day, three experiments were conducted to measure the permeability coefficient. Then let the permeable bricks dry for 24 hours. Then we used the same method to measure the permeation rate of the permeable bricks. Then let the permeable bricks dry for 72 hours. Then repeat the previous infiltration experiment. Then let the permeable bricks dry for 7 days.
Measurements of Infiltration Capacity’s Full Recovery Time

We did the same experiment process for one permeable sample. We dried the brick for 24 hours first. We did the same experiment process as number 1 and number porous brick on the first day afternoon. We measured the water weight three times. Then we calculated the hydraulic conductivity. After we measured the third time of the water weight, we stop the experiment process and put the brick in a dry and shady place. After 24 hours, we did the same process of the experiment. After we calculated the hydraulic conductivity, we can observe that the infiltrate ability had partially recovered. Then we put the brick in a dry and shady place for three days. After that we do the same experiment process. Then we put the brick in a dry and shady place for seven days. Then we do the same experiment. Then we put the brick in a dry and shady place for fourteen days. We can see every time the infiltrate ability recovered. Finally, for drying seven days or fourteen days, it can recover as the first time we do the experiment. Each time we did the experiment we measured the water weight during 30 minutes experiment. Each time we measured three times continuously.

The Experiment Data shows in Table 7 (Table 7). We knew that if we dry the brick sample more time, the more permeability will recover. If we dry it for one week, the permeability of the brick will almost fully recover (Figure 57). The hydraulic conductivity data is in Table 8 and Figure 58.
Table 7: Water Weight of Each Hydraulic Conductivity Test (kg)

<table>
<thead>
<tr>
<th></th>
<th>Brick 1</th>
<th>Brick 2</th>
<th>Brick 3</th>
<th>Brick 4</th>
<th>Brick 5</th>
<th>Brick 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>2.53</td>
<td>3.18</td>
<td>3.42</td>
<td>3.62</td>
<td>4.96</td>
<td>2.49</td>
</tr>
<tr>
<td>Day 1</td>
<td>1.58</td>
<td>1.28</td>
<td>2.53</td>
<td>2.365</td>
<td>3.115</td>
<td>2.015</td>
</tr>
<tr>
<td>Day 1</td>
<td>1.18</td>
<td>1.115</td>
<td>1.735</td>
<td>1.57</td>
<td>2.05</td>
<td>1.365</td>
</tr>
<tr>
<td>Day 2</td>
<td>1.26</td>
<td>1.555</td>
<td>2.08</td>
<td>1.52</td>
<td>2.51</td>
<td>1.185</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.965</td>
<td>0.92</td>
<td>1.185</td>
<td>0.6</td>
<td>1.09</td>
<td>0.865</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.815</td>
<td>0.73</td>
<td>1.01</td>
<td>0.525</td>
<td>1.07</td>
<td>0.72</td>
</tr>
<tr>
<td>Day 5</td>
<td>1.395</td>
<td>2.23</td>
<td>2.105</td>
<td>2.23</td>
<td>3.26</td>
<td>1.725</td>
</tr>
<tr>
<td>Day 5</td>
<td>1.095</td>
<td>1.355</td>
<td>1.285</td>
<td>1.08</td>
<td>1.34</td>
<td>1.115</td>
</tr>
<tr>
<td>Day 5</td>
<td>0.845</td>
<td>0.91</td>
<td>0.87</td>
<td>0.735</td>
<td>0.94</td>
<td>0.805</td>
</tr>
<tr>
<td>Day 12</td>
<td>2.835</td>
<td>3.74</td>
<td>4.55</td>
<td>3.285</td>
<td>5.962</td>
<td>2.225</td>
</tr>
<tr>
<td>Day 12</td>
<td>1.58</td>
<td>1.675</td>
<td>2.26</td>
<td>3.695</td>
<td>4.665</td>
<td>2.605</td>
</tr>
<tr>
<td>Day 12</td>
<td>1.025</td>
<td>1.025</td>
<td>1.43</td>
<td>2.33</td>
<td>2.94</td>
<td>1.82</td>
</tr>
<tr>
<td>Day 26</td>
<td>2.28</td>
<td>3.46</td>
<td>4.015</td>
<td>4.42</td>
<td>7.68</td>
<td>3</td>
</tr>
<tr>
<td>Day 26</td>
<td>1.77</td>
<td>3.18</td>
<td>3.655</td>
<td>4.17</td>
<td>5.785</td>
<td>2965</td>
</tr>
<tr>
<td>Day 26</td>
<td>1.69</td>
<td>3.155</td>
<td>3.075</td>
<td>4.11</td>
<td>5.09</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Figure 57: Water Weight Variation

Table 8: Hydraulic Conductivity for Brick 1

<table>
<thead>
<tr>
<th></th>
<th>Weight(kg)</th>
<th>Hydraulic Conductivity(cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>2.53</td>
<td>0.003471</td>
</tr>
<tr>
<td>Day 1</td>
<td>1.58</td>
<td>0.002167</td>
</tr>
<tr>
<td>Day 1</td>
<td>1.18</td>
<td>0.001619</td>
</tr>
<tr>
<td>Day 2</td>
<td>1.26</td>
<td>0.001728</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.965</td>
<td>0.001324</td>
</tr>
<tr>
<td>Day</td>
<td>Conductivity (cm/s)</td>
<td>Hydraulic Conductivity</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>2</td>
<td>0.815</td>
<td>0.001118</td>
</tr>
<tr>
<td>5</td>
<td>1.095</td>
<td>0.001502</td>
</tr>
<tr>
<td>12</td>
<td>2.835</td>
<td>0.003889</td>
</tr>
<tr>
<td>12</td>
<td>1.025</td>
<td>0.001406</td>
</tr>
<tr>
<td>26</td>
<td>1.77</td>
<td>0.002428</td>
</tr>
</tbody>
</table>

**Figure 58:** Hydraulic Conductivity Variation


**Discussions**

The dense layer above this type of permeable pavement prevents particulate matter from entering the pavement and blocks the permeable passage. However, through the experiment we can know that with the liquid infiltration time increases, this permeable pavement penetration capacity will still decline (Johnston, N. and Beeson, C.M. 1945). The dense layer absorbs water into the road with capillary force. According to our knowledge, the smaller the water content, the greater the capillary force (Das, B. 1998). When the water content of the pavement gradually increased, the capillary force also decreased (Figure 58). So we can know that in the experiment with the infiltration time increases, the surface dense layer of water content increased, the water absorption capacity gradually decreased, resulting in this permeable pavement permeability decreased. When we dry the brick for some time, the moisture content of the permeable brick dense layer decreases, the water absorption capacity increases, and the permeation capacity of the permeable pavement is restored.
Figure 59: Relationship between Water Content and Suction

als-and-subgrade-soils-terminology/)

We also want to know how long it takes the brick sample to recover its permeable ability. So we designed an experiment for drying the brick for different time duration. Then we observed when the permeable ability recovered as its first time in the experiment.
Conclusion

According to the study results, this special permeable brick with a dense upper layer has the following advantages. (1) The pores of the dense layer on the upper surface of the permeable bricks are small and the particles will not easily enter. (2) The particles will be prevented from clogging the pores or the degree of clogging will be minimized, and thus the cost of cleaning the permeable bricks on a regular basis will be reduced. (3) The compressive strength of this special type of permeable brick is larger than that of the ordinary permeable bricks, and thus the degree of safety will be higher in the practical applications. (4) The permeability of this permeable brick can be self-recovered in the dry state, and thus the ability for water to penetrate will be maintained in the practical applications.

The disadvantage of this special permeable brick with a dense upper layer is that the permeability rate is smaller than ordinary permeable bricks. With the increase in seepage time, the infiltration rate will gradually decrease. As a result, this type of permeable pavers may not be most suitable for applications in the areas with long-duration and frequent rain fall events.
Further Research

Some recommendations for further research are described below:

- A permeable brick with a dense layer is theoretically able to organize the particles into the brick body. In order to verify its use, you can design the experiment. Penetration experiments can be conducted using sand-containing water and compare with changes in the permeation rate using pure water experiments. In the experiment, observe whether there is particulate matter flowing from below the brick. After the experiment, the brick can be scanned to see if there are particles in the brick.

- The upper dense layer and the lower coarse layer of the permeable brick are made of different materials, and the porosities are not the same. The dense layer can be scanned using a higher-precision scanning instrument. The porosity and pore size of the dense layer can be analyzed. Thus the infiltration process can be further analyzed.

- Through the previous experiments we understand the permeability of permeable brick will need time to restore. In the subsequent study we can select a region and analyze the practicality of permeable bricks according to the distribution of precipitation in this area. The numerical simulation model can be used to simulate response of the infiltration rate of the permeable brick to the precipitation over a long period of time.
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