Characterization of Long-Term Solids Removal and Clogging Processes in Two Types of Permeable Pavement under Cold Climate Conditions

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ABSTRACT

This paper summarizes the approach to, and findings of, a study investigating the processes and characteristics of solids removal and clogging in two types of permeable pavements: UNI Eco-Stone® and porous asphalt, conducted in Calgary, Alberta, Canada. The objectives of this research were to establish regional data on the long-term performance of these two types of permeable pavements with respect to hydraulic performance and water quality enhancement, and advancing the understanding of the mechanisms and processes of solids removal and clogging of permeable pavement structures. Field installations as well as laboratory models replicating 20 years of sediment loadings were used to measure the pavements' hydraulic and water quality responses to a simulated runoff influent that was loaded with a known quantity and size distribution of a 'representative' road sediment. The effects of proposed maintenance activities, and winter road sanding on hydraulic performance were also investigated. Study results showed that UNI Eco-Stone® was more effective at retaining its surface infiltration capacity, and also showed a greater promise to recover its infiltration capacity through maintenance.

KEYWORDS

Clogging; cold climate; infiltration capacity; maintenance; permeable pavement; sediment accumulation

INTRODUCTION

Permeable or porous pavements were introduced as stormwater management measures in the early 1970s, and the early experiences with such pavements were reported by Field at al. (1982) in the US and Fujita (1994) in Japan. It was observed that such pavements allowed stormwater to infiltrate into the pavement and the underlying soil and thereby contributed to such benefits as reduced runoff volumes and discharges (Field et al. 1982; Fujita 1994), high stormwater pollutant removals (Pratt et al., 1995; Balades et al., 1995; Rushton, 2001), durability, noise reduction, and increased traffic safety due to reduced spray generation (USEPA, 1999). However, in spite of these favourable findings, a number of serious concerns remained, particularly with applications on fine-grained soils and in cold climate.

The use of permeable or porous pavements in stormwater management has increased dramatically over the past ten years, partly because of increased interest of designers, city planners, and stormwater management engineers across Europe, North America, and Japan and Australia in this promising, cost-effective source control measure, and partly because of increased research addressing the earlier concerns, leading to improved design and construction specifications (Brattebo and Booth, 2003 and Collins et al, 2006). Besides advantages of permeable pavements, their limitations were also addressed. Toward this end, Backstrom and Bergstrom (2000) reported that the infiltration capacity of porous pavements was reduced in cold weather by about 40% at freezing point, and even more (up to 90%) during repeated melt-freeze cycles. Dreelin et al. (2006) tested a porous pavement on clay soils and noted that the pavement remained a viable option for reducing stormwater runoff and some pollutants from small storms, or the first flush of large storms (2006).

In spite of these advances, a considerable amount of research on permeable pavements remains to be done before they can be successfully implemented in all situations, including the cold climate. Of particular importance is the establishment of regional data for their performance with regards to long-term surface infiltration capacity and water quality improvement. Although there has been extensive research in these areas, specifically with respect to short-term performance, the long-term success of permeable pavements is highly dependent on local geological and climatic conditions, as well as road maintenance practices, and therefore studies from different geographical locations often have limited applicability to the local installation of permeable pavements. Also, to date there has been little research into the specific size ranges of particles that can be removed, and precisely where in the pavement structure they are removed. This information is however crucial, not only to provide a better understanding of the clogging and filtration processes within permeable pavements, and their maintenance, but also because local and regional policies often set stormwater treatment targets based on specific size ranges of particles (Alberta Environment, 2001).

This paper presents a study of the processes and characteristics of solids removal and clogging in two types of permeable pavement: UNI Eco-Stone® and porous asphalt, conducted in Calgary, Alberta, Canada. The main objectives were to determine the long-term performance of these two permeable pavements with respect to hydraulic performance and enhancement of stormwater quality, and to advance the understanding of the mechanisms and processes of solids removal and clogging within permeable pavement structures.

METHODOLOGY - FIELD EXPERIMENTS

Field Installations

Two pilot-scale permeable pavement installations, with surface courses of porous asphalt and UNI Eco-Stone® open-joint paving blocks, respectively, were installed adjacent to each other on Hochwald Avenue SW in Calgary, Alberta, in November 2005. The street is a collector road located at Currie Barracks, a former military base. The site is located directly in front of a stop sign, and receives moderate light-duty to occasional heavier-duty (i.e., trucks) traffic. While permeable pavements are typically recommended for low traffic applications, such as parking lots, this site was selected based on the desire of its owner to evaluate the extreme limits of permeable pavements with regard to hydraulic and structural robustness.

Both the porous asphalt and UNI Eco-Stone® pavement sections were approximately 8 metres long by 6 metres wide. A detailed description of the field installation can be found elsewhere (Brown, 2007 and Brown et al., 2008). Figure 1 illustrates the composition of the pavement structure for the UNI Eco-Stone® installation.

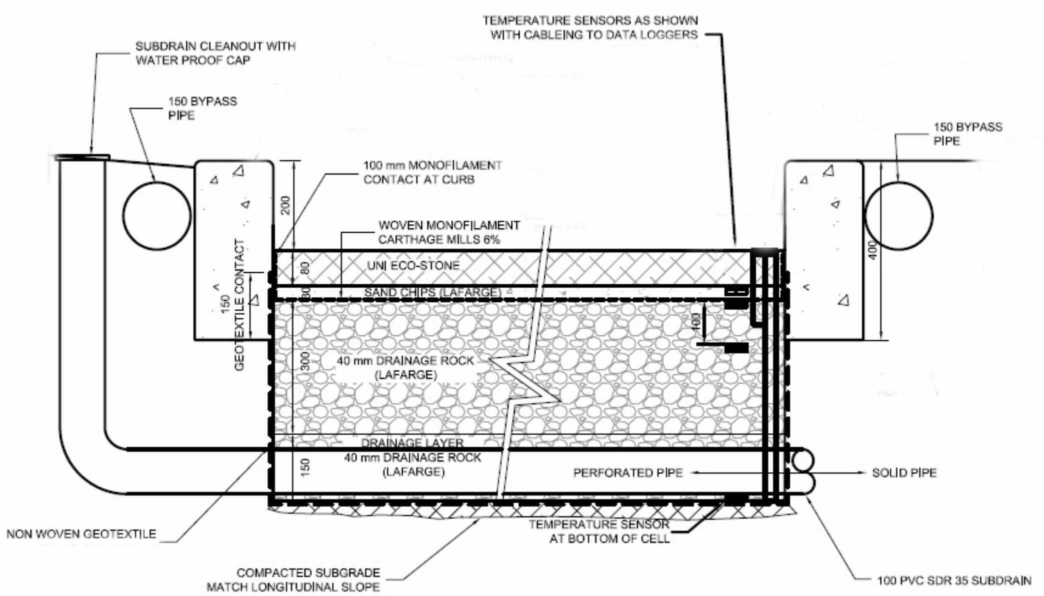

Figure 1. Currie Barracks Permeable Pavement Cross-Section (Eco-Stone® installation shown. Porous Asphalt installation is identical except for the surface course) (Courtesy Westhoff Engineering Resources, Inc.)

Field Procedures

Surface Infiltration Capacity and Maintenance Experiments

During the period from May to October 2006, pavement surface infiltration capacities were measured periodically, and two different maintenance procedures were applied using a vacuum sweeper (Schwarze Model A8000). The first maintenance procedure, consisting of a single dry pass, was applied on June 5, 2006. The second procedure, in the form of three passes with water spraying for dust control, was carried out on October 23, 2006. Surface infiltration capacity measurements were made using 30 cm diameter, galvanized steel ring infiltrometers, which were sealed to the pavement surfaces with Plumber's Putty, as suggested by Bean et al (2004). The locations of the infiltrometers were initially chosen randomly, and the same locations were used throughout all subsequent infiltration measurements. A detailed discussion of these procedures and their limitations can be found elsewhere (Brown, 2007 and Brown et al., 2008). In total, 15 locations were sampled: 7 on the porous asphalt and 8 on the Eco-Stone® paving blocks. During the five month study period, there was approximately 340 mm of natural rainfall, which was supplemented by 90 mm of simulated runoff applied 3 times in the amount of about 30 mm per application. These runoff applications were part of other concurrent studies done at the pavement site that are beyond the scope of this paper.

METHODOLOGY - LABORATORY EXPERIMENTS

Laboratory Models and Procedures

Surface Infiltration Capacity and Maintenance Experiments

Two lab-scale 465 mm x 465 mm permeable pavement models were constructed in the Hydraulics Laboratory at The University of Calgary to study simulated long-term hydraulic behaviour of the pavements. The composition of the pavement structures for the laboratory models was almost identical to the layers at the field installations at Currie Barracks. A detailed description of the laboratory installations and procedures followed can be found in Brown (2007) and Brown et al (2008). A third structure was used to investigate the effect of winter sanding on the long-term surface infiltration capacities for both pavement surfaces.

Simulated Runoff - Sediment Characteristics

Long-term runoff simulations were performed in the laboratory by systematically applying water loaded with a fine fraction of sediment collected from Calgary streets, which would pass through a 250 μm sieve. This fine fraction was desired for two reasons: (a) it represents the material that is ultimately responsible for clogging permeable pavements (Gerrits, 2001), and (b) it is of particular importance in stormwater treatment as a carrier of particular pollutants and it can be relatively easily mobilized, entrained and transported by stormwater discharges (Barnes et al, 2001; Sartor et al, 1974; Roger et al, 1998; Andral 1999).

For all laboratory simulations, the target concentration of sediment applied to the surfaces was 500 mg/L, which is close to the average Event Mean Concentration recorded by the City of Calgary over multiple storm events. For this series of experiments, sediment-loaded water was applied to the pavement models for a simulated period of time. A total of 20 years worth of runoff and sediment application was simulated for both pavement types.

Long-term Decline in Laboratory Surface Infiltration Capacities

The surface infiltration capacity of the pavements was measured at the end of each simulated year. This was done to evaluate the long-term hydraulic performance of the pavements. The same type of infiltrometer that was used in the field was also used in the laboratory. The maximum measurable infiltration capacity in the laboratory was limited by the flow rate of the hose used for water application and was determined to be approximately 30 m/hr.

Size Distribution of Particle Accumulating Throughout the Pavement Structure

After the 20 years of simulated stormwater runoff application, the pavement models were carefully disassembled, and samples of accumulated sediment were collected from various layers of both pavement models so that the particle size distribution (PSD) could be analyzed throughout the structures. Data from this analysis were needed to gain appreciation of the depth of penetration of solids into the pavement structures. Figure 2 illustrates the locations where sediment was collected for the Eco-Stone® model. A similar approach was adopted for the porous asphalt model.

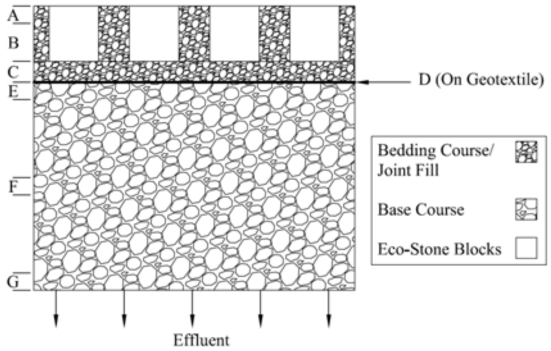

Figure 2. Sampling locations for PSD analysis at various layers of laboratory Eco-Stone® Model after the 20 years of simulated runoff

The Effects of Winter Sanding Material on Surface Infiltration Capacity

As part of the laboratory experiments the effect of winter sanding material on the long-term surface infiltration capacity of both permeable pavement surfaces was also investigated. The sanding material used in the laboratory was from the same source as the material used for sanding the streets at Currie Barracks, which is almost identical to that used by The City of Calgary on most of Calgary's roads. The practice of applying new sanding material each winter and then removing a portion of it by street sweeping in the spring was not simulated. Since winter sanding material appears to be readily broken down into smaller particles by vehicular traffic, brief breakage load experiments were conducted to decide how to simulate this highly variable factor. The procedures and results for these experiments are detailed in Brown (2007). From the results of these tests, and from observing actual material at the field site, it was decided to manually crush 20% of the sanding material, by applying a point load until fracture, before applying it. Simulated runoff application then proceeded in much the same way as the other long-term experiments, using the same TSS material and concentration.

RESULTS AND DISCUSSION

Field Results

Surface Infiltration Capacity and Maintenance Experiments

Due to the fast onset of freezing temperatures in the fall of 2005, surface infiltration capacities could not be measured immediately after installation of the pavements. However, soon after, on November 24, 2005, water was applied to the pavement surfaces to check their functionality. From videos and photographs taken on that date, surface infiltration capacity was very roughly calculated to be in the range of 25 – 40 m/hr.

The results for all surface infiltration capacity measurements between the spring and fall of 2006 for the Eco-Stone® pavers are shown in Figure 3, with error bars indicating the average percent deviations across all measurements. In most cases, by the spring of 2006, the surface infiltration capacity had substantially decreased compared to the initial estimation. There were some exceptions, typically at the very edges of the pavement. This was likely due to the lack of traffic at these locations. A high degree of spatial variability was observed, which supports the findings of Kresin et al (1997). The remaining surface infiltration capacities were measured before and after two separate maintenance activities. The discussion of the maintenance results and their implications follows.

Maintenance #1 – Single dry pass, Schwarze A8000

For the porous asphalt, all but one of the monitored locations showed a substantial decrease in surface infiltration capacity after the street sweeping activities. For the Eco-Stone®, some locations increased, some exhibited little change, and some decreased in infiltration capacity.

The poor results of the first vacuum sweeping maintenance on the porous asphalt may be attributed to a "grinding and crushing" effect by the street sweeper. That is, coarse solids may have been broken down into finer solids which were then spread out and embedded more permanently into the pavement surface. This phenomenon, which would increase the potential for clogging, is certainly reported to occur over time as a result of vehicular traffic (Kresin, 1996), and it is possible that the vacuum sweeper used in this case caused a similar outcome.

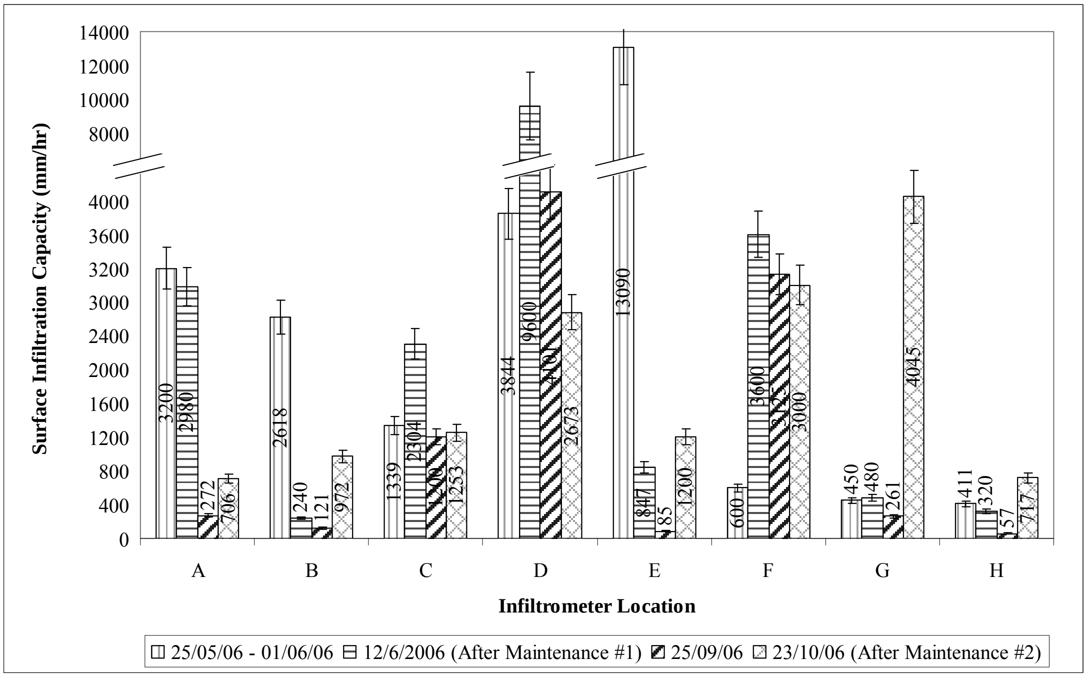

Figure 3. Surface Infiltration Capacities for Eco-Stone® at Currie Barracks

For the Eco-Stone®, the locations showing improved infiltration rates had a visibly higher volume of joint fill material removed by the vacuum sweeper than those locations which showed no improvement or degradation in infiltration rate. Those locations that showed no improvement or degradation still retained most of their joint fill material, and the material was visibly held in by a "crust" of fine material. Increased joint fill material removal appeared to be correlated with an improved infiltration rate. This agrees with the observations by Kresin et al (1997) and James and Gerrits (2003). One can speculate that additional passes of the vacuum sweeper would show further improvement for the UNI Eco-Stone®.

Maintenance #2 – Three wet passes, Schwarze A8000

The measured infiltration capacities before and after the second maintenance procedure are also shown on Figure 3. By the time the second procedure was applied, all porous asphalt locations appeared to be irreversibly clogged. The decline in surface infiltration capacity over the initial 10 months was likely due to the application of winter sanding materials, compression of the asphalt (and thus reduction in void spaces) due to traffic, and the grinding and crushing action of traffic. Also, the specific asphalt mix used may not have been ideal for this installation. Further investigation into all of these factors is needed in future studies.

In contrast, the Eco-Stone® showed very positive results after the second maintenance procedure probably due to more passes removing joint fill material to a greater depth, rather than due to the fact that it was a wet application. As with the first maintenance event, improvement in infiltration capacity appeared to be proportional to the depth to which joint fill material was removed. In addition, Balades et al (1995) found that wetting followed by sweeping actually had a negative effect on the infiltration capacity of permeable pavements. Because of the correlation between the depth of joint fill material removal and improvement in surface infiltration capacity, a visual examination of the removal of joint fill might suffice in maintenance practice. Repeated passes could be made until a satisfactory amount of joint fill removal was observed, provided that the drainage voids would be periodically replenished with additional joint fill material to maintain structural integrity.

Laboratory Results

Long-term Surface Infiltration Capacity

The results of the long-term laboratory surface infiltration capacity measurements are shown in Figure 4. The first several years of data in Figure 4 were found through linear extrapolation due to limitations in the maximum measurable infiltration capacity in the laboratory setting. Therefore, the accuracy of the data in this figure is reliable only below an infiltration capacity of about 30,000 mm/hr.

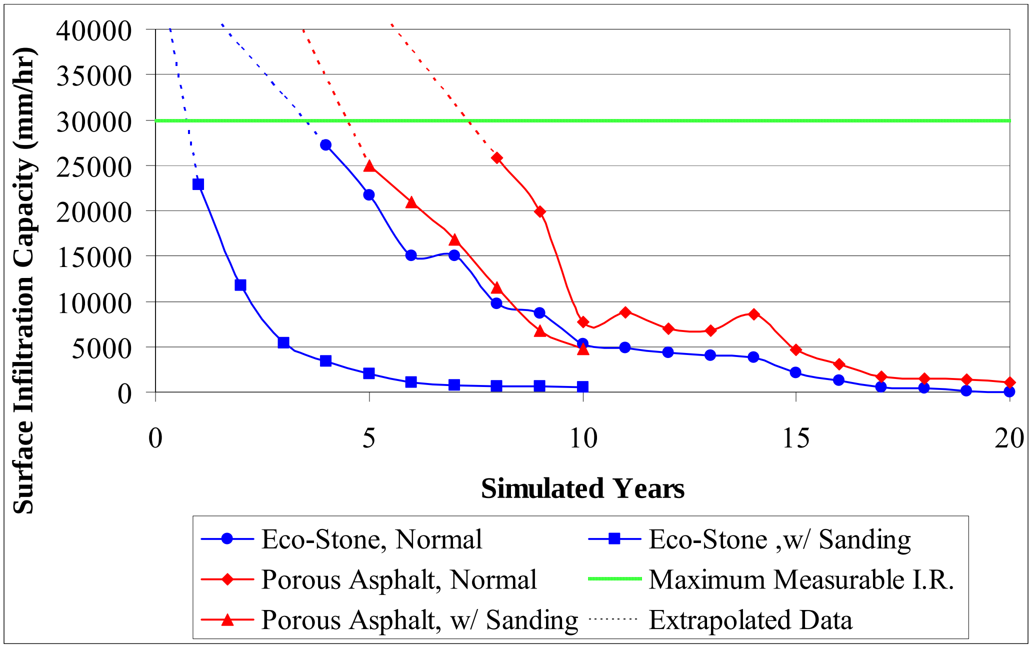

Figure 4. Long-term Laboratory Surface Infiltration Capacity of Porous Asphalt and Eco-Stone® with and without the presence of winter sanding material

Both pavement surface types showed a gradual decline over the 20 simulated years of applied runoff. However, the decline was much slower in the laboratory than in the field. Also, in the laboratory, the porous asphalt consistently showed higher infiltration capacities than the Eco-Stone®, which was different from what was observed in the field. The most likely reason for these discrepancies was the absence of vehicular traffic from the laboratory models. It is believed that heavy loads on asphalt compress the void spaces. Infiltration capacities are therefore rapidly reduced, as reported by Ferguson (2005).

Another possible reason for the discrepancy is the effect of “drying time”, or long periods of exposure to sunlight without any precipitation. It is conceivable that these periods could make moisture-laden sediments aggregate within the pavement structure, forming non-permeable crusts. These “drying time” conditions could not be simulated in the laboratory because of time and feasibility constraints.

The laboratory experiments also served to investigate the effects of the presence of winter sanding material on the long-term surface infiltration capacities of the permeable pavement surfaces. Figure 4 shows the results of the laboratory winter sanding experiments compared to the standard laboratory long-term surface infiltration capacity experiments. A clear trend was observed: the surface infiltration capacities decreased substantially for both pavement types when winter sanding material was present, regardless of the presence or absence of vehicular traffic. The porous asphalt surface infiltration capacity remained significantly above that of the Eco-Stone®, and the effects of winter sanding material were less pronounced. These findings are, again, contradictory to the results seen in the field, where the surface infiltration capacity of the porous asphalt declined much more rapidly than that of the Eco-Stone®. This suggests that the presence of vehicular traffic is a very significant factor for the long-term hydraulic performance of porous asphalt surfaces, since this was one of the only significant variables absent in laboratory testing. Despite the discrepancies, this set of experiments does show that winter sanding material on permeable pavement surfaces substantially decreases the surface infiltration capacity and as such would likely lead to more rapid clogging and the ultimate failure of the pavements. This was corroborated by St. John and Horner (1997).

Size Distribution of Particle Accumulation Throughout the Structure

Results from the study showed that both pavement types are capable of excellent removal of suspended solids, in the range of 90-96% of incoming solids. Particle size distribution analysis of accumulated sediment within the structure and in the influent and effluent showed that the particles in the effluent of the pavements are substantially finer than those in the influent, and that, although solids removal occurs throughout the entire structure, the “filtration action” occurs primarily by the geotextile.

Figure 5 shows the results for the PSD analyses of the various layers of the Eco-Stone® pavement model. For both pavement types, the laboratory experiments suggest that the surface and bedding course layers above the geotextile have little influence on the filtration of specific particle sizes, while relatively dramatic changes occur above and below the geotextile (Locations D and E for Figure 5). The deposited material is substantially finer below the geotextile as compared to the material above. These findings are significant in that they demonstrate the role geotextiles can have in filtration by permeable pavements. At the same, these findings appear to contradict the findings of the field experiments in which filtration primarily took place at the surface of the pavement; this may be due to the influent characteristics and the lack of “crust” formation in the laboratory.

CONCLUSIONS AND RECOMMENDATIONS

The objectives of this research program were to determine the long-term performance of the two types of permeable pavement contemplated in Calgary, Alberta, Canada, with respect to hydraulic performance and to gain a better understanding of the mechanisms and processes of solids removal and clogging within permeable pavement structures.

The laboratory experiments suggest that the “filtration action” is prominent at the geotextile layer. This appears to be contradictory to the findings of the field experiments and other studies in which filtration primarily took place at the surface of the pavement; this may be due to the influent characteristics and the lack of “crust” formation in the laboratory. The findings in this study are significant in that they highlight the importance of selecting appropriate materials for the various courses and geotextiles in the pavement. The findings also highlight the complimentary nature of the laboratory and field investigations. Most field studies are typically short in duration and, as such, do not allow the examination of the long-term performance or the optimization of the composition of the pavement structure. On the other hand, in the case of laboratory experiments, challenges need to be overcome with replicating traffic impacts, wetting and drying cycles, and real-life maintenance activities. Therefore, an appropriate balance needs to be found between both approaches.

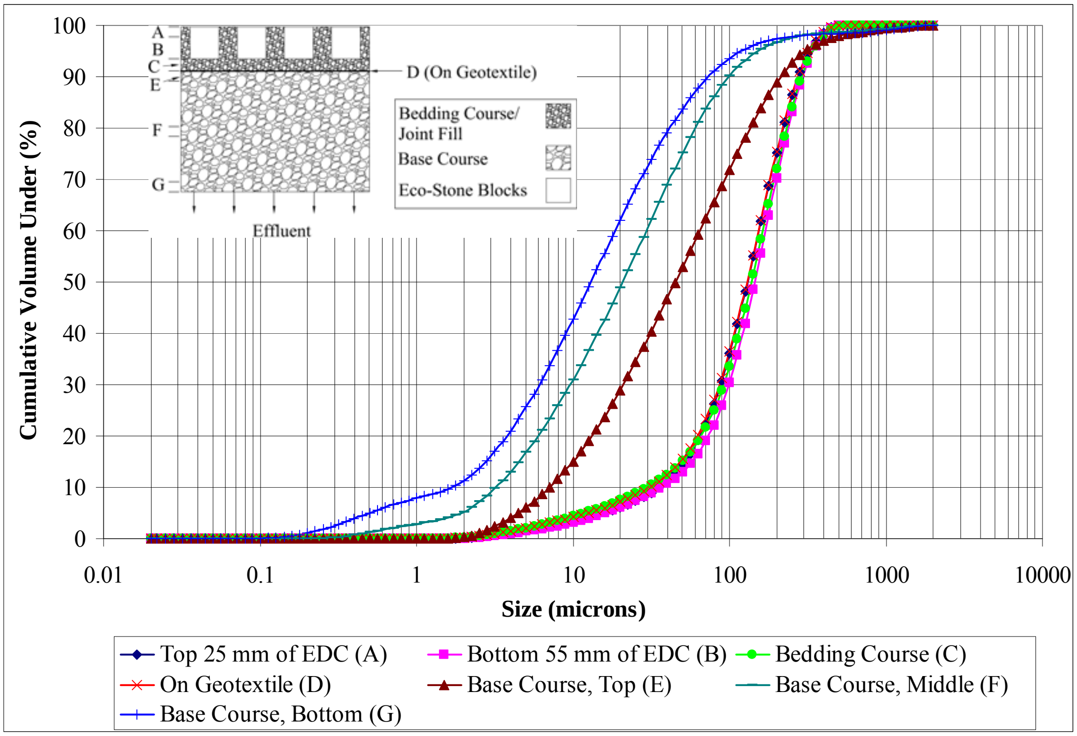

Figure 5. Particle Size Distributions for Eco-Stone® Layers Throughout Pavement Model After 20 Years of Simulated Runoff (Layer Locations Superimposed in Upper Left Corner)

The porous asphalt surface in the field was found to clog substantially faster than the Eco-Stone® within the first year of operation. If installed in a similar setting, this particular type of porous asphalt would not be suitable for long-term use due to its poor hydraulic performance, whereas the Eco-Stone®, after one year, was still functioning sufficiently. Finally, the application of winter sanding material, and its subsequent breakage into finer materials by vehicular traffic, has a very significant impact on the long-term surface infiltration capacity of both permeable pavement types.

Recommendations for future research include examining the influences of different joint fill and bedding materials, as well as different geotextiles, and geotextile locations throughout the pavement structure, as this may provide more insight into what combination provides the best balance between solids removal and long-term hydraulic performance. Additionally, the influence of drying time by direct sunlight, as well as vehicular traffic action, on the long-term surface infiltration capacities would provide more data on the hydraulic performance of these systems. In the case of the porous asphalt other mixes should be investigated. Other potential maintenance activities, especially those serving to break up the crust with a minimal removal of the joint fill layer, also need to be examined. Finally, the composition of the winter sanding materials warrants further investigation to arrive at an optimum combination of traffic safety and minimal clogging.

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