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HYDROLOGIC PROPERTIES OF PERVIOUS CONCRETE

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ABSTRACT. *Pervious concrete is concrete made by eliminating most or all of the fine aggregate (sand) in the concrete mix, which allows interconnected void spaces to be formed in the hardened product. These interconnected void spaces allow the concrete to transmit water at relatively high rates. The main objective of this project was to conduct research on the potential application of pervious concrete in agricultural settings, specifically for use in animal feed lots, manure storage pads, animal manure and bedding compost facilities, or floor systems in animal buildings. Laboratory tests were conducted on replicated samples of pervious concrete formed from two rock sources (river gravel and limestone) for coarse aggregates and different size fractions to determine hydrologic relationships. Linear relationships were found between density and porosity, density and permeability, porosity and permeability, and porosity and specific yield. The results suggest that properties such as permeability, porosity, and specific yield are not significantly affected by different aggregate types. However, density and porosity can be effective methods for predicting porosity, specific yield, and permeability. In addition, t-tests were conducted to determine the effect of aggregate types on the solid/liquid separation properties of the pervious concrete after adding composted beef cattle manure and bedding to the surface of the specimens. The amount of composted beef cattle manure and bedding retained within the specimens was significantly less ($p = 0.012$) when samples constructed of #8 river gravel were used rather than the other aggregates. The #8 river gravel also had significantly less reduction in permeability compared to other aggregates. Although the #8 river gravel had a different effect on the compost retained and the reduction in permeability for the specimens, all four aggregates exhibited a significant reduction in the permeability after the compost was applied.*

Keywords. *Compost, Concrete, Density, Filtration, Pavement, Permeability, Porosity.*

Water quality is one of our most important environmental issues. Water quality can be impaired by various sources, including agricultural practices, urban development, and mining/industrial activities. In the *National Water Quality Inventory: 1998 Report to Congress*, the U.S. Environmental Protection Agency (EPA) associated the leading sources of stream impairment in the U.S. with agriculture. Animal feeding operations were identified as contributing 16% of the total pollution from agricultural practices resulting in stream impairment (USEPA, 2000). Current operational practices include confinement barns, handling facilities, manure storage pads, animal manure and bedding compost facilities, and paved feedlots that concentrate animals and their waste products. One of the major problems with these practices is the use of concrete or other impervious surfaces that contribute to increased runoff and increased levels of total pollutants in the runoff from these facilities. Research has shown that separating solid particles and sediments from a wastewater stream can reduce excess nutrients, pathogens, and other toxic substances (USDA-NRCS, 1997). As water quality standards become more stringent, further development of the treatment systems is necessary to optimize the reduction of pollutants in natural environments. A key component to the refinement of these treatment systems is the reduction of runoff.

Pervious concrete has been used for many years to reduce runoff in urban settings and could be a promising component in the treatment of wastewater from agricultural facilities, more specifically in animal production operations. Pervious concrete consists of Portland cement, uniform-sized coarse aggregate, and water. Chemical admixtures, supplementary cementitious materials (such as fly ash or slag), fine aggregate, and fiber reinforcement may also be used. Eliminating of most or all of the fine aggregate in the concrete mix provides void spaces in the hardened concrete, essentially gaps between the coarse aggregate particles, which are held in place by the cement paste. This interconnected void structure allows for rapid water flow through the concrete matrix (Ghafoori and Dutta, 1995a).

Researchers have conducted laboratory tests to determine the physical properties of pervious concrete. Four properties that have typically been the focus of these investigations include: density, porosity, permeability, and compressive strength (Malhotra, 1976; Ghafoori and Dutta, 1995b; Crouch et al., 2003; Yang and Jiang, 2003; Sung-Bum and Mang).

The density and porosity of pervious concrete depend on various factors, including the material properties, the proportions of materials, and the methods used for placement and

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compaction. Pervious concrete densities typically range between 1,570 and 2,000 kg/m^3 (Ghafoori and Dutta, 1995b; Tennis et al., 2004). During laboratory experiments, Ghafoori and Dutta (1995c) varied the density of pervious concrete specimens by changing the amount of coarse aggregate in the mix designs. Reducing the amount of coarse aggregate resulted in an increase in density due to the lower specific gravity of coarse aggregate compared to Portland cement.

Porosity is a measure of the void space between the coarse aggregate particles. Methods for determining the porosity of pervious concrete from field cores have recently been researched (Montes et al., 2005). Individual void sizes can be controlled to some degree by the size of the coarse aggregate used in the concrete mix. Mix designs utilizing larger aggregates result in larger void spaces, while smaller aggregates result in smaller and more numerous void spaces. It could be possible to develop a method for filtering desired particles from a fluid based on the aggregate size by controlling the size of the individual voids. Total void space can also be affected by the methods utilized for placement and compaction. Crouch et al. (2003) found that high-density paver placement resulted in "lower mean effective voids" (18.4% voids) compared to the same pervious concrete mixture placed by hand (27.8% voids). Adequate compaction of pervious concrete is necessary to ensure that aggregates are tightly adhered to one another.

The permeability of pervious concrete is directly related to the porosity of the mixture and is, therefore, controlled by the materials, proportions, and placement techniques. Increasing compaction effort will reduce the porosity of the pervious concrete mixture, which will in turn reduce the permeability. Modifying the size of aggregates or the aggregate-cement ratio will also change the porosity of the mixture and offers another method for controlling pervious concrete permeability. Flow rates in pervious concrete mixtures typically range from 2.0 to 5.4 L/s/m^2; however, flow rates in excess of 11.5 L/s/m^2 have also been measured (Ghafoori and Dutta, 1995b; Tennis et al., 2004). Controlling the permeability of pervious concrete allows for the control of effluent discharge rates in pervious concrete installations.

The compressive strength of pervious concrete is of particular importance because potential applications can be limited by the strength of the concrete (Crouch et al., 2003; Yang and Jiang, 2003). Compressive strengths in the range of 3.45 to 12.76 MPa can be attained that make pervious concrete suitable for several different applications. Major factors influencing the strength of a given mixture include the types of materials, the proportions of those materials, and the methods used for placement and compaction (Tennis et al., 2004). Laboratory tests have demonstrated that the compressive strength of pervious concrete is inversely related to the void content (Crouch et al., 2003).

Because limited information exists on the ability of pervious concrete to provide solid/liquid separation, additional studies are necessary to determine the potential performance of pervious concrete in these applications. By observing pervious concrete installations in urban settings, researchers have determined that failure due to clogging is possible (Thelen et al., 1972; MCIA, 2002). However, no studies have been conducted to determine to what extent clogging will occur or how different materials will affect clogging. For agricultural purposes, more research is needed to determine to what extent materials such as animal waste, composted animal waste and bedding, or animal feed could affect clogging in pervious concrete. It is thought that pervious concrete could be used for the control and treatment of runoff from animal feeding operations. Grooved concrete floor systems with perforations have been tested for use in cattle buildings in the Netherlands (Swierstra et al., 2001). These floor systems provide adequate slip resistance by allowing some animal waste to pass beneath the floor. Additional tests found that ammonia emissions were reduced by allowing animal urine to drain through the floor system into a storage pit below (Swierstra et al., 2001). The open pore surface of pervious concrete would be an improvement for slip resistance, as with grooved perforated flooring systems.

The purpose of this research project is to study pervious concrete for potential uses in agricultural practices. Pervious concrete flooring could be useful in applications such as animal feeding pads, manure storage pads, animal manure and bedding compost facilities, or floor systems in animal buildings. The study focused mainly on the hydrologic properties of pervious concrete that pertain to animal production facility applications. Tests were performed to determine the porosity, permeability, and water retention characteristics of pervious concrete mix designs before and after beef cattle manure and bedding compost material had been added to the pervious concrete specimens. Material retention properties were examined after the compost was placed on top of the specimens to determine if effective solid/liquid separation is possible using pervious concrete.

MATERIALS AND METHODS

TEST MATERIALS

The pervious concrete specimens used for testing were 0.45 m in length and width with a thickness of 140 mm. Sixteen mixtures were created from four aggregate sizes while varying the use of fibers and fly ash in the pervious concrete. Each of the mixtures received 90 kg of water, 4.4 g of an air-entraining admixture per 100 kg of cementitious material (cement or cement plus fly ash), and 0.93 g of a retarding admixture per 100 kg of cementitious material. Three replicates were made for each mixture, resulting in a total of 48 specimens. The proportions of materials in each of the 16 mix designs are listed in table 1. A 0.25 m^3 concrete mixer was used for mixing, and the pervious concrete was placed by hand in forms fabricated from 38 × 140 mm lumber. The concrete was placed into the forms in one lift and struck off 15 mm above the final height of 140 mm. The pervious concrete was then compacted using a steel hand roller 45 kg in weight and 1 m in width. The compaction of the specimens was stopped when the final height of 140 mm was achieved. Once compaction was complete, the specimens were covered with plastic and allowed to cure for 28 days.

A sieve analysis of the four aggregate types indicated that the #8 river gravel, #57 river gravel, #9 limestone, and #57 limestone corresponded to D_{50} (particle size corresponding to 50% passing) particle sizes of 6.9, 11.0, 12.1, and 13.7 mm, respectively. The coefficient of uniformity (C_u) for the aggregates was 15 for the #8 river gravel, 3 for the #57 river gravel, 5 for the #9 limestone, and 2 for the #57 limestone.

Table 1. Pervious concrete specimen mix design proportions.[a]

Pervious Concrete Mix Designs	Coarse Aggregate (1227.3 kg)		Cement (272.2 kg)	Cement (227.3 kg)	Fly Ash Class F (45.5 kg)	Fiber (0.45 kg)
1-4	#8	River gravel	1,2	3,4	3,4	2,3
5-8	#57	River gravel	5,6	7,8	7,8	5,7
9-12	#9	Limestone	9,10	11,12	11,12	9,11
13-16	#57	Limestone	13,14	15,16	15,16	13,15

[a] The mixture identification is listed below each component.

The C_u of an aggregate is found by dividing the D_{60} value (particle size corresponding to 60% passing) by the D_{10} value (particle size corresponding to 10% passing) for the aggregate. A C_u value less than 4 indicates a well sorted (narrow particle size distribution) aggregate, while a C_u greater than 6 indicates a poorly sorted (wide particle size distribution) aggregate.

TEST METHODS

Density

The bulk density (kg/m^3) of each specimen was calculated by dividing the weight of the specimen by the respective volume.

Porosity, Specific Retention, and Specific Yield

The specimens were placed in a container of known volume. Water was added to the container until the specimen was completely submerged. Additional water was added on 30 min intervals to maintain submersion of the specimen. After 1 h, the volume of water required to fill the container was recorded. The water was drained from the specimen in place using a valve in the bottom of the container, and the volume of recovered water was recorded. The void volume was calculated by subtracting the difference in container and specimen volumes from the volume of water required to fill the container. The porosity (cm^3/cm^3) of the specimen was determined by dividing the volume of voids in the specimen by the volume of the specimen. Specific retention represents the percentage of water that remained in the specimens immediately after the water was drained from the container. The specific retention of each specimen was calculated by dividing the volume of water retained in the specimen (after draining) by the volume of the specimen. Specific yield represents the percentage of water that freely drained from the specimens. The specific yield was determined as the difference between the porosity and specific retention for each specimen.

Permeability

A constant-head permeameter designed in the laboratory was used to measure the permeability. The specimens were placed in the apparatus, which was designed to maintain a vertical column of water above the surface of each specimen. The apparatus was clamped around each specimen and seals restricted the flow of water such that water entered and exited only through the top and bottom of each specimen. The water level was maintained at 76 mm above the specimen surface. This ensured that turbulence on the surface would not affect the flow of water into the specimen. The flow rate was measured using a flowmeter (ISCO UniMag 4401 magnetic flowmeter) in the water line. The flow rate was adjusted until a constant head of 76 mm was maintained above the specimen for 10 min. When flow equilibrium was reached, the rate of flow through the specimen (L/s) was recorded. The permeability of each specimen was calculated by dividing the recorded flow rate by the surface area for each specimen (L/s/m^2).

Solid/Liquid Separation Testing

Composted beef cattle manure and bedding was used as the material to evaluate solid/liquid separation efficiency because it provided, essentially, equivalent particle sizes of manure and wood shavings associated with typical beef cattle and dairy operations, without the accompanying pathogens and odor. Composted beef cattle manure and bedding will be referred to as "compost." The amount of compost added was designed to reproduce the approximate height and area of fecal material that could be deposited based on the size of average feeder cattle.

The solid/liquid separation properties of the pervious concrete specimens were determined by the following test procedures. Four hollow cylinders constructed of schedule 40 PVC pipe, each with a 100 mm interior diameter, were placed on the specimens. Each cylinder was filled with a known amount (oven-dry weight) of organic matter in the form of compost. The four cylinders limited the contact area between the compost and specimen to 0.031 m^2 or approximately 15% of the total surface area. One liter of water was poured into each of the cylinders. After 24 h, another 1 L of water was poured into each of the cylinders. The 2000 mL of water represents a depth of 254 mm in accumulated rainfall, approximately one-fifth of the average yearly accumulated rainfall for Kentucky based on the area of the cylinders. The effluent was captured to determine if any solid material passed through the specimens, but this was determined to be negligible. The compost remaining in each cylinder was removed by sliding a thin sheet of metal between the cylinder and the surface of the specimen. This ensured that the compost would not be pressed into the specimen or exposed to the surface of the specimen outside the cylinder. Any of the compost material that had become attached to the cylinders was removed and placed with the compost removed from the surface of the specimens. The compost was oven-dried at 105°C for 24 h, and the oven-dry weight was recorded. The difference between the oven-dry weight of compost added to the specimen and the oven-dry weight of compost removed from the specimen was used to calculate the percentage of compost retained on the surface. The permeability was retested utilizing the procedures previously described. Data from the second permeability test were used to determine how the addition of compost to the surface of the specimens affected water infiltration rates.

Statistical Analysis

The experimental results for density, porosity, specific retention, specific yield, permeability, and compost retention were tested for normality. If the results were normally distributed, the statistical analysis proceeded with testing for

Table 2. Results of t-test for effects of aggregate type on specimen physical properties.[a]

Aggregate		Mean Density (kg/m^3)	Mean Porosity (%)	Mean Specific Retention (%)	Mean Specific Yield (%)
#8	River gravel	1817 a	27.0 a	7.0 a	20.0 a
#9	Limestone	1869 b	25.8 a,b	6.2 b	19.6 a,b
#57	River gravel	1933 c	23.3 b,c	6.1 b	17.3 b
#57	Limestone	1925 c	21.3 c	6.8 a	14.6 c

[a] Mean values followed by the same letter are not significantly different ($p \geq 0.05$).

trends, relationships, and treatment effects. Linear regression was performed on the data collected to determine if trends or relationships existed between the pervious concrete properties. In addition, t-tests were conducted to determine if the use of aggregate types as treatments resulted in a significant difference in any of the pervious concrete properties that were measured. The t-tests were conducted using the two-tailed least significant difference (LSD) test with an alpha value equal to 0.05 (Montgomery, 1997).

EXPERIMENTAL RESULTS

DENSITY

The density of the pervious concrete specimens varied from 1,739 to 2,023 kg/m^3. The p-value of the F statistic for the effect of aggregate type on density was less than 0.0001, indicating that there was a highly significant difference among the aggregates. The #57 limestone and #57 river gravel aggregates did not show a significant difference between their mean densities (table 2).

POROSITY

The porosity of the pervious concrete specimens varied from 16.9% to 32.9%. The p-value of the F statistic for the effect of aggregate type on porosity ($p = 0.0004$) indicated that there was a significant difference among the aggregates. There was a significant difference between the #8 river gravel and #57 limestone/river gravel aggregates (table 2). A similar difference was noted when comparing the #57 limestone to the #8 river gravel and #9 limestone aggregates. This supports the idea that a similar porosity can be achieved with different aggregate types and sizes. The porosity of the specimens appeared to follow a consistent trend with respect to the measured density. The relationship between the specimen density and porosity was analyzed by performing linear regression. For the range of densities studied, the linear regression revealed a significant ($p \leq 0.05$) inverse relationship between the density and porosity of the specimens (fig. 1).

SPECIFIC RETENTION

The specific retention of the specimen represents the portion of the total porosity that does not readily drain after saturated conditions have been reached. Water can be retained in the micropores associated with the matrix, within the aggregates, and within dead-end pores that do not freely drain. The specific retention of the pervious concrete specimens varied between 4.5% and 7.5%. The statistical analysis indicated significant differences in the specific retention values based on aggregate type ($p < 0.0001$). The treatment analysis results showed no significant difference in the effect on specific retention between the #8 river gravel and #57 limestone; however, both are different from the #9 limestone and #57 river gravel (table 2). Aggregate porosity (limestone vs. river gravel) and size may have affected specific retention differently; however, no relationship was determined from the data available. There was no significant relationship between specific retention and density or porosity based on linear regression ($p \geq 0.05$).

SPECIFIC YIELD

The specific yield of the specimens represents the portion of the total porosity that readily drains after saturated conditions have been reached and is a reflection of the connectivity between pores. The specific yield for the

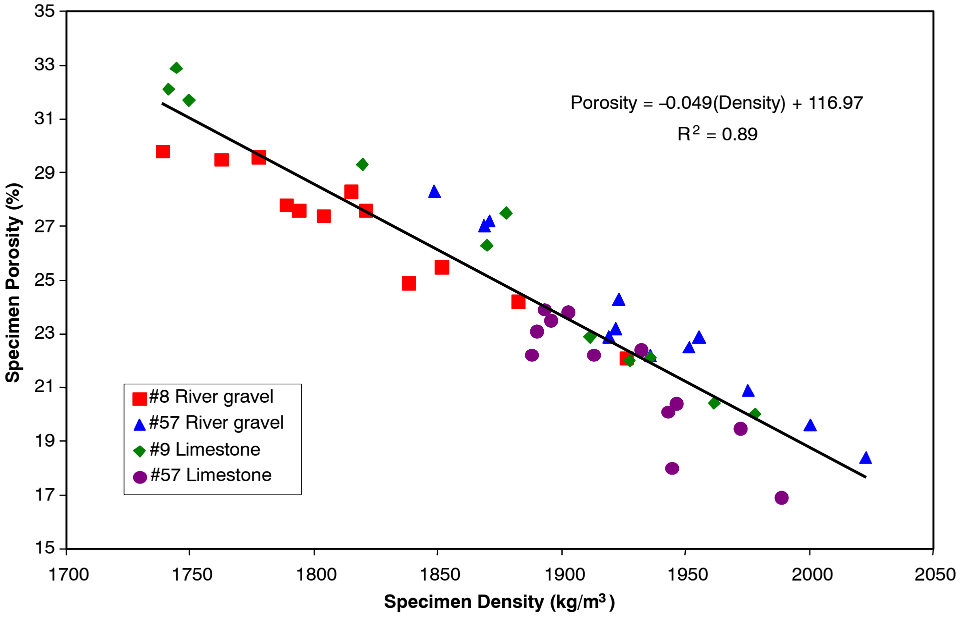

Figure 1. Specimen porosity versus density.

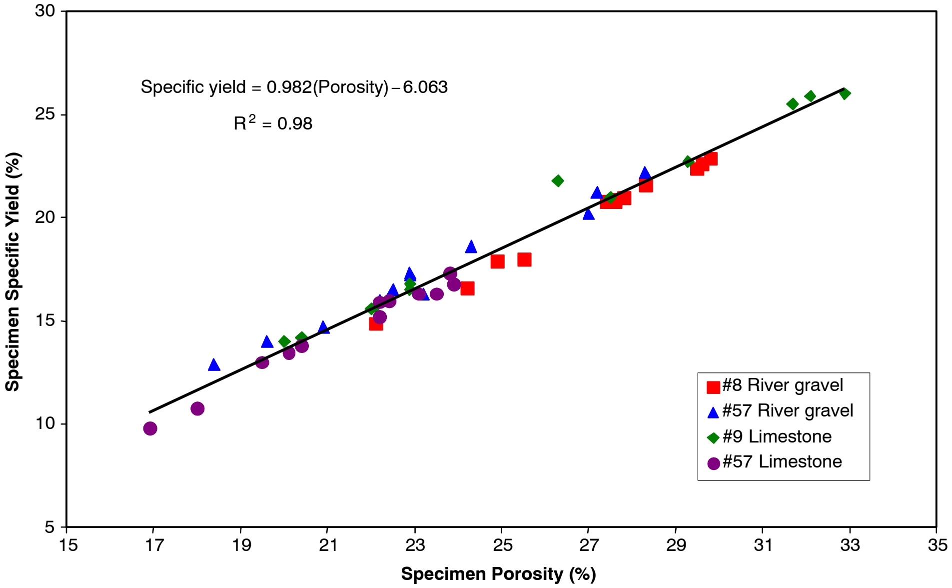

Figure 2. Specimen specific yield versus porosity.

pervious concrete specimens varied between 9.8% and 26.0%. There were significant differences among the aggregate types ($p = 0.0005$). The treatment analysis results (table 2) show a significant difference in specific yield between the #57 limestone aggregate and all other aggregate types. A significant difference was also found between the specific yields of #8 and #57 river gravel. The specific yield measured for the specimens followed a similar trend as specimen porosity. Linear regression revealed a significant relationship between the specific yield and porosity of the specimens (fig. 2).

Permeability

The permeability of the pervious concrete specimens ranged between 4.2 and 25.0 L/s/m^2. There was a significant effect of the different aggregates ($p < 0.01$) (table 3). The #57 limestone aggregate had a significantly lower permeability than the #8 river gravel and #9 limestone aggregates. The regression model for specimen density and permeability suggests that if the density of the concrete mixture were to increase, the permeability would be greatly reduced (fig. 3). The loss of permeability would be attributed to the lack of interconnected voids in the mixture at high densities.

The relationship between the specimen porosity and permeability was also analyzed by performing linear regression on the data collected (fig. 4). As the porosity is reduced, the interconnected voids are eliminated, greatly reducing the permeability of the pervious concrete. Therefore, at a low value of porosity, the pervious concrete would be ineffective at allowing water to infiltrate rapidly through the matrix.

Compost Retained

The compost retained represents the percent of added compost that was retained within the specimen (table 3). There were significant differences among the aggregate types ($p = 0.012$). Significantly less compost was retained in the #8 river gravel aggregate compared to all other aggregate types. The #8 river gravel aggregate consisted of a much smaller particle size (D_{50} of 6.9 mm) and less uniform mixture (C_u of 15) than the other three aggregates. As a result of smaller individual pores at the surface, less compost penetrated into the specimens. In addition, the method used for removing compost was more effective on specimens made with #8 river gravel than on the other aggregate types. This was due to the smoother surface that was achieved during the compaction of the specimens made with the #8 river gravel. Overall, the pervious concrete was effective in separating liquid and solids. Less than 8% of the compost was retained in the matrix even after 2000 mL of water was applied.

Reduction in Permeability

The reduction in permeability measures the percent loss of permeability between the initial values and the values after compost had been added to each specimen (table 3). The percent reduction in permeability for the specimens ranged from 1.3% to 77.3%. There were significant differences among the aggregate types ($p = 0.0009$). Reduction in permeability was significantly less in the #8 river gravel than other aggregate types (table 3). The specimens made with #8 river gravel retained significantly less compost, which could

Table 3. Results of t-tests for effects of aggregate type on specimen permeability.[a]

Aggregate		Mean Initial Permeability (L/s/m^2)	Mean Compost Retained (%)	Mean Permeability After Compost (L/s/m^2)	Mean Reduction in Permeability (%)	Significant Difference in Permeability
#8	River gravel	14.0 a	2.8 a	11.1 a	22.2 a	Yes
#9	Limestone	13.1 a	7.2 b	7.8 a,b	48.0 b	Yes
#57	River gravel	11.3 a,b	6.1 b	6.1 b,c	46.2 b	Yes
#57	Limestone	7.2 b	5.7 b	3.3 c	52.8 b	Yes

[a] Mean values followed by the same letter are not significantly different ($p \geq 0.05$).

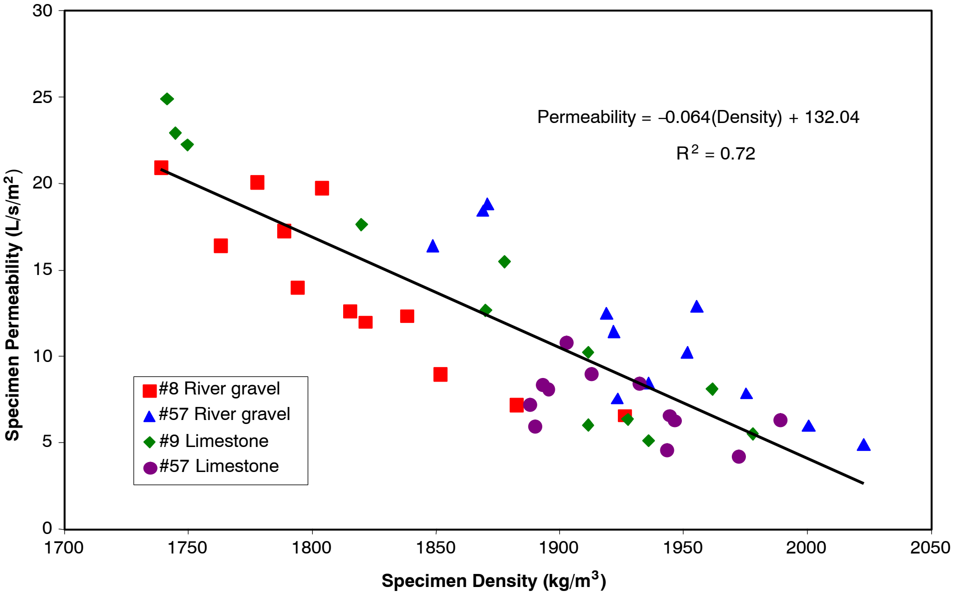

Figure 3. Specimen permeability versus density.

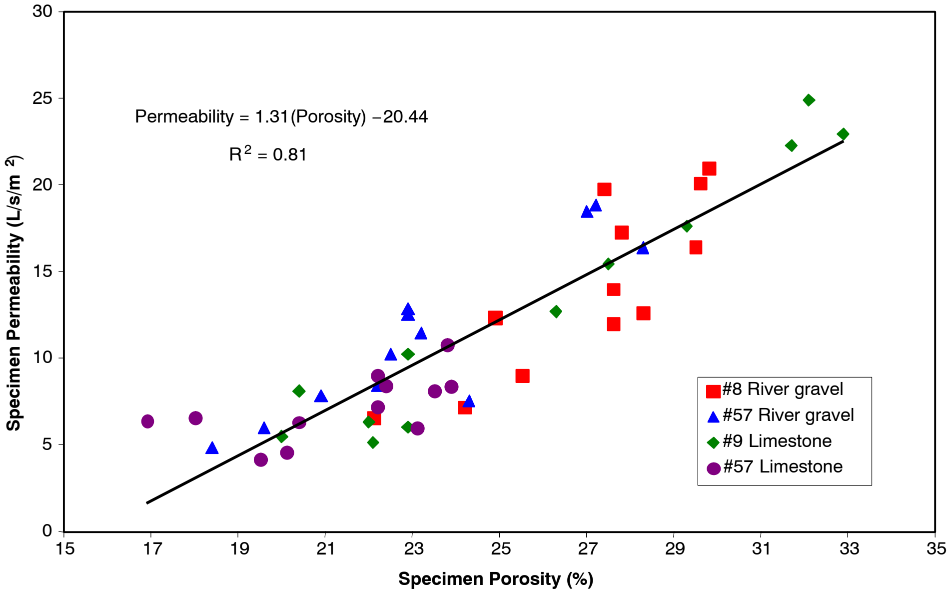

Figure 4. Specimen permeability versus porosity.

be one reason why these specimens experienced less reduction in permeability. To determine if compost addition significantly affected the specimen permeability, a t-test was conducted to determine if there was a significant difference in permeability before and after compost addition (table 3). The results indicated that permeability was significantly reduced in all four aggregates (p-values < 0.0001 for all aggregates).

CONCLUSIONS

Pervious concrete has been used in urban settings to limit runoff from paved areas. There is potential for pervious concrete applications in agricultural settings to reduce runoff and provide solid/liquid separation with wastewater. Sixteen combinations of aggregate type and size were tested to determine the hydrologic properties of pervious concrete mixtures. There were significant differences in the densities of the four different aggregates. Although aggregate type had an effect on the remaining hydrologic properties, specimen density was the best predictor of hydrologic conditions. For these properties, linear regression revealed significant relationships between density and porosity, density and permeability, porosity and permeability, and porosity and specific yield. Therefore, density and porosity can be an effective method for predicting porosity, specific yield, and permeability. Low values of specific retention (4.5% to 7.5%) indicated that water was not readily retained in the pervious matrix.

The test results suggest that pervious concrete would be effective at providing solid/liquid separation in agricultural settings. Negligible amounts of compost were collected in the effluent from the pervious concrete specimens, and less than 8% of the added compost was retained in the surface voids. The material collected in the surface voids reduced the permeability by 22% to 53%, but the resulting permeability exceeded typical rainfall events. Future research should include long-term testing to determine how pervious concrete behaves over time when exposed to materials that exist in agricultural areas.

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REFERENCES

Crouch, L. K., M. A. Cates, V. J. Dotson Jr., and K. R. Honeycutt. 2003. Measuring the effective air void content of Portland cement pervious pavements. *Cement, Concrete, and Aggregates* 25(1): 16-20.

Ghafoori, N. D., and S. Dutta. 1995a. Building and nonpavement applications of no-fines concrete. *J. Materials in Civil Eng.* 7(4): 286-289.

Ghafoori, N. D., and S. Dutta. 1995b. Laboratory investigation of compacted no-fines concrete for paving materials. *J. Materials in Civil Eng.* 7(3): 183-191.

Ghafoori, N. D., and S. Dutta. 1995c. Development of no-fines concrete pavement applications. *J. Transportation Eng.* 121(3): 283-288.

Malhotra, V. M. 1976. No-fines concrete: Its properties and applications. *American Concrete Institute* 73(11): 628-644.

MCIA. 2002. Pervious concrete: The pavement that drinks. Ridgeland, Miss.: Mississippi Concrete Industries Association. Available at: www.mississippiconcrete.com. Accessed 16 August 2006.

Montes, F., S. Valavala, and L. M. Haselbach. 2005. A new test method for porosity measurements of Portland cement pervious concrete. *J. ASTM International* 2(1): DOI: 10.1520/JAI12931.

Montgomery, D. C. 1997. *Design and Analysis of Experiments*. New York, N.Y.: John Wiley and Sons.

Sung-Bum, P., and T. Mang. 2004. An experimental study on the water-purification properties of porous concrete. *Cement and Concrete Res.* 34(2): 177-184.

Swierstra, D., C. R. Braam, and M. C. Smits. 2001. Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. *Applied Eng. in Agric.* 17(1): 85-90.

Tennis, P. D., M. L. Leming, and D. J. Akers. 2004. *Pervious Concrete Pavements*. Skokie, Ill.: Portland Cement Association, and Silver Spring, Md.: National Ready Mixed Concrete Association.

Thelen, E., W. C. Grover, A. J. Hoiberg, and T. I. Haigh. 1972. Investigation of porous pavements for urban runoff control. Water Pollution Control Research Series. Washington, D.C.: U.S. Environmental Protection Agency.

USDA-NRCS. 1997. Water Quality and Agriculture: Status, Conditions, and Trends (Working Paper 16). Washington, D.C.: USDA Natural Resources Conservation Service.

USEPA. 2000. National water quality inventory report to Congress (305b report): 2000 water quality report. Washington, D.C.: U.S. Environmental Protection Agency. Available at: www.epa.gov. Accessed 16 March 2006.

Yang, J., and G. Jiang. 2003. Experimental study on properties of pervious concrete pavement materials. *Cement and Concrete Res.* 33(3): 381-386.