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Runoff and Pollution Abatement Characteristics of Concrete Grid Pavements

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ABSTRACT

Problems of water quality and quantity have forced many communities to redefine their approaches to local stormwater management. New approaches-alternatives to the conventional means of piping a problem downstream-focus on maintaining predevelopment runoff levels by increasing opportunities for runoff infiltration, by controlling runoff velocities and volumes, and by reducing nonpoint pollutants. Concrete grid pavements have potential as a technology capable of performing these functions, but they have not yet been evaluated to the satisfaction of officials who must endorse or implement stormwater management strategies.

This research measured, in a laboratory setting, runoff volume and pollutant load reductions associated with three types of grid pavements. A concrete slab was used as a control. Reductions in pollutant concentration and mass in water that percolated through the grids in the pavements were also measured. Runoff from the surface of the pavements and from water within the soils beneath the pavements was analyzed for phosphorus, nitrogen, organic carbon, chromium, lead, and zinc.

Results show that the grid pavements greatly reduced runoff volume, as compared to the concrete slab. The masses of 10 pollutants found in the runoff from this slab were much greater than those in the runoff from the grid pavements. The soils beneath the grid pavements acted effecively in removing significant quantities of pollutants from the water at infiltrated into them.

Key Words: Pavement, Concrete Grid Pavement, Urban Runoff, Stormater Runoff, Stormwater Management, Heavy Metals, Nitrogen, Phosphorus, Plant Nutrients

ABBREVIATIONS AND SYMBOLS

g	grams-unit of mass
meq	milliequivalent-unit of ionic charge number
mg	milligram-unit of mass
ml	milliliter-unit of volume
mm	millimeter-unit of length
µm	micrometer-unit of length
pH	negative logarithm of hydrogen ion activity-measure of acidity or basicity of solution
r^2	correlation coefficient-statistical parameter
RPM	revolutions per minute-measure of rotational speed
Cr	chromium-all oxidation states
Pb	lead-all oxidation states
Zn	zinc-all oxidation states
$N0_3$ + $N0_2$-N	nitrate + nitrite nitrogen-oxidized nitrogen
NH_3-N	ammonia nitrogen-includes ammonia plus ammonium
Organic-N	organic nitrogen-generic term for organically bound nitrogen
Total $P0_4$-P	total phosphate phosphorus-generic term for all phosphorus in phosphate form
Ortho $P0_4$-P	ortho phosphate phosphorus
Organic $P0_4$-P	organic phosphate phosphorus-organically bound phosphate
TOC	total organic carbon-generic term for all carbon in organic form

INTRODUCTION

The use of concrete grid pavements for parking surfaces began in Stuttgart, West Germany. While rebuilding post-war Stuttgart, urban planners and architects incorporated the processes of the natural environment in attenuating the urban heat island (phenomenon of higher temperatures in the city than in rural areas), improving local air quality, and reducing urban stormwater runoff. One such technology used throughout the city was the lawned parking lot. Because such lots are paved with concrete grids containing grass, their surfaces reduce the absorption of solar radiation and the storage of excess heat normally associated with solid asphalt or concrete parking lots. These surfaces also reduce the volume of stormwater runoff.

The lawned parking lots of Stuttgart originated from the use of slotted, flexible steel runways for temporary repair of damaged airfields by the United States military forces. In 1961, Stuttgart's municipal authorities borrowed hundreds of these steel runway sections from the U.S. Air Force to serve as temporary parking lots for the first Federal Garden Show. Implementation of Stuttgart's climate-based city plan was already under way at the time, and the idea of converting the garden show's parking facilities around sports stadiums and cultural installations to lawned parking lots to bring additional green space to the inner city was a logical consequence. A sizable building program ensued using perforated confete slabs available from local manufacturers.

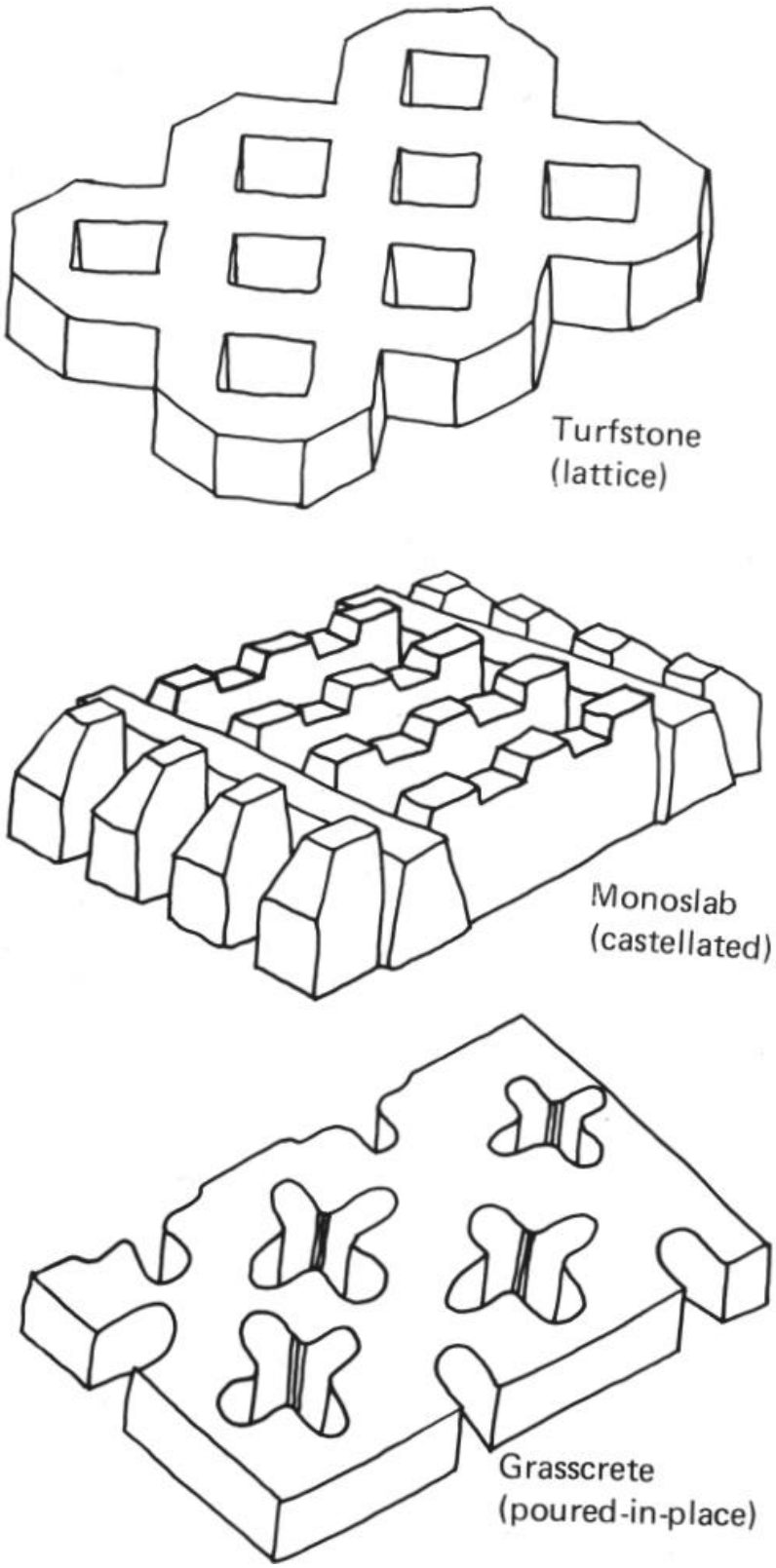
Today, lawned parking lots of many types are found throughout western rope and England. Two major German manufacturers now account the annual sale of hundreds of thousands of square feet. The slabs available in numerous patterns and unit sizes depending on their intended use. European applications of grid pavements include not only parking lots, but slope stabilization, access paths for emergency vehicles around housing projects , and walkways in recreational areas.

Grass paving materials marketed in the United States can be divided into three categories based on their surface configurations and/or method of installation: lattice pavers castellated pavers and poured in place pavers. Latice pavers have a flat grid-like configuration. Castellated pavers are characterized by raised battlements or sections above the major portion of the exposed upper surface. Both lattice and castellated pavers are molded in a fashion similar to concrete blocks and range in surface area from 2 to 4 sq ft. With poured-in-place pavements, concrete is poured over plastic forms containing steel reinforcing bars. Lattice-type products include the Unigreen, Turfstone, and Grasstone brand names. Monoslab and Checkerblock are examples of castellated blocks, while Grasscrete represents a poured-in-place paver. *Figure 1* shows the three grid paver types used in this study.

Although grid pavements see frequent use in Europe, their use in the United States to reduce urban stormwater runoff is limited. Unfortunately, very little runoff quantity or quality performance data exist for these pavements by which an evaluation of their cost effectiveness can be made. For this reason, a laboratory experiment was devised to test and observe these runoff characteristics of certain of the grid pavements. An indoor testing facility that in some ways approximated field conditions was used in the experiments. It is difficult, if not impossible, to duplicate exactly field conditions with bench-scale testing equipment Admittedly, the experimental conditions achieved in this study were less than ideal, but the results were interpreted with these limitations in mind, An advantage of using an indoor testing facility was that certain environ mental conditions could be more easily controlled-soil type and rain fall intensity, for example. Tests were conducted in October and Nov. ember 1980 at Virginia Tech's College of Architecture and Urban Studies Price's Fork Environmental Systems Laboratory in Blacksburg.

Three pavements representing the lattice, castellated, and poured-in-place types currently on the market were selected: Turfstone (lattice), Monoslab (castellated), and Grasscrete (poured-in-place). The Turfstone and Monoslab units measure approximately 24 x 16 x 4 in. and weigh 6!1 and 85 pounds, respectively. Grasscrete is poured to the required size on site. Previous tests by Day [1978] have shown that these pavements reduce runoff quantities by 50 to 80 percent, depending on the soil subase, water saturation conditions, slope, and type of pavement. This experiment focused upon the runoff volume and pollutant load abatement characteristics as well as the removal of pollutants from the infiltrated water. The data generated here represent an initial effort which future in-field studies can support and verify.

FIGURE 1
Representative Grid Pavements Used



MATERIALS AND METHODS

I. Materials

Special equipment was required to conduct laboratory tests on the pavements. Three major components of materials were used in the experiments: a rainfall simulator, pavements and soil subbases, and the sampling apparatus. *Figure 2* illustrates the entire testing apparatus whose components are discussed below.

A. Rainfall Simulator

The rainfall simulator, based on a design described by Chow and Yen [1974], consisted of two boxes, each having inside measurements of 37.25 x 34.25 x 1.75 in. Plexiglas (3/8 in. thick) was screwed and caulked together to form these watertight boxes. In the bottom face of both boxes, 1,400 holes were drilled 1 in. on center. Inserted into each hole was a 1-in.-long blunt, hollow stainless steel needle with an insil diameter of approximately 0.023 in. The size and spacing of these need) provided a raindrop and distribution similar to that of naturally occurri rainfall [Chow and Yen, 1974]. The top of each simulator box wasfitt with a vent hole to aid in unclogging the needles, and a $^{1}/2$-in. opening permit the rainwater to enter these distribution boxes.

These two boxes were suspended in a metal and wooden frame approximately 13 ft. above the ground. This height was equivalent to 8 ft. ab, the surface of the pavements, which yielded a raindrop velocity of at' 75 percent of terminal velocity or 18.4 ft/sec. The frame was equip' with leveling screws on each corner of both boxes. Wheels on the bottom of this frame allowed the rainfall simulator to be moved over each pavement for testing.

Ten 5-gal. carboys were placed 4 ft. above the simulator boxes. T comprised the rainwater reservoir. Plastic tubing and PVC pipe connected' two groups of five carboys each, in parallel. The single tubes from banks of five carboys were routed through valves and flowmeters then into the two simulator boxes. The carboys were filled before rainfall event with well water that had passed through a stone filter, water softener, and deionizer. Rubber hose, without metal fittings, was to convey this deionized water to the carboys. *Figure 3* shows the fall simulator.

FIGURE 2
Laboratory Apparatus Showing Rain Simulator and Testing Bins with the Pavements

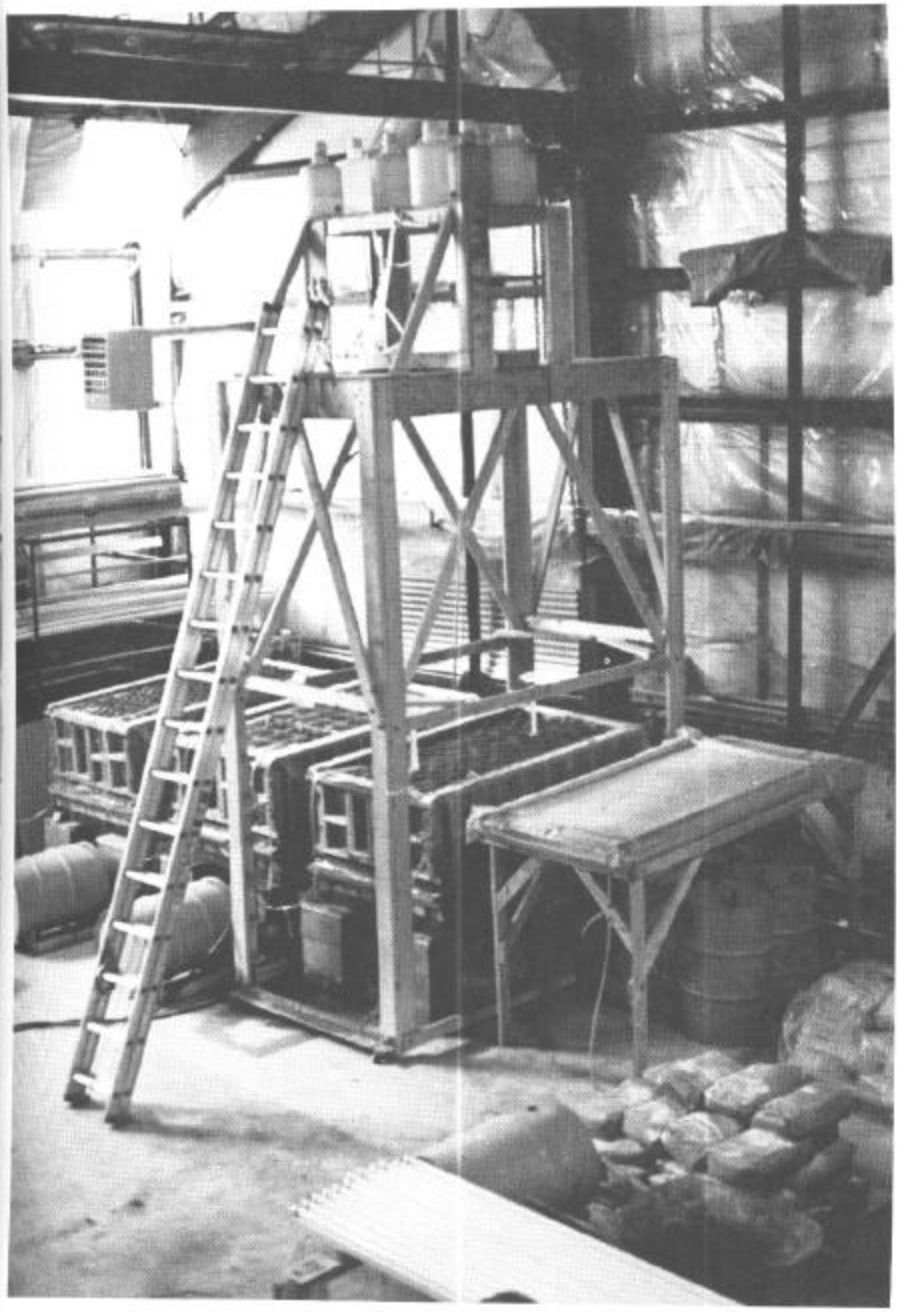
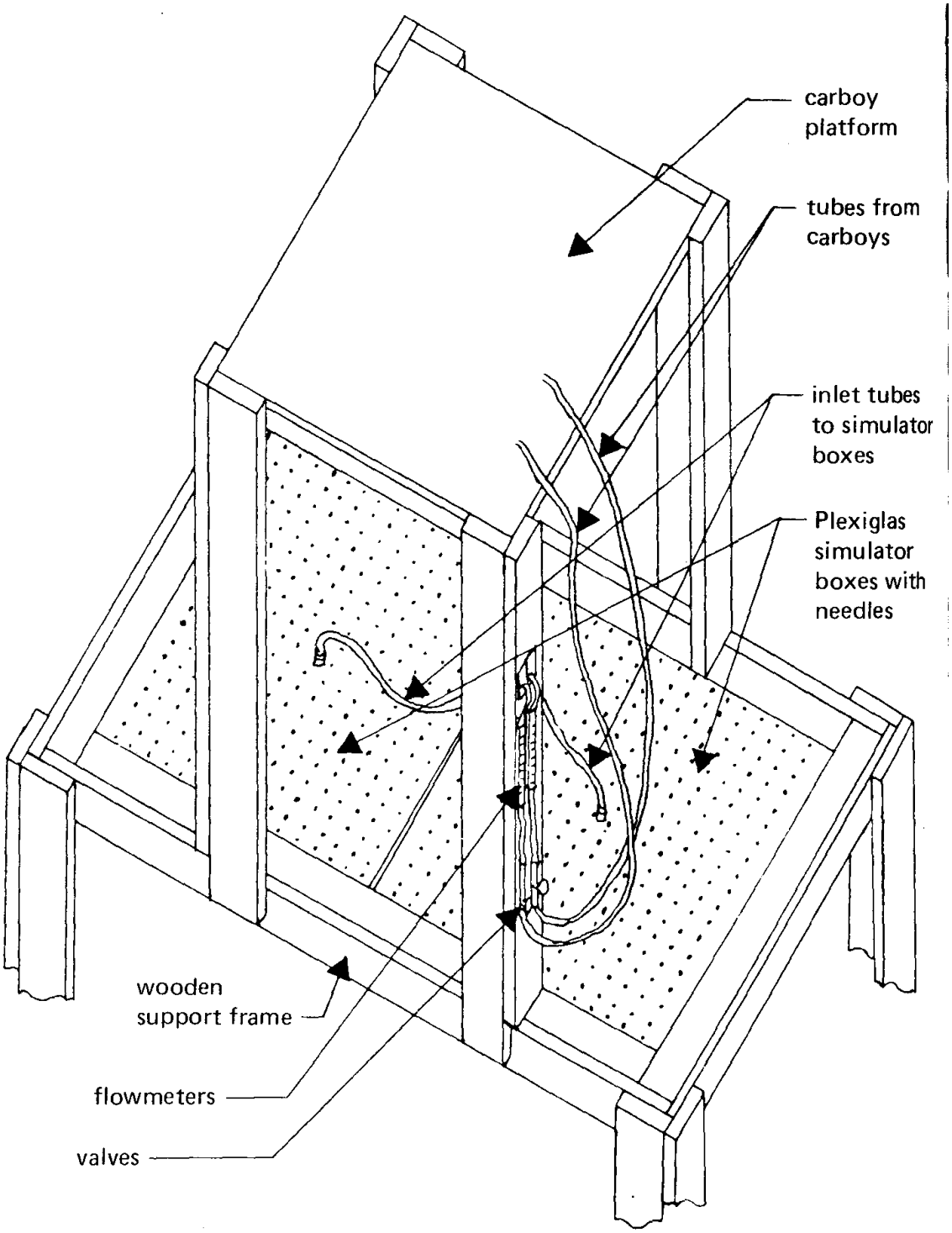


FIGURE 3
Schematic of Rainfall Simulator



Trial runs with this rainfall simulator initially produced intensities greater than those desired. Since it was not possible to substantially lower the intensities by adjusting the valves, every other needle in the simulator was plugged with silicone caulking to reduce the intensity. It was decided that such an action would not seriously affect the rainfall distribution. Filling these needles had the desired effect, and the simulator was able to produce rainfalls of common occurrence, that is, low-return periods. A fair test of the grid pavements' runoff production characteristics should include storms of frequent occurrence; hence, the tests were conducted with simulated rainfall events of low-return period. While a storm of great intensity and duration would probably cause a good deal of runoff from the grid pavements, the frequency of such a storm would be very low, that is, a high-return period, and therefore would be of less interest than a more common storm.

B. Bins

The purpose of the bins was to allow adequate representation of actual parking lot conditions for the grid pavements on a laboratory scale. To this end, the bins were constructed large enough to contain a fair area of pavement surface and deep enough to hold a sub-base and soil layer. Four bins were made of plywood over a wooden frame. Three of the four had dimensions of 71.25 x 39.25 x 24 in. The fourth bin was of the same surface area but only 4 in. deep. The bins were lined with plastic sheeting to render them watertight and were placed at a 4 percent slope to approximate typical parking lot conditions. Steel gutters, coated with an alkyd-oil base paint, were placed on the downslope end of each bin, at both top and bottom. These served to convey surface runoff and sub-surface flow to the measuring devices. Corrugated Fiberglas sheets placed on the bottom of the three bins extended under the front wall of the bins, allowing water that had percolated through the soils in these three bins to be transported via the bottom gutters to the measuring barrels. Measurements of surface runoff and underflow (subsurface flow) volumes were made by the use of 55-gal. drums placed on their sides. The diameters of the ends of these drums were spanned with transparent plastic tubing, which allowed viewing of the water level in each barrel. The plastic tubing was marked off in 5-gal. increments. Plastic tubing connected the two gutters from each bin to two such measuring barrels, and these tubes acted as sampling ports for runoff and underflow.

The three bins to contain the various grid pavements were filled by placing 1 to 2 in. of gravel on the corrugated drains, followed by 10 to 12 in. of Groseclose soil, hand-tamped to a compaction of greater than 2 tons per sq ft. This soil layer was covered, according to the pavement manufacturers' specifications, with 6 in. of gravel and then 1 to 2 in. of sand, lightly tamped and leveled. The grid pavements were then placed on this sub-base. Topsoil was used to fill the voids within the pavements, and a sod mixture of rye grass and tall fescue, obtained from Virginia Tech's Turfgrass Research Center, was then fitted into these voids to complete these three bins. The fourth bin contained a 3-in.-thick slab of concrete to serve as a control for runoff quantity and quality. A detailed characterization of the soils and sand used in these bins appears in *Tables 1* and 2. *Figure 4* shows a cross section of a representative bin.

C. Porous Ceramic Cup Samplers

In addition to sampling surface runoff and underflow, water was sampled within the soil layers of the bins. This sampling had to be done in a manner that would not disturb the soil layers. To accomplish this, porous ceram. is cup samplers were buried in the soil in each bin, and tubes extended from these samplers to the surface through which the samples were drawn,

The ceramic cup samplers used in this study were similar to those de• scribed by Wagner [1962]. The cup portions used were purchased from Soil moisture Equipment Corporation and had diameters of 1.875 in and lengths of 2.75 in. These cups were glued to 4-in. lengths of PVC pipe, the other ends of

which were sealed with two-hole rubber stoppers Glass tubing was inserted into the holes with enough length protruding to affix 5-ft sections of flexible plastic tubing that protruded to the surface of the grass/pavement system. When buried in soil and a sustained vacuum placed on the cups via the plastic tubing, a sample of water could be drawn through the porous cup and removed from the cup and pipe assembly. *Figure* 5 shows a ceramic cup sampler apparatus.

The cups were leached by gravity flow with about 200 ml of 1 *N* hydrochloric acid, followed by about 10 ml of deionized water, as describe by Grover and Lamborn [1970]. Following this, 10 cup samplers we set in a pail of deionized water, and a vacuum of 70-80 centibars was applied to each to measure intake rates. After one hour, the cup sample were emptied, the volume of water in each measured, and the intake rates determined. All cup samplers showed similar intake rates of between 120 and 145 ml/hr.

FIGURE 4

End View Section Through Representative Pavement Bin

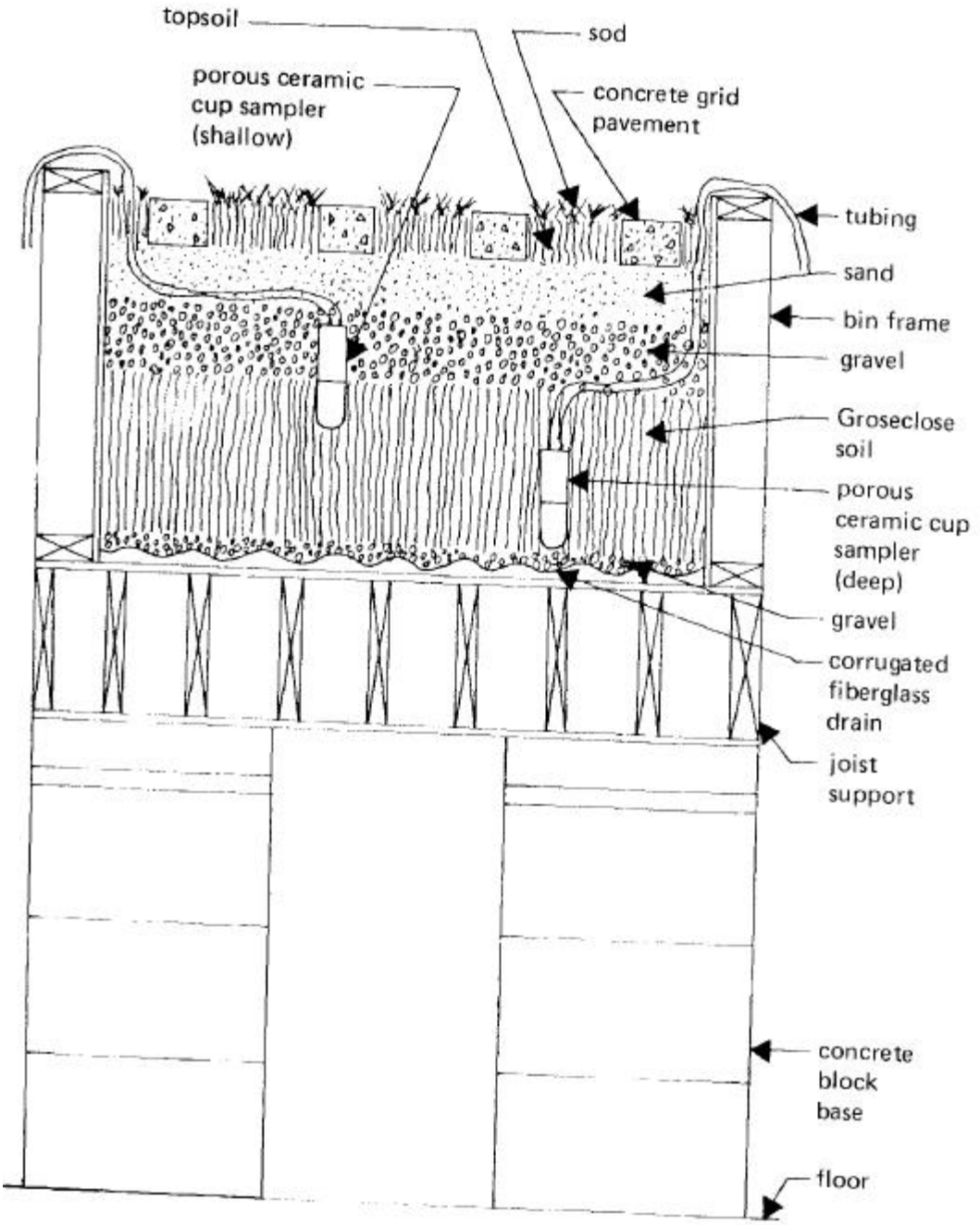
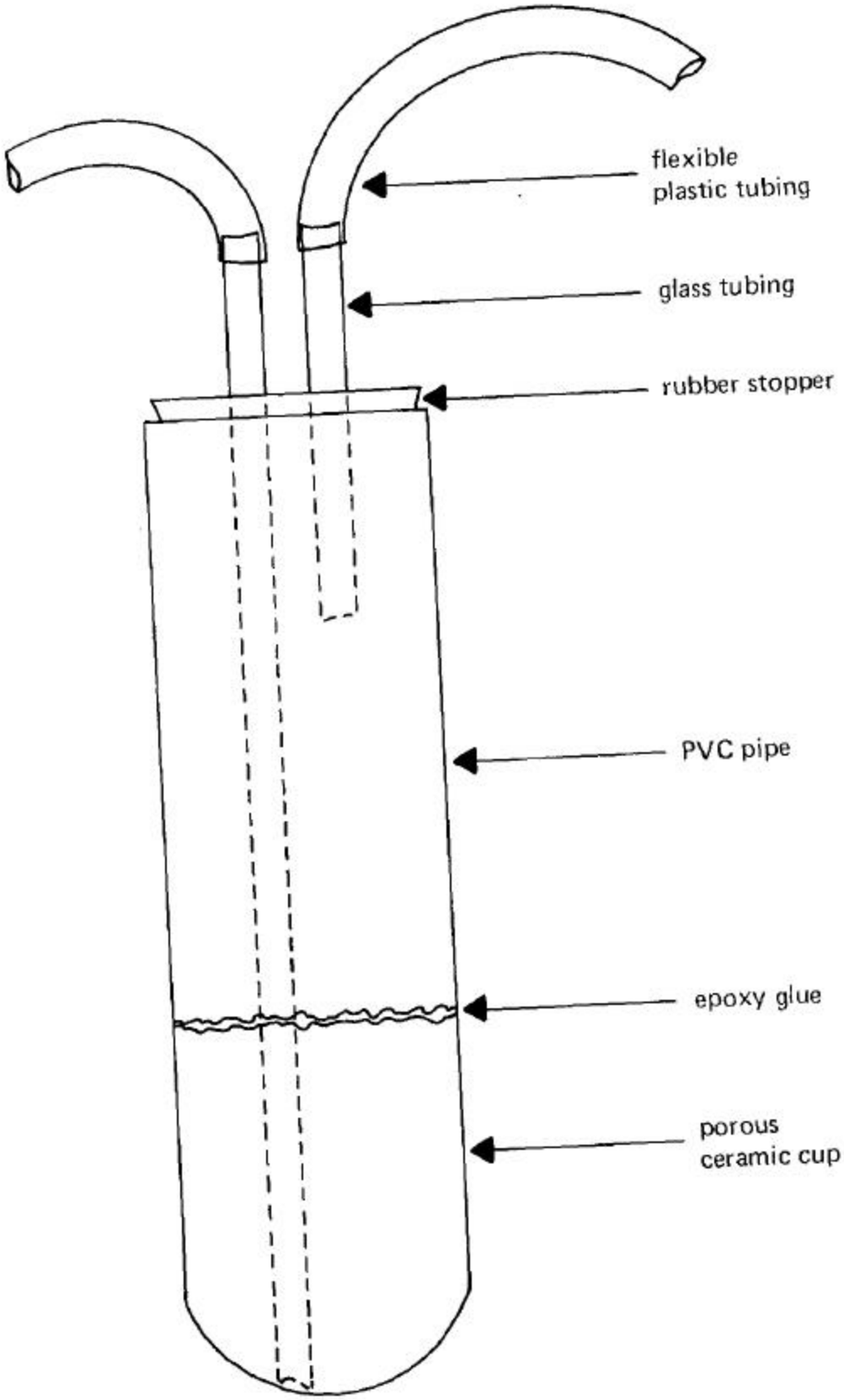


FIGURE 5
Schematic of Porous Ceramic Cup Sampler



After these preliminary tests were completed, four cups were placed in each of the three bins to contain the grid pavements. *Figure 6* shows the location of each cup sampler in the bins. Two samplers were positioned in each bin such that the tops of the ceramic cup portions were parallel with the surface of the Groseclose soil layer. These cup samplers were designated as "shallow" cups. The remaining two samplers were placed such that the bottoms of the ceramic cup portions were within '/2 in. of the bottom of the Groseclose layer. These cups were designated as "deep" cups. The augered holes for these samplers were sprinkled with 1/8 to 1/4 in. of sand, according to the cup manufacturer's recommendation, prior to emplacement of the samplers.

II. Methods

At least 10 rainfall events were simulated on each of the four test pavements and were characterized by variations in both rainfall intensity and duration. Intensities used varied from 0.91 in./hr to 3.54 in./hr. A storm of 1.0 in./hr for 30 minutes is equivalent to a storm in the Washington, D.C., area with a return period of less than two years. A storm of 60 minutes' duration and 2.40 in./hr, for example, has a return period of about 20 years in the Washington, D.C., area. Most of the rainfall events simulated in this study had return periods of less than 10 years. As mentioned before, it was desirable to use storms of common occurrence-thus, the relatively low rainfall intensities and durations.

While every attempt was made to simulate identical rainfall events on each pavement, this was not possible because of inadequacies in the rainfall simulator. Rainfall intensities for each event were computed, based on the volumes of rainfall, the surface areas of the pavement bins, and the event durations.

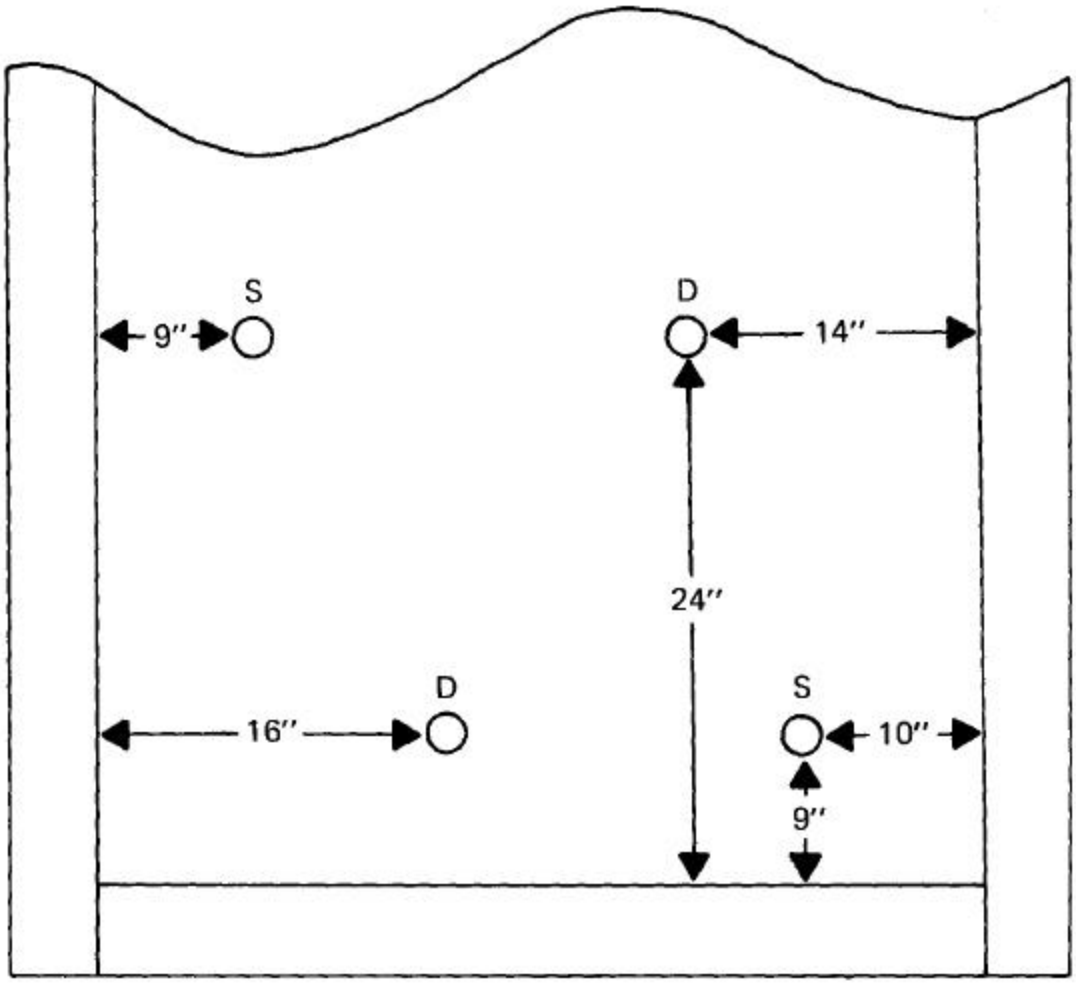
The procedure for generating a rainfall event was as follows. Stock pollutant solutions were made at the beginning of each test day by dissolving carefully weighed amounts of each pollutant form in 100 ml of distilled, deionized water. The 10 carboys that comprised the rainfall simulator's reservoir were filled with deionized water. Ten-ml quantities of the freshly prepared stock pollution were then pipetted into each of the 10 carboys, and 1 N sulfuric acid was added to each carboy to reach a solution pH of between 4.0 and 4.5, as obtained by calculation, to simulate acid rain conditions. This mixture was stirred with a length of plastic tubing to ensure homogeneity. *Table 3* shows the amounts and forms of pollutants used and the concentration of the rainfall yielded.

While there is evidence that rainfall is often contaminated with pollutants, the concentrations are generally much less than those found in urban stormwater runoff. Ideally, the pollutants used in this study should have been applied to the grid pavement/soil surfaces in dry form to simulate more closely the processes that occur in the field. This was considered somewhat infeasible, and the decision was made to dissolve the pollutants in the rainfall, fully realizing the limitations of this.

After the mixture of polluted rainfall had thus been prepared, two graduated cylinders were placed on the surface of the pavement being tested to collect the rainfall samples, and the water level in the appropriate underflow collection barrel was recorded. The valves on the rainfall delivery system were then opened to 100 percent flow for about four minutes to allow the simulator boxes to become wetted over their inside bottom surfaces and to permit rapid leveling of the boxes. After this four-minute period, the valves were adjusted to deliver the desired approximate rainfall intensity. It was necessary to readjust the valves a few times throughout each event to maintain a fairly consistent intensity. At the end of an event, the valves were shut and the rainfall samples were collected. Two hours after the start of an event, the underflow sample was collected and a vacuum was applied to the four cup samplers in the bin. Two to four hours after this vacuum was placed on the cups, it was released, the cups were emptied, and the samples were collected. The specific collection procedures employed are detailed below.

FIGURE 6

Location of Porous Ceramic Cup Samplers in Pavement Bins (Top View)*



front of bin

*S = shallow cup sampler-top of ceramic cup portion even with top of Groseclogsoil layer.
D = deep cup sampler-bottom of ceramic cup portion extends to within ½ in. of bottom of Groseclose soil layer.

A. Water Sample Collection and Analysis

The various water samples collected from each bin were of distinctly different characters, which necessitated different collection procedures for each. The rainfall samples were collected in two plastic graduated cylinders fitted with plastic funnels. One of these cylinders was placed under each panel (front and back) of the rainfall simulator prior to each rainfall event. At the end of each event, approximately equal amounts from each cylinder were combined to yield a sample of sufficient size for analysis.

The in-soil samples were collected by the use of the previously mentioned porous ceramic cup samplers. Two hours after the start of an event, a vacuum of 75 to 80 centibars was pulled on the four cups in the bin being tested. Between two and four hours later, the vacuum in these cups was released and the samples extracted. The samples in the two cups that were located at the top of the Groseclose soil layer (shallow cups) were combined to yield one sample. The deep samples were obtained in a similar manner from the two cups located at the bottom of the Groseclose layer.

The underflow samples were collected two hours after a rainfall event began. As was the case for the in-soil samples, this two-hour lag period was chosen to allow the water from the previous rainfall event to flush out of the soil in the bin being tested, prior to the start of sampling for the event of interest.

Runoff samples were collected from both the concrete slab and any of the three bins containing the grid pavements that produced runoff. Samples from the slab, or control bin, were collected at the halfway point of each event. For example, if the event was to last one hour, the runoff sample would be collected a half hour after the starting time. This was done to allow the rainfall, and thus the runoff concentrations, to reach an equilibrium. The runoff samples from the other three bins containing the grid pavements were collected over the entire duration of each event to obtain enough samples to complete all of the chemical analyses.

All water samples were filtered through Millipore 0.45-pm filters at the time of collection to remove the larger soil particles and permit comparison of filterable (dissolved) components. On the few occasions that run off occurred from one of the bins containing the grid pavers, half of each of the runoff samples was filtered and the other half was not. If there was not sufficient volume for this procedure, the entire sample was filtered. Due to the highly turbid nature of the underflow samples, these were filtered first through Millipore 5.0-pm filters and then throw the 0.45-pm filters. After filtering, water samples were preserved in accordance with *Standard Methods* [American Public Health Association (APHA) et al., 1976).

Water samples were subjected to the following analyses: oxidized nitrogen (nitrate + nitrite), ammonia, organic nitrogen, total phosphate, acid-hydrolyzable phosphate, ortho phosphate, total organic carbon (TOC), lead, zinc, and chromium. All of these analyses were performed in conformance with *Standard Methods. Table 4* indicates the specific procedures used for each analysis.

B. Soil Sample Collection and Analysis

In addition to the water samples described above, samples of the soil, sand, topsoil, and sod soil were collected at the time the bins were filled. Portions of each sample were frozen for subsequent nitrogen analysis, and the remaining portions of the samples were allowed to air-dry for other analyses. Air - dried subsamples were analyzed by the Soil Testing and Plant Analysis Laboratory at Virginia Tech. Analyses of interest performed by the lab were pH, phosphorus, and organic matter. The specific procedures followed by the lab are outlined in Virginia Cooperative Extension Service [1980].

Lead, Zinc, and Chromium: Mix 10 g air-dried, sieved soil (#10 sieve) with 25 ml 0.05 N hydrochloric acid; shake for 15 minutes; centrifuge at 2,500 RPM for five minutes and decant into 50 ml volumetric flask; repeat extraction with another 25-ml portion of hydrochloric acid; shake, centrifuge, and decant centrate; make centrates to 50-ml volume with hydrochloric acid; filter through Whatman #1 filter paper and analyze for lead, zinc, and chromium by atomic absorption spectrophotometer (adapted from Boswell [1975]; Giordano and Mortvedt [1976]).

Total Nitrogen: Mix 200 mg air-dried, sieved (50-mesh sieve) soil with 1.5 Kel Pak mercury catalyst in 50-ml graduated cylinders; add 2.5 ml concentrated sulfuric acid, stir, and put into digestion block; digest until an aqua-green color appears and then for an additional 30 minutes (about three hours); add distilled, deionized water slowly to bring solution to 50-ml volume; determine ammonia concentration with specific ion electrode [Nelson and Sommers, 1972].

Oxidized Nitrogen: Combine 2.5 g air-dried, sieved soil and 25 ml 2 N potassium chloride; shake for one hour, centrifuge at 5,000 RPM for five minutes; filter through Whatman #1 filter paper; analyze filtrate by cadmium reduction method [APHA et al., 1976].

Cation Exchange Capacity : Combine 2.5 g air-dried, sieved soil and 25ml 1*N* sodium acetate (buffered at pH = 4.8); shake for five minutes, centrifuge at 2,500 RPM for five minutes, and discard centrate; repeat procedure twice; repeat above procedure three times with 15-ml aliquots of 1 *N* sodium chloride; repeat procedure twice with 15 ml aliquots of propanol; displace sodium by adding 15 ml 1 *N* ammonium acetate (pH = 7.0) to soils, shaking, centrifuging, and decanting centrate into 100-ml volumetric flasks; repeat procedure twice and make contents of flasks up to volume with the ammonium acetate; analyze for sodium by atomic absorption spectrophotometer [Black (Pt. 2), 1965].

Particle-size analyses were performed on the soil samples by technicians in the soil testing lab of Dr. D. Amos, Agronomy Department, Virginia Tech. This lab employed the pipette method for clay-size material fractionation [Black (Pt. 2), 1965]. Standard sieves were used to separate the sand and silt fractions.

RESULTS

The purposes of this study were to observe and document the effects of the three grid pavements on runoff quality and quantity and to observe and document the effects of the soil under the pavements on the quality of water passing through them. The following results begin to fulfill these two objectives, while a more detailed treatment of them is contained in *Discussion (p. 24).*

I. Runoff Volume

Tables 5-8 contain data characterizing the rainfall events that occurred on the three grid pavements and the concrete slab. Rainfall intensities were calculated from rainfall volumes, durations, and the surface area of each test bin. Every attempt was made to ensure that identical rainfall events were simulated on each pavement, but some variability was, of course, expected. A comparison of average overall rainfall volumes and intensities used on each pavement type reveals that these conditions were kept reasonably constant. A striking feature of the data in these *Tables is* that no runoff was observed on Monoslab or Turfstone in any instance. The runoff volumes for Grasscrete were exceedingly low also.

A convenient measure employed to compare runoff production potential of various surfaces is the coefficient of runoff, a value computed by dividing runoff volume by rainfall volume. The resulting value is, therefore, dimensionless and theoretically ranges between 0 and 1.0. This procedure expresses the runoff as a percentage of the rainfall. Such coefficients have been computed for the corresponding runoff volumes observed and appear in *Tables 5-8.*

Linear regression analyses were performed on the runoff data for Grasscrete and the concrete slab. In particular, it was desired to determine whether runoff volume was a linear function of either rainfall volume or rainfall intensity, and similarly, whether the coefficient of runoff was a linear function of rainfall volume and/or intensity. *Tables 9* and *10* contain the correlation coefficients for each of these four functions for Grasscrete and the concrete slab.

II. Runoff Quality

Table 11 contains the average concentrations of each pollutant measured in the filtered and unfiltered portions of the runoff of Grasscrete and the slab. It should be noted that for the slab, the unfiltered samples characterize runoff resulting from different rainfall events than that for the filtered samples. For Grasscrete though, the unfiltered and filtered portions were derived from the same sample for the various events. In the case of the unfiltered portions, the average concentrations in the runoff from Grasscrete are somewhat higher than those in the runoff of the concrete slab. Notable exceptions to this trend are the three heavy metal concentrations, in which the runoff of the slab is much more concentrated than that of Grasscrete. This pattern is similar, if not slightly less pronounced, for the filtered portions of runoff from the two pavements.

Table 11 also contains the sums of the individual masses (computed for each event) of each pollutant in the runoff. In contrast to the similarities observed in the pollutant concentrations for both pavements, the total masses of each pollutant in the runoff from the concrete slab are much larger than the corresponding masses in the runoff from Grasscrete. These large differences are primarily due to the effects of differences in runoff volume between these two pavements.

Table 12 provides another useful comparison of runoff concentrations, Each rainfall event was unique, not only in terms of volume and intensity, but also in terms of the concentration of each pollutant in the rain water. Therefore, a fairer comparison of the quality of runoff from these two pavements is given by

the normalization of the pollutant concentrations in the runoff. To this end, the individual runoff pollutant concentrations were divided by the corresponding rainfall pollutant concentrations for each event. The averages of these values for each pollutantwer, computed and appear in *Table 12.* Perhaps most notable of the data in this *Table is* the production of nitrate/nitrite from Grasscrete and the large attenuation of lead and zinc by both pavement types.

It seemed probable that an increase in rainfall volume would cause increase in the masses of each pollutant in the runoff leaving the two pavements. To test this relationship, linear regression analyses were performed and correlation coefficients computed. *Table 13* contains these correlation coefficients for the runoff of Grasscrete and the concrete slab. In general, the data for the slab exhibit stronger associationsth do those for Grasscrete.

III. Percolating Water

The water percolating through the soils under each of the three grid pavements was sampled at three locations previously designated as shallow, deep, and underflow. The various soil layers under each pavement theoretically were identical among bins, but variations were inevitable. In an attempt to measure the effects these soils had on the water percolating through them, the percentage of removal at the three sampling levels was computed for each event and pollutant. The percentage of removal was calculated by subtracting the concentration of the pollutant of interest at the desired sampling location from the corresponding concentration in the rainfall, dividing the result by the rainfall concentration, and expressing the quotient as a percentage. These percentages were averaged over all the events according to pollutant and pavement type and appear in *Tables 14-16.* An examination of these data readily reveals that nitrate/ nitrite moved easily through the soils and, indeed, was leached from the soils to a great extent. There was a fair removal of heavy metals in each grid pavement bin.

In addition to calculating percentages of removal for pollutant concentrations, it was also possible to calculate percentages of removal for pollutant masses for the underflow samples. Such values allow the determination of the overall efficiency of the pavement/soils systems. *Table 17 is* analogous to *Tables 14-16* except that the underflow and rainfall masses were used instead of concentrations. Since no measure of the volumes of water passing a particular point in the soil was feasible or desired, masses for the shallow or deep samples were not calculated. Again, in most instances the average percentage of removal of heavy metals was quite high on a mass basis.

By means of mass balancing, the total mass of each pollutant that was stored in or removed from the soils under each pavement was calculated. *Table 18* contains these data as well as an overall percentage-removed value for each pollutant and pavement type.

IV. Sampling Cups and Filters

It was mentioned previously that some analyses were performed on the porous ceramic cups and filters used in the study to assess their pollutant removal or leaching properties. Data pertinent to these tests can be found *in Tables 19-21,* and a discussion of these data follows in the next section.

DISCUSSION

I. Runoff Volume

The foremost observation that can be made about the data presented in *Tables 5-8* is that there was much less runoff *produced* on all three of the grid pavements than on the concrete slab. This was reflected in both the values of runoff volume and coefficient of runoff for each pavement type. Also, no runoff was produced from Monoslab or Turfstone for any rainfall event used in this study. While the study was not designed to identify definitively mechanisms responsible for observed phenomena, it seemed that the design of these two grid pavements had a marked effect on their not allowing any runoff. The void spaces in these grid, pavements permitted water-both that which fell directly into them and that which ran into them from adjacent concrete surfaces-to infiltrate into the soil and thus reduce the ultimate runoff volume. Other factors that may have played a role in the lack of runoff from these pavements include slope and rainfall intensity. The slopes of each pavement were identical, and they were typical of many parking lots. The rainfall intensities were held as constant as possible among pavements, and all were in the range of commonly occuring storms. It is probable that if steeper slopes and/or greater intensities were used, runoff from these two grid pavements would have been observed. The absence of runoff from Monoslab and Turfstone is similar to results obtained by Day [1978] in his study involving various types of grid pavements. He found that as slope increased, the coefficient of runoff and volume of runoff both increased.

In contrast to the results for Monoslab and Turfstone, Grasscrete pro duced small amounts of runoff for the majority of rainfall events simulated on it. It is apparent from a comparison of the data for Grasscrete and the concrete slab, however, that Grasscrete was very effective in attenuating rainfall and reducing runoff. The fact that it did allow some runoff may have been a function of its design and layout of voids with respect to the direction of slope. With the voids aligned parallel with the ; slope direction, as in this study, the concrete surrounding these void presented a continuous surface in this same direction. This may have allowed the water to flow down the uninterrupted strips of concrete and be measured as runoff. If each row of voids had been offset some what, such continuous strips of concrete would not have existed, and the runoff volumes produced would presumably have been decreased.

Another possible explanation for the slight difference in runoff volume between Grasscrete and the other two grid pavements used here may be that Grasscrete received somewhat higher rainfall volumes and intensities than did the other two. An additional reason for the small amount of runoff from Grasscrete may be that its surface has an average of 30 percent open area at the top surface, whereas the other two grid pavements have average open areas of 40 percent. In spite of the fact that Grasscrete did produce some runoff, the average coefficient of runoff of 0.005 is very low. Such a value is equivalent to about 4 teaspoons of runoff produced for every gallon of rain that falls on its surface.

The concrete slab, used as a control in this study, performed as expected. The slab produced large volumes of runoff for each rainfall event, as reflected in the corresponding coefficients of runoff. The reason for this seems clear. The slab presented a continuous, virtually impermeable surface to the rainfall. Rain that contacted the surface could not infiltrate readily through the concrete and therefore moved downslope due to gravity, thus producing runoff. It should be noted that the slab received the second greatest average rainfall volume and intensity of the four pavements tested. This fact may have had a small effect on the volume of runoff.

The coefficients of runoff for the concrete slab were all greater than 0.50; the average was 0.78. These values may be considered somewhat lower than that commonly accepted for concrete surfaces of 0.95. A possible reason for this may have been the effect of raindrop splash over the edge of the slab, which resulted in some

loss of runoff volume. On the test bin (about 6 x 4 ft), the ratio of perimeter to surface area is 0.83, whereas on a parking lot, say, of 200 x 200 ft, this ratio is 0.02. Clearly, the percentage of effect of splash-over loss is much greater for the concrete slab used in this study than for an actual parking lot.

Various factors that may have affected runoff volume and/or coefficient of runoff on Grasscrete and the concrete slab include rainfall volume and rainfall intensity. According to the correlation coefficients presented in *Tables 9* and *10,* there was agreement between rainfall volume and runoff volume on the slab and a somewhat poorer one on Grasscrete. This result for the slab was anticipated and obvious. In the case of Grasscrete, it appears that the voids helped dampen the effects of an increase in rainfall volume upon runoff volume. As expected, increased rainfall volume had little perceivable effect on the coefficient of runoff for either Grasscrete or the slab. Operationally, the coefficient of runoff is the ratio of runoff volume to rainfall volume, that is, an increase in the denominator would have a similar increase in the numerator, thus resulting in a more or less constant value.

Rainfall intensity had extremely weak correlations with both volume and coefficient of runoff for both pavements. A theory in hydrology holds that only when the rainfall intensity exceeds the infiltration rate of the soil will runoff result. It is possible that the infiltration rates of the Grasscrete and slab surfaces were less than the rainfall intensities used in this study. Any increase in rainfall intensity would have had little effect on the runoff volume. As explained above, the coefficient of runoff was not expected to exhibit any effect of increased rates of rain, that is, greater intensity.

In summary, the lowest intensities obtained in this study were fairly low; the simulated storms had return periods of less than 25 years. With these common events, the grid pavements produced little or no runoff, whereas the concrete slab produced a great amount of runoff.

II. Runoff Quality

The average concentrations of each of the 10 pollutants in the unfiltered and filtered portions of the runoff from Grasscrete and the concrete slab are listed in *Table 11.* These values are within the ranges reported for urban runoff [Whipple, Hunter, and Yu, 1974; Northern Virginia Planning District Commission and Virginia Polytechnic Institute and State University, 1978; Bryan, 1972]. Examination of the data for the unfiltered samples reveals a number of trends. The concentrations in the runoff from Grasscrete were greater than the corresponding ones for the slab except for organic phosphorus and the metals. This trend was identical to that for the values of runoff concentration divided by rainfall concentration in *Table 12.* This was not altogether surprising; the sod and the soil within the voids of Grasscrete provided an excellent environment for microorganisms and other macroscopic fauna to live and metabolize. The water passing over the surface could have washed *away* grass clippings and other organic residue as well as inorganic ions on the surface of Grasscrete. Nitrification was clearly a much more important phenomenon on Grasscrete than on the concrete slab, as evidenced by the large increase in nitrate/nitrite concentration from rainfall to runoff on the former pavement.

Adsorption of the three metals on the concrete surface of Grasscrete probably accounted for the great reductions in their concentrations on this pavement. It is not known why Grasscrete removed greater percentages of the metals than did the slab, or why the slab actually may have produced some chromium. In general, the values in *Table 12* for unfiltered runoff from Grasscrete were greater than 1.0 and those for the concrete slab were less than 1.0. This indicated that the Grasscrete surface was being eroded while the slab removed most pollutants from the runoff.

The filtered portions of runoff from the two pavements exhibited features similar to those for the unfiltered portions mentioned above. The concentrations of five of the pollutants for Grasscrete were larger than those for the slab: ortho phosphorus, nitrate/nitrite, ammonia, organic nitrogen, and TOC. This illustrated again that for many pollutants, Grasscrete produced more concentrated runoff and removed less or released more amounts of pollutants than did the concrete slab. The removal of metals on the slab was good in all cases, except for chromium, which was identical to that for the unfiltered runoff samples. Nitrification was probably also important, as before, in causing a great increase in the nitrate/nitrite concentration from rainfall to runoff on Grasscrete.

A comparison of data for unfiltered samples with data for filtered samples reveals some interesting results. For many contaminants, the filtered portion was more concentrated than the unfiltered portion. This was probably due to bias introduced by the filters used. For Grasscrete, the unfiltered portion of runoff contained higher concentrations of the three phosphorus forms than did the filtered portion. This was not surprising; it has been well documented that phosphorus binds to the sediment fraction in runoff [Munn et al., 1973; Reddy et al., 1978]. In addition to phosphorus, lead seems to have been associated with solids in the runoff from Grasscrete.

A caution should be observed when examining the cumulative mass of each pollutant data presented in *Table 11.* The figures for the unfiltered samples for both pavements were developed from a smaller number of rainfall events than the figures for filtered samples. The value of such totals lies in a gross comparison of the magnitudes for Grasscrete versus the slab. Obviously, the pollutant load, and consequently the impact on a receiving body of water, are much less for the runoff from Grasscrete than for that from the slab. For instance, the total filtered lead mass in the runoff from the concrete slab was about 350 times greater tbari the runoff of Grasscrete. These great differences in mass occurred despite the fact that the runoff from Grasscrete was somewhat more concentrated for many of the pollutants than that from the slab. The reason for such large differences in mass was the wide disparity in runoff volume between these two pavements.

A logical relationship exists between runoff volume and total pollutant load, and it seems natural to suppose that a similar relationship between rainfall volume and total pollutant load would exist. The data in *Table* 13 show that the slab generally exhibited a greater correlation between these latter two variables than did Grasscrete. Perhaps the primary rea son for this was that the slab had a better correlation between runoff volume and rainfall volume than did Grasscrete (0.95 versus 0.64, from *Tables 9* and *10).* The tendency of Grasscrete to erode or release pollutants to a greater extent than the slab was not enough to offset the effects of an increase in rainfall volume.

The extreme mobility of nitrate porbably accounted for the strong correlation for nitrate/nitrite on the slab. While Grasscrete contributed nitrate/nitrite to the runoff, an increase in rainfall volume had little effect on the amount of this contribution. In addition to nitrate/nitrite, the slab exhibited good correlation between rainfall volume and the masses of lead, zinc, and chromium. In all cases, the correlation coefficients for the slab were greater than the corresponding ones for Grass. , crete. Finally, there appeared to be a trend among the phosphorus species that the unfiltered portions of both pavements' runoffs showed greater correlation than those for the filtered portions. This seemed to indicate that more rain would cause more sediment to be released from the pave ments' surfaces and thus increase the amount of phosphorus in the unfiltered portions of the runoff.

III. Percolating Water: Shallow Cups

An examination of *Tables 14-16* shows a generally better than 75 percent removal of the three phosphorus forms for Monoslab, Grasscrete, and Turfstone at the shallow cup samplers. A number of researchers have found good removal of phosphorus from solutions passing through soil material

[Kuo and Lotse, 1972; Lance, 1977; Toffelmire and Chen, 1977]. Since the shallow cups sampled rainwater that had passed through 2 in. of alkaline (pH = 8.7-9.0) sand and 6 in. of limestone gravel, adsorption on both of these was probably responsible for a good portion of this removal. The ceramic cup samplers themselves presumably adsorbed additional phosphorus. While all three forms of phosphorus were removed well in each pavement bin at the shallow cup level, there was no clear pattern as to which form was removed better than any other.

In contrast to the observed removal of phosphorus, nitrate/nitrite exhibited tremendous amounts of leaching. Again, it was not surprising that there was no removal of nitrate/nitrite; both Allison [1966] and Hook and Kardos [1978] found that the amount of nitrate applied to soils essentially equalled the amount of nitrate found at various depths in the soil. Nitrification must have been important in producing nitrate in the sod and topsoil of each bin during periods between rainfall events. While nitrification was probably quite active in the upper soil layers of the three grid pavement bins, the poor removal of ammonia seemed somewhat puzzling. Although ammonium ions can be adsorbed onto soil particles via cation exchange capacity, other cations can compete for exchange sites. The cation exchange capacity of the sand in the bins was quite low, and the topsoil's was only somewhat higher. The sod soil had a fairly high cation exchange capacity, but there was only about a 1- to 2-in. layer of such soil in each bin. In addition to this, in spite of the rainwater's contacting the alkaline sand and gravel, the pH of the acidic rainwater may not have been raised high enough to allow precipitation or volatilization of ammonia. These factors, in combination, were presumably great enough to prevent removal rates of ammonia in excess of 50 percent. These moderate removals of ammonia, coupled with the huge amounts of nitrate/nitrite leached from the top layers of soil probably means that the primary source of ammonia for the nitrification process was natural soil ammonia, that is, not that applied in the rainwater. Indeed, as can be seen from an examination of the data in *Table* 2, there was a good deal of reduced nitrogen in the sod soil and topsoil in the bins.

The average organic nitrogen removal for each pavement bin at the shallow cup level was fairly good (70 to 80 percent), whereas the TOC removal was somewhat less than this. The heavy metals were all removed fairly well at the shallow level; zinc experienced lesser removal rates than the other two metals. Adsorption of the metals on the concrete surfaces of the grids, sand, and gravel was probably important, as was cation exchange within the sod soil and topsoil.

It will be remembered that each of the individual bins was filled with soil, sand, gravel, topsoil, and sod as similarly as possible. In spite of this attempt, the Turfstone bin accomplished (in some instances significantly) less removal of all forms of phosphorus, organic nitrogen, TOC, and chromium than the other two grids. It should be noted that the scatter in these data for Turfstone at the shallow cups was substantial. For this reason, it is difficult to assess the extent, if any, of the differences in removal of these six pollutants between Turfstone and the other two grid pavements. There was less of a trend for the remaining four pollutants at the level of the shallow cups.

IV. Percolating Water: Deep Cups

The deep cup samplers collected water that had passed through not only the sod, topsoil, sand, and gravel that were above the shallow cups, but also the 10-12 in. of Groseclose soil between the deep and shallow cups. Particle-size analysis led to classification of this Groseclose as a clay soil. It was no surprise then, that all three pavement bins exhibited better than 80 percent removal of all three forms of phosphorus. Robbins and Smith [19771 reported that phosphorus removal increased with an increase in accumulative depth of clay-sized material. There seemed to be a slightly better average removal of ortho phosphorus than of the other two forms of phosphorus.

Nitrate/nitrite was easily carried through the soil and therefore showed up in high concentrations in

the deep cup samples. The nitrate/nitrite concentration in the Groseclose was about 8-10 mg/l, which probably accounted for some of that leached by the percolating rainwater. Ammonia experienced poor removals in all three bins at the deep sampling level, as it did at the shallow cups. The cation exchange capacity of the Groseclose was about 12-13 meq/100g-notan insignificant value. Again other cations, such as the lead, zinc, and chromium in the rainwater, could have competed for exchange sites, partially explaining the-poor removal of ammonia. As was the case for the shallow cups, organic nitrogen removal at the level of the deep cups was good (over 80 percent), and the TOC removal was somewhat less. Good removal of lead and chromium was observed in each grid pavement with significantly poorer removal of zinc. It may have been that soil cation exchange mechanisms favored the former two metals over the latter one.

Differences in removals at the level of the deep cups among the grid pavements were evident, but no one pavement bin was significantly less effective in removing pollutants than the other two.

V. Underflow

The underflow samples differed from the deep samples only in that they had passed through an additional inch of gravel and were not collected by the use of the porous ceramic cups described previously. Trends similar to those observed for the deep cup results were apparent at the underflow. For all three grid pavements, the order of removal for the phosphorus forms at the underflow was, rather markedly, organic phosphorus > total phosphorus > ortho phosphorus. However, the average removals for ortho phosphorus in particular had high variability about them. Nitrate/nitrite was still being leached to a great extent to the level of the underflow. Ammonia, organic nitrogen, and TOC were poorly removed in most cases, while the metals were removed to a fairly good extent except for chromium on Turfstone. Among bins, Turfstone leached total and ortho phosphate as well as TOC. Conversely, this bin did not appear to leach as much nitrate/nitrite as the other two grids.

VI. Differences with Depth in Soil

For all three grid pavements, the order of removal for the three phosphate forms, organic nitrogen, and TOC was deep cups > shallow cups> underflow. The first of these comparisons probably indicated the effects that the Groseclose had on the five pollutants, that is, a 10- to 12-in. layer of clay soil accomplished the removal of certain amounts of these pollutants. The fact that the removals at the shallow cups were greater than those at the underflow for the five pollutants may indicate the effect the ceramic cups had on the samples drawn through them.

There were no such overall trends for nitrate/nitrite or ammonia. For all three pavements, the leaching of nitrate/nitrite varied widely, but in all cases the percentage leached to the level of the deep cups was less than that to the shallow cups. This may indicate that denitrification was at work in the Groseclose soil layer.

Lead concentrations tended to increase with depth in the soil in all bins, but good removal was achieved at all levels. Zinc was also removed markedly better because of adsorption on the alkaline gravel. Chromium, on the other hand, was removed better with an increase in depth in the soil, but its removal dropped off at the underflow. It may be that the gravel was contributing chromium to the underflow, but it seems more likely that the ceramic cups were responsible for removing some chromium from the shallow and deep samples.

VII. Mass Percent Removals

For each pollutant, Grasscrete exhibited a greater removal at the underflow on a mass basis than did the other two grid pavements *(Table 17).* One might think that some of this difference was due to the portion of the pollutants that fell on this bin that were carried off the bin in runoff. This loss had an insignificant effect on the amount of pollutants subsequently available for removal from the percolating water and the resulting mass percent removals. Turfstone actually exhibited leaching of total and ortho phosphate as well as TOC on a mass basis. There was substantial removal of most pollutants for Monoslab and Grasscrete with generally excellent removal of the three metals. The mass percent removals at the underflow did not equal the concentration percent removals at the underflow because there was always some amount of water storage capacity in the soils of each bin.

On an overall mass basis, the same trends outlined in the preceding paragraph were evident *(Table 18).* The cumulative mass of total and ortho phosphate applied to Turfstone was greater than that applied to the other two grid pavements. Clearly, these differences cannot have accounted for such large overall mass removals of these two pollutants. Further, the removal or leaching of pollutants did not appear to depend on the volume or rate of rain applied because Grasscrete had the greater average rainfall volume and intensity of the three grid pavements tested.

VIII. Ceramic Cups

An examination of the data in *Table 19* reveals that the porous ceramic cups used in this study removed significant portions of total, ortho, and organic phosphate as well as lead. It will be recalled that the underflow samples always exhibited lesser percentage removals for these phosphate forms than did the shallow or deep cups. It is probable that the removal of phosphorus by the cups at least partially explains this phenomenon. In addition, the cups may have contributed various amounts of TOC and zinc, but the variability of these data was quite high. Chromium concentration was only slightly affected by passage through the cups.

These tests on the ceramic cups did not include analyses of nitrogen forms because traditionally it has been thought that the cups have an insignificant effect on these compounds.

IX. Filters

The tests on the Millipore filters were inconclusive, for the most part. The variations within each filter type for each pollutant were so high that it was difficult to conclude anything about their tendency to leach pollutants. They all appeared to contribute widely varying amounts of total phosphate and TOC.

CONCLUSIONS

1. The use of concrete grid pavements is a very effective way to reduce the quantity of stormwater runoff from areas such as parking lots that ,~ would otherwise be covered by more traditional impervious surfaces.

2. The impervious surface investigated--a concrete slab-produced very large amounts of runoff compared to the grid pavements tested, for similar rainfall intensities and durations. When compared to the only grid pavement that produced runoff-Grasscrete-the concrete slab had an average coefficient of runoff about 150 times that calculated for Grasscrete.

3. The volume of runoff from the concrete slab was positively and strongly correlated with the volume of rainfall incident to its surface. The same correlation was considerably weaker for Grasscrete and non-existent for the other two grid pavements.

4. The experimental system simulated rainfall conditions similar to natural ones. The concentrations of the 10 pollutants measured in the runoff from Grasscrete and the concrete slab were within ranges commonly reported for urban runoff.

5. The runoff from Grasscrete contained higher concentrations of 11 of 20 pollutants (10 unfiltered and 10 filtered) than the runoff from the concrete slab. This was apparently the result of leaching and erosion. The total mass of pollutants in the Grasscrete runoff was only about 1.8 percent of that from the concrete slab, however, because of the large difference in runoff volume.

6. The masses of the 10 pollutants in the runoff from the concrete slab could be statistically correlated with an increase in rainfall volume, while such relationships were weak for Grasscrete.

7. The grid pavement/soil systems tested effected significant removals of most pollutants from the rainwater percolating through them. A notable exception was nitrate/nitrite, which tended to increase because of leaching from the soil. Heavy metal removal appeared to be especially good.

8. The 10- to 12-in. layer of Groseclose soil that was obtained from the field accomplished significant removal of five of the 10 pollutants measured in all three grid pavement bins.

9. Porous ceramic cups will adsorb significant amounts of some pollutants when used for sample collections from sub-surface locations.

RECOMMENDATIONS

Based on the data gathered and conclusions reached in this study, recommendations include the following.

1. Concrete grid pavements should be used on a trial basis by public and private concerns in many applications of low traffic volume in the United States to effect significant reductions in stormwater runoff. If possible, such installations should be monitored for runoff quantity reduction, runoff pollutant load reduction, and potential groundwater contamination.

2. More in-field tests should be conducted to better assess the cost effecttiveness of concrete grid pavements as an alternative stormwater management technique.

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TABLES

TABLE 1

Characteristics of Soils Used

Class Soil Sample (Subsample Number)	Cation Exchange Capacity (meq/100 g)	Pb (mg/l)	Zn (mg/l)	Cr (mg/l)	Textural Class
Groseclose (1)	12.50	11.59	2.51	0.11	clay
Groseclose (2)	12.08	10.01	1.16	0.10	clay
Groseclose (3)	12.87	11.28	1.62	0.07	clay
Topsoil (1)	3.43	8.69	6.70	0.18	silt loam
Topsoil (2)	3.68	8.89	7.29	0.17	silt loam
Topsoil (3)	3.52	8.60	6.44	0.16	silt loam
Sod soil	13.34	26.40	42.15	35.90	clay
Sand (1)	0.54				sand
Sand (2)	0.62				sand
Sand (3)	0.65				sand

TABLE 2

Characteristics of Soils Used

Soil Sample (Subsample Number)	pH	P04-P (mg/l)	NO3 + N02-N (mg/l)	Total N (mg/l)	Organic Matter(%)
Groseclose (1)	4.7	3.0	8.73	335.0	0.6
Groseclose (2)	4.8	1.0	8.41	297.5	0.6
Groseclose (3)	4.8	2.0	10.22	272.5	0.6
Topsoil (I)	6.5	9.0	24.98	102.8	2.0
Topsoil (2)	6.6	11.0	22.65	101.0	2.1
Topsoil (3)	6.5	9.0	23.85	105.0	2.0
Sod Soil	5.5	60.0	3.40	3,812.5	7.5
Sand (1)	8.7	5.0	1.21	130.0	0.7
Sand (2)	9.0	2.0	1.14	130.0	0.6
Sand (3)	8.8	3.0	1.54	130.0	0.6

TABLE 3

Stock Pollution and Rainfall Characteristics

Pollutant Form	Amount of Pollutant Used to Make 100 ml of Stock Pollution (mg)	Approximate Concentration of Rainfall (mg/l)
KNO_3	708.1	$N0_3$-N = 0.62
$Pb(N0_3)_2$	229.0	Pb^{++} = 0.76
$(NH_4)_2HPO_4$	103.2	$P0_4$-P = 0.13
NH_4Cl	169.2	NH_3-N = 0.35
$ZnCl_2$	217.1	Zn^{++}= 0.55
$Cr0_3$	26.9	Cr... = 0.07
Glucose-6-phosphate, monosodium salt	401.6	Organic $P0_4$-P = 0.26
Gelysate Peptone	3,075.6	Organic-N = 2.60
		Organic carbon = 7.21
		Cl^- = 1.29
		K^+ = 1.45
		Na^+ = 0.29

TABLE 4

Chemical Analysis Procedures Employed

Constituent	Procedure	Comments
NO_3/NO_2-N	Cadmium reduction	All colorimetric analyses performed on a Bausch & Lomb Spectronic 100
NH_3-N	Distillation followed by Nesslerization	
Organic-N	Kjeldahl followed by Nesslerization	
Total PO_4-P	Sulfuric/nitric acid digestion followed by ascorbic acid	
Acid hydrolyzable PO_4-P	Autoclave for 30 min. followed by ascorbic acid	
Ortho $P0_4$-P	Ascorbic acid	
TOC	Envirotech Organics Analyzer	
Pb	Direct aspiration	Atomic Absorption Spectrophotometer
Zn	Direct aspiration	
Cr	Furnace method	

TABLE 5

Rainfall and Runoff Characteristics on Monoslab

Rainfall Volume (l)	Rainfall Duration (min.)	Rainfall Intensity (in./hr)	Return Period* (yr)	Runoff Volume (l)	Coefficient of Runoff
22.0	30	0.93	<2	0	0
28.0	30	1.19	<2	0	0
43.0	60	0.91	<2	0	0
49.0	30	2.08	<2	0	0
55.0	30	2.33	<2	0	0
56.0	60	1.19	<2	0	0
101.5	120	1.08	2 - 3	0	0
101.5	120	1.08	2 - 3	0	0
105.5	60	2.24	8	0	0
112.5	60	2.39	10	0	0
X^T = 67.4		1.54		0	0
SD = 34.4		0.63		0	0

*For Washington, D.C., area. Source: U.S. Department of Commerce [1955].
† X = average; SD = standard deviation.

TABLE 6

Rainfall and Runoff Characteristics on Grasscrete

Rainfall Volume (l)	Rainfall Duration (min.)	Rainfall Intensity (in./hr)	Return Period* (yr)	Runoff Volume (l)	Coefficient of Runoff
30.0	30	1.27	<2	0	0
30.0	30	1.27	<2	0	0
53.0	30	2.25	<2	0.685	0.013
57.0	60	1.21	<2	0.187	0.003
66.0	60	1.40	<2	0.367	0.006
83.6	30	3.54	10	0.512	0.006
101.5	120	1.08	2 - 3	0.290	0.003
107.0	120	1.13	3 - 4	0.535	0.005
120.5	60	2.55	17	1.045	0.009
125.0	60	2.65	20	0.880	0.007
X^T = 74.9		1.85		0.409	0.005
SD = 34.5		0.78		0.360	0.004

*For Washington, D.C., area. Source: U.S. Department of Commerce [1955].
†X = average; SD = standard deviation.

TABLE 7

Rainfall and Runoff Characteristics on Turfstone

Rainfall Volume (1)	Rainfall Duration (min.)	Rainfall Intensity (in./hr)	Return Period* (yr)	Runoff Volume (l)	Coefficient of Runoff
30.0	30	1.27	<2	0	0
40.5	30	1.72	<2	0	0
47.0	60	1.00	<2	0	0
50.0	60	1.06	<2	0	0
56.0	30	2.37	<2	0	0
60.5	30	2.57	2-3	0	0
98.0	120	1.04	2-3	0	0
102.5	60	2.17	6 - 7	0	0
104.0	60	2.20	7-8	0	0
107.5	120	1.14	3	0	0
X^{T} = 69.6		1.65		0	0
SD = 30.0		0.62		0	0

*For Washington, D.C., area. Source: U.S. Department of Commerce [1955].
† X = average; SD = standard deviation.

TABLE 8

Rainfall and Runoff Characteristics on Concrete Slab

Rainfall Volume (l)	Rainfall Duration (min.)	Rainfall Intensity (in./hr)	Return Period* (yr)	Runoff Volume (l)	Coefficient of Runoff
30.0	30	1.27	<2	21.2	0.71
35.5	30	1.51	<2	22.7	0.64
38.0	30	1.61	<2	34.1	0.90
55.0	30	2.33	<2	35.2	0.64
63.5	60	1.35	<2	36.7	0.58
64.5	30	2.73	3	47.3	0.73
65.0	30	2.76	3 - 4	42.8	0.66
68.5	60	1.45	<2	55.6	0.81
76.0	60	1.61	2	66.2	0.87
80.5	60	1.71	2 - 3	68.1	0.85
109.5	60	2.32	9	100.3	0.92
109.8	120	1.16	3	90.8	0.83
115.0	120	1.22	3 - 4	107.9	0.94
121.5	60	2.58	18	98.4	0.81
126.5	60	2.68	21	100.3	0.79
X† = 72.3		1.91		57.4	0.78
SD = 31.7		0.59		29.7	0.11

*For Washington, D.C., area. Source: Department of Commerce [19551.
†X = average; SD = standard deviation.

TABLE 9
Correlation Coefficients for Runoff and Rainfall Relationships on Grasscrete

Relationship	Correlation Coefficient (r^2)
Runoff volume (Y) vs. rainfall volume (X)	0.64
Coefficient of runoff (Y) vs. rainfall volume (X)	0.22
Runoff volume (Y) vs. rainfall intensity (X)	0.12
Coefficient of runoff (Y) vs. rainfall intensity (X)	0.12

TABLE 10
Correlation Coefficients for Runoff and Rainfall Relationships on Concrete Slab

Relationship	Correlation Coefficient (r^2)
Runoff volume (Y) vs. rainfall volume (X)	0.95
Coefficient of runoff (Y) vs. rainfall volume (X)	0.27
Runoff volume (Y) vs. rainfall intensity (X)	0.03
Coefficient of runoff (Y) vs. rainfall intensity (X)	0.02

TABLE 11
Average and Standard Deviation of Pollutant Concentrations and Cumulative Mass of Pollutants in Runoff on Grasscrete Slab

Total PO_4-P	Ortho PO_4-P	Organic PO_4-P	NO_3 + NO_2-N	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Grasscrete-Unfiltered Samples									
X=0.57	0.28	0.19	1.47	1.34	3.39	14.98	0.115	0.160	0.050
SD=0.51	0.28	0.14	1.10	0.99	2.39	11.12	0.106	0.130	0.034
M=2.44	1.18	0.87	6.65	5.75	15.16	64.80	0.503	0.733	0.236
Grasscrete-Filtered Samples									
X=0.47	0.24	0.19	1.84	1.61	3.83	19.49	0.061	0.194	0.054
SD=0.27	0.14	0.11	1.13	1.02	2.19	12.99	0.043	0.142	0.029
M=2.48	1.19	1.06	9.89	9.42	21.16	98.63	0.326	1.065	0.309
Concrete Slab – Unfiltered Samples									
X=0.39	0.13	0.25	0.50	0.95	2.30	10.08	0.430	0.405	0.076
SD=0.05	0.07	0.04	0.08	0.12	0.04	2.49	0.045	0.027	0.003
M=117.80	42.11	74.35	154.00	281.54	696.33	2,938.20	126.390	121.440	22.670
Concrete Slab – Filtered Samples									
X=0.51	0.18	0.23	0.72	1.03	2.10	7.22	0.184	0.252	0.071
SD=0.52	0.13	0.20	0.11	0.27	0.61	1.01	0.091	0.063	0.008
M=374.59	115.48	155.68	443.26	583.78	1,519.89	4,707.38	124.736	146.880	44.035

*X = average (mg/l); SD = standard deviation (mg/l); M = total mass (mg).

Table 12
Runoff Concentrations Divided by Rainfall Concentrations for Grasscrete and Concrete Slab *

Total PO_4-P	Ortho PO_4-P	Organic PO_4-P	NO_3 + NO_2-N	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Grasscrete-Unfiltered Samples									
X=1.54	2.10	0.86	2.02	1.23	1.76	1.90	0.31	0.30	0.74
SD=1.38	1.74	0.64	1.50	0.89	1.53	1.38	0.44	0.25	0.51
Grasscrete-Filtered Samples									
X=1.19	1.58	0.85	2.59	1.50	1.93	2.48	0.12	0.37	0.78
SD= 0.73	1.07	0.48	1.59	0.90	1.32	1.56	0.11	0.29	0.41
Concrete Slab – Unfiltered Samples									
X=0.84	1.45	1.02	0.97	0.89	0.89	0.83	0.57	0.67	1.07
SD= 0.36	1.62	0.73	0.17	0.10	0.17	0.22	0.04	0.05	0.03
Concrete Slab – Filtered Samples									
X=1.29	1.24	1.00	1.01	0.90	0.96	1.16	0.35	0.50	1.05
SD= 1.26	1.07	0.85	0.06	0.14	0.08	0.29	0.15	0.19	0.05

* X = average (mg/l); SD = standard deviation (mg/l).

TABLE 13
Correlation Coefficients for Mass of Pollutant in Runoff Versus Rainfall Volume for Grasscrete and Concrete Slab*

	Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Grasscrete-Unfiltered Samples										
r^2 = 0.66	0.75	0.89	0.60	0.76	0.76	0.66	0.42	0.61	0.89	
Grasscrete-Filtered Samples										
r^2 = 0.73	0.57	0.65	0.43	0.50	0.50	0.29	0.47	0.11	0.60	
Concrete Slab-Unfiltered Samples										
r^2 = 0.80	0.30	0.97	0.98	0.72	0.84	0.71	0.79	0.94	0.93	
Concrete Slab-Filtered Samples										
r^2 = 0.33	0.39	0.30	0.92	0.84	0.95	0.92	0.72	0.83	0.95	

r^2 = correlation coefficient of relationship between mass of pollutant in runoff (Y) vs. rainfall volume (X).

Table 14
Percentage of Removal (Concentration Basis) by Sampling Location for Monoslab*

	Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Shallow Cups										
X=88.0	82.0	85.6	-1,042.1	34.7	79.9	53.6	83.4	50.4	84.9	
SD= 11.7	21.1	10.7	365.0	14.3	10.1	12.2	21.8	33.1	18.8	
Deep Cups										
X=89.9	92.7	86.0	-691-3	24.6	83.8	64.9	87.6	47.0	94.1	
SD= 4.6	8.7	11.4	273.1	9.7	5.8	10.3	13.6	46.2	7.4	
Underflow										
X=69.4	39.7	75.6	-927.7	43.9	76.0	45.2	91.9	77.1	77.0	
SD=22.6	55.9	22.1	392.0	9.1	15.7	33.3	8.9	55.8	23.1	

*X= average percentage of removal; SD = standard deviation.

Table 15

Percentage of Removal (Concentration Basis) by Sampling Location for Grasscrete*

	Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Shallow Cups										
X=89.9	94.8	86.4	-919.7	41.3	79.7	60.2	88.1	71.3	96.6
SD= 9.1	5.6	12.6	171.5	13.1	9.5	9.8	18.6	11.5	2.8
Deep Cups										
X= 93.3	98.2	89.9	-896.7	42.9	84.3	67.1	91.7	64.9	99.6
SD= 5.3	3.0	9.0	121.7	9.7	8.7	8.9	7.9	20.0	0.4
Underflow										
X= 59.9	35.2	86.3	-777.2	34.1	57.2	26.3	94.2	91.9	80.2
SD= 35.9	80.3	11.7	280.2	13.8	25.3	32.5	4.4	3.4	24.9

*X= average percentage of removal; SD = standard deviation.

Table 16

Percentage of Removal (Concentration Basis) by Sampling Location for Turfstone*

	Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Shallow Cups										
X= 67.4	43.6	81.7	-963.1	42.0	69.9	23.4	82.2	66.1	79.0
SD= 42.5	100.7	17.5	274.4	11.6	12.4	27.5	21.8	25.3	5.4
Deep Cups										
X= 91.2	90.1	91.1	-687.4	46.2	83.6	40.5	92.6	69.1	99.2
SD= 13.5	22.8	9.9	192.0	13.2	12.3	43.4	8.0	10.0	0.9
Underflow										
X= 58.9	-285.4	67.8	-592.5	31.7	39.4	-49.5	92.8	93.3	26.1
SD= 86.5	261.2	20.4	136.6	14.0	27.6	53.0	5.7	2.8	16.0

*X= average percentage of removal; SD = standard deviation.

Table 17

Percentage of Removal (Mass Basis) at Underflow for the Three Grid Pavements*

Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Monoslab									
X= 75.1	50.1	82.5	-649.0	54.9	82.3	52.8	94.1	90.0	81.2
SD= 20.4	50.0	15.4	315.7	19.1	13.4	45.2	6.9	18.3	20.8
Grasscrete									
X= 87.3	80.5	95.7	-195.1	77.7	86.4	76.1	98.4	97.1	94.3
SD= 10.6	20.6	3.6	100.0	6.7	6.8	8.4	1.4	1.9	7.0
Turfstone									
X= 24.7	-192.3	75.3	-385.7	26.0	56.0	-4.6	94.9	95.4	45.5
SD= 84.2	254.4	18.8	123.8	71.5	20.2	35.0	4.3	1.9	21.1

*X= average percentage of removal (mass basis); SD = standard deviation.

Table 18

Cumulative Rainfall and Underflow Pollutant Masses, Masses Stored, and Overall Percentage of Removal (Mass Basis) for the Three Grid Pavements*

Total $P0_4$-P	Ortho $P0_4$-P	Organic $P0_4$-P	$N0_3$ $N0_2N$	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Monoslab									
RM= 276.1	101.7	150.7	478.9	685.7	1,711.4	5,903.9	396.9	394.4	52.8
UM= 89.8	63.8	24.4	3,425.7	325.8	391.4	3,084.1	16.0	25.9	13.8
DF=186.3	37.9	126.3	-2,946.8	359.9	1,320.0	2,819.8	380.9	368.5	30.0
OP=67.5	37.3	83.8	-615.3	52.5	77.1	47.8	96.0	93.4	73.9
Grasscrete									
RM= 323.2	135.2	179.8	560.4	810.7	1,668.0	6,164.1	461.2	434.3	53.6
UM= 45.9	28.5	9.1	1,538.2	173.9	240.7	1,538.9	7.0	10.9	4.4
DF=277.3	106.7	170.7	-977.8	636.8	1,427.3	4,625.2	454.2	423.4	49.2
OP=85.8	78.9	94.9	-174.4	80.0	90.0	80.0	98.5	97.5	91.8
Turfstone									
RM= 346.2	151.2	166.9	501.2	759.1	1,621.5	5,460.7	383.5	350.3	46.4
UM= 406.3	344.1	43.3	2,506.0	487.0	733.0	5,583.6	15.1	15.8	27.1
DF= -60.1	-192.9	123.6	-2,004.8	272.1	888.5	-122.9	368.4	334.5	19.3
OP= -17.4	-127.6	74.1	-400.0	35.8	54.8	-2.3	96.1	95.5	41.6

*RM = cumulative rainfall mass (mg); UM = cumulative underflow mass (mg); DF = difference between rainfall mass and underflow mass (mg); OP = overall percentage of removal on a mass basis.

TABLE 19

Percentage of Removal and Difference Between Stock and Sampled Water for Porous Ceramic Cup Samplers*

	Total PO_4-P	Ortho PO_4-P	Organic PO_4-P	TOC	Pb	Zn	Cr
Percentage of Removal							
X = 57.1	79.2	46.8	-19.4	94.7	-75.3	11.6	
SD = 33.6	29.6	40.6	60.7	4.8	64.1	12.0	
Absolute Removal (mg/l)							
X = 0.25	0.11	0.14	-1.73	0.756	-0.450	0.009	
SD = 0.15	0.04	0.12	5.41	0.040	0.390	0.009	

"X = average; SD= standard deviation.

Table 20

Percentage of Removal and Difference Between Stock and Filtered Water for 0.45-Micormeter Filters Used*

	Total PO_4-P	Ortho PO_4-P	Organic PO_4-P	NO_3 NO_2N	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Soaked 0.45 µm—Percentage of Removal										
X = 257.5	—	-252.5	-53.3	-7.4	18.7	-32.0	-85.0	—	—	
SD= 321.1	—	325.5	44.7	3.9	4.3	27.9	129.7	—	—	
Soaked 0.45 µm—Absolute Removal (mg/l)										
X=0.04	0	-0.03	-0.01	-0.05	0.06	-0.19	-0.001	-0.01	0	
SD= 0.03	0	0.03	0.01	0.03	0.05	0.17	0.003	0.003	0	
Unsoaked 0.45 µm—Percentage of Removal										
X= -60.0	—	-100.0	—	-2.7	-67.9	-34.0	—	—	—	
SD= 54.8	—	0	—	6.9	234.9	21.5	—	—	—	
Unsoaked 0.45 µm— Absolute Removal (mg/l)										
X= -0.01	0	-0.01	-0.01	-0.01	0.09	-0.17	0	-0.002	0	
SD= 0.01	0	0	0.01	0.05	0.17	0.08	0	0.002	0	

*X = average; SD = standard deviation.

TABLE 21

Percentage of Removal and Difference Between Stock and Filtered Water for 0.50-Micrometer Filters Used*

Total PO_4-P	Ortho PO_4-P	Organic PO_4-P	NO_3 NO_2N	NH_3-N	Organic N	TOC	Pb	Zn	Cr
Soaked 5.0 µm-Percentage of Removal									
X = -80.0	¾	-80.0	¾	3.9	31.6	-8.4	¾	¾	¾
SD = 44.7	¾	44.7	¾	6.3	42.4	6.0	¾	¾	¾
Soaked 5.0 µm-Absolute Removal (mg/l)									
X = -0.01	0	-0.01	-0.01	0.03	0.07	-0.06	-0.003	-0.004	0
SD = 0	0	0	0.01	0.05	0.09	0.04	0.003	0.001	0
Unsoaked 5.0 µm-Percentage of Removal									
X = -60.0	¾	0	¾	-1.1	-180.0	-32.5	¾	¾	¾
SD = 54.8	¾	100.0	¾	11.0	146.5	7.8	¾	¾	¾
Unsoaked 5.0 µm-Absolute Removal (mg/1)									
X = -0.01	0	0	-0.01	-0.01	-0.05	-0.11	0	-0.002	0
SD = 0.01	0	0.01	0.01	0.06	0.04	0.03	0	0.003	0

*X = average; SD = standard deviation.

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