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LABORATORY EVALUATION ON THE EFFECT OF CLOGGING ON PERMEABILITY OF POROUS ASPHALT MIXTURES

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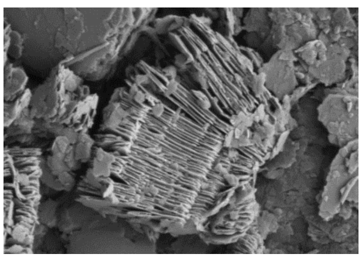
Graphical abstract



Abstract

Porous asphalt mixture is one of the alternative solutions to increase pervious surface area due to urbanization. The uniqueness of porous asphalt surface textures and internal structures allows the mixture to become a temporary storm-water retention and capable to channel excessive storm water. However, one of the major problems that affect the performance of porous asphalt mixtures is the clogging. Therefore, this study aims to determine the effect of clogging towards the permeability of porous asphalt. A total of 30 gyratory compacted samples were fabricated according to aggregate gradation recommended by Malaysia Public Works Department. The clogging materials were collected from two different location, residential area and major highway. The composition and characteristics of the clogging materials were investigated using Plastic Limit, Liquid Limit and Scanning Electron Microscope (SEM). The permeability test was conducted to investigate the permeability rate of the compacted samples based on different clogging material types, clogging concentrations and clogging cycles. In addition, the compacted samples were scanned using X-ray Computed Tomography to obtain the air voids distribution throughout the samples for comparison. It was found that higher concentration of clogging materials and clogging cycles reduced the rate of permeability. Clogging material collected from residential area has higher tendency to clog the void spaces compared to the one obtained from highway.

Keywords: Porous asphalt, permeability, clogging, concentration

1.0 INTRODUCTION

Porous asphalt mixture is an alternative wearing course to conventional dense graded hot mix asphalt. This mixture type uses open graded gradation that consists of limited amount of fine aggregates to create large quantity of interconnected voids that allows surface runoff to seep through. The water is absorbed through the pores surface texture and later channel through the internal interconnected voids (micro-pores) until it transmitted to the edge of the road. The removal of surface runoff from the pavement surface will reduce the hydroplaning effect, spraying, traffic noise and improve skid resistance and visibility during wet weather [1 & 2]. Besides, porous asphalt is a special mix designed with high interconnected air voids of 18 to 25% and offers high rate of permeability compared to conventional pavement mixes [3-5]. The interconnected air voids can be defined as the proportion of air void that form an internal connected pathway for air and water transport through asphalt mixtures. Other than improving roadway safety criteria, porous asphalt can also be effectively used in stormwater management system for the purpose of stormwater runoff storage, treatment, and improvement of water quality through pollutant removal [6 & 7].

Despite its benefits, the performance and service life of porous asphalt pavement is limited due to poor durability and loss of permeability as a result of clogging. Numerous researchers have reported that permeability of porous asphalt significantly reduced after years in service due to the surface texture and internal structure of the mixtures are clogged with fine road debris [8-11]. The phenomenon of clogging can be easily spotted when there is a water ponding on the porous asphalt surface particularly after the rainfall. The open structure of porous asphalt allows foreign particles in the runoff to be trapped within the pores of porous layer, causing it to clog and reduce the mixture hydraulic conductivity [12]. The major cause for reduced drainage capacity comes from the particles in the surface runoff when they flow through the pavement surface [13]. In addition, fine particles such as dust, debris, tyre wear by-products or stripped fine bitumen coated aggregate are the potential clogging materials that clogged the pores of porous asphalt mixture on the surface texture and also internally [14 & 15]. Therefore, it can be said that clogging is a process that develops over time, where the accumulation of sufficient amount of sediments from stormwater, wind and debris that are transported from various tyre vehicles takes place in the porous layer [16 & 17].

On the other hand, it should be noted that the permeability of porous asphalt is also subjected to different properties of clogging material (i.e. types, concentration, and particle size distribution) as well as the loading state (cycle of clogging). Since the clogging limits the ability of porous asphalt layer to transmit water internally, a number of studies have been conducted on the factors that could possibly affect the permeability rate of porous asphalt due to clogging phenomenon. Previous studies have claimed that the clay-sized materials are far greater concern than sand-sized materials. It was reported that sand clogging can reduce the permeability rate, but does not fully clogged because the water still can flow through the porous layer [18]. A study on the physical clogging of gravel infiltration systems found that sediment particles less than 6 μm in diameter are the main cause of clogging [19]. The pores in the porous asphalt mix will become more obstructed as more fine particles are trapped and increase the rate of clogging [20 & 21]. Furthermore, the concentration of solids in stormwater runoff varies among sites. The median concentration reported in a national survey was 99 mg/L for runoff from freeways and about half of that for residential and commercial drainage areas [22]. Other study on highway stormwater loads found that the concentration in highway runoff was affected by the number of vehicles passing the site. It can be concluded that roads with high daily traffic volume have higher total suspended solids concentration compared to those with low traffic volume [23]. In a recent study which involving the clogging and cleansing procedure indicated that porous asphalt is more prone to clogging after a few clogging and cleansing cycles. It was discovered that the rate of permeability decreased as the porous asphalt specimen was subjected to loading cycles [14]. Therefore, this study was conducted to investigate the effect of clogging on the permeability of porous asphalt in order to provide more information regarding this phenomenon.

2.0 EXPERIMENTAL PROGRAM

2.1 Materials Properties

2.1.1 Aggregates and Bitumen

The crushed granite used in this study was supplied by Malaysian Rock Product (MRP) quarry in Ulu Choh, Johor. The gradation limit of the combined aggregate for porous asphalt mixture was selected in accordance to Malaysia Public Works Department specification, PWD (2008) as shown in Figure 1 [24]. The specimens were prepared to achieve the aggregate gradation enveloped for porous asphalt mixture Grading B (nominal maximum aggregate size, 14 mm). Two percent of hydrated lime was added to the mixture as a filler and anti-stripping agent.

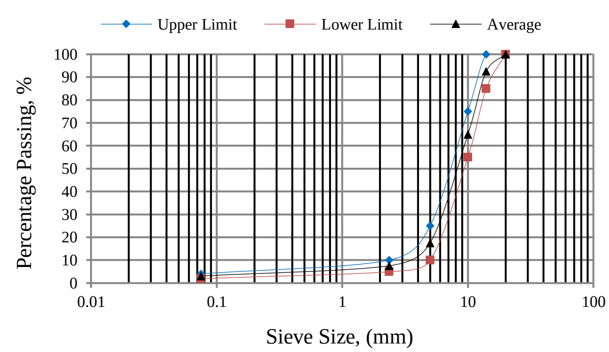


Figure 1 Malaysian gradation limits for porous asphalt mixtures, Grading

The aggregate was tested for specific gravity, water absorption and aggregate impact value. The specific gravity and water absorption for the coarse and fine aggregates were determined as in ASTM C127 and ASTM C128 respectively. While aggregate impact value was determined in accordance to ASTM D5874-02. Tables 1 and 2 show the result of specific gravity and water absorption for the coarse and fine aggregates accordingly. The aggregate impact value was averaged at 26%.

Table 1 Coarse aggregate properties

Coarse Aggregate Properties	Value
Specific Gravity Bulk	2.601
Specific Gravity Saturated Surface Dry (SSD)	2.625
Specific Gravity Apparent	2.665
Water Absorption (%)	0.914

Table 2 Fine aggregate properties

Fine Aggregate Properties	Value
Specific Gravity Bulk	2.427
Specific Gravity Saturated Surface Dry (SSD)	2.477
Specific Gravity Apparent	2.554
Water Absorption (%)	2.048

Polymer modified bitumen, PG76 was used as a binder for the mix design. PG76 is a bituminous binder with improved resistance to age hardening as the binder's properties are shown in Table 3.

Table 3 Bitumen properties for PG 76

Properties	Result
Viscosity at 135°C	1.1 Pa.s
Penetration at 25°C	40.6 mm
Softening point	75°C
Specific gravity at 25°C	1.030 g/cm^3

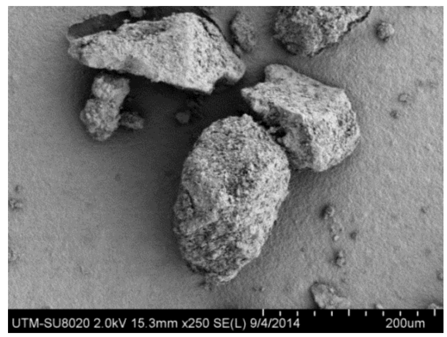
2.1.2 Clogging Materials Properties

The clogging materials were collected at two different local areas, highway (Bukit Indah Highway, Johor) and residential area (Taman Pulai Indah, Kangkar Pulai, Johor). These locations were selected due to the high water runoff observed during rainfall. The physical properties of the clogging materials were investigated based on sieve analysis and plastic index. Sieve analysis test was carried out to determine the grading of the clogging materials following ASTM C33 specification. Liquid limit and plastic limit tests were conducted as a basic measurement of the critical water contents of a fine-grained soil which later can be used to express its relative consistency or plasticity index.

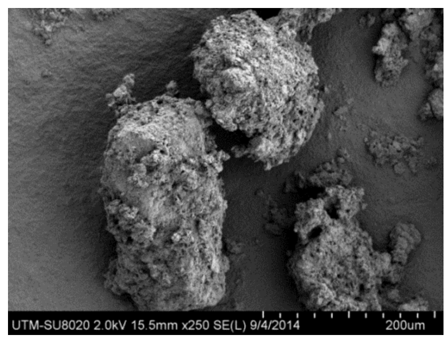
Table 4 Clogging materials properties

Sieve size (mm)	Cumulative Percentage Passing (%)	
	Highway	Residential Area
2.36	89.76	98.42
1.18	68.62	90.62
0.6	46.52	77.04
0.3	30.44	51.64
0.15	15.28	27.66
0.075	3.9	10.86
Liquid Limit (%)	29.80	23.70
Plastic Limit (%)	-	17.59
Plasticity Index (%)	-	6.12

From Table 4, both of the clogging materials are categorized as coarse and medium sand according to the Unified Soil Classification System (USCS). The sieve analysis result indicated that clogging material from the residential area is finer than the one collected from highway area. The plastic limit test for the clogging material taken from highway cannot be conducted due to the least percentage of material passing 0.075 mm sieve size (less than 10%) and the composition mostly consists of coarse sand. Whereas, the clogging material collected from residential area consists of small portions of silt and clay and the percentage of material passing 0.075 mm is more than 10%. Therefore the plastic limit test was conducted to determine its plasticity index value. It was found that the plasticity index for this clogging material is 6.12%



(a)



(b)

Figure 2 Surface texture for clogging materials at magnification of 200 µm for (a) highway and (b) residential

In addition, the investigation on the surface texture for the clogging materials was conducted using Field Emission Scanning Electron Microscope (FESEM). This is to obtained images of the clogging materials at the micro-scale to better understand their microstructural properties. According to previous researcher, surface area plays an important factor in influencing behaviour of the physical and chemical properties of the clogging material [25]. Figure 2 shows the macro texture of these clogging materials at both sites. For the clogging materials collected at highway area and residential, it shows clogging material exist in the form of singular grain structure. Clogging material collected from highway is more angular with clean surface texture compared to residential clogging materials that appear to be more rounded shape with clay minerals attached to its structure. Closer observations were conducted on the micro texture of the clogging materials as shown in Figure 3. The micrographs show that particles obtained from highway are in solid grains with small quantities of Kaolin platelets attached to its structure. While the clogging materials collected from residential area appear to be clay formation with Kaolin minerals (hexagonal stack-of-cards shape) bonded to each other. Figures 2 and 3 show the FESEM images of the clogging materials taken from both sites at different magnification levels.

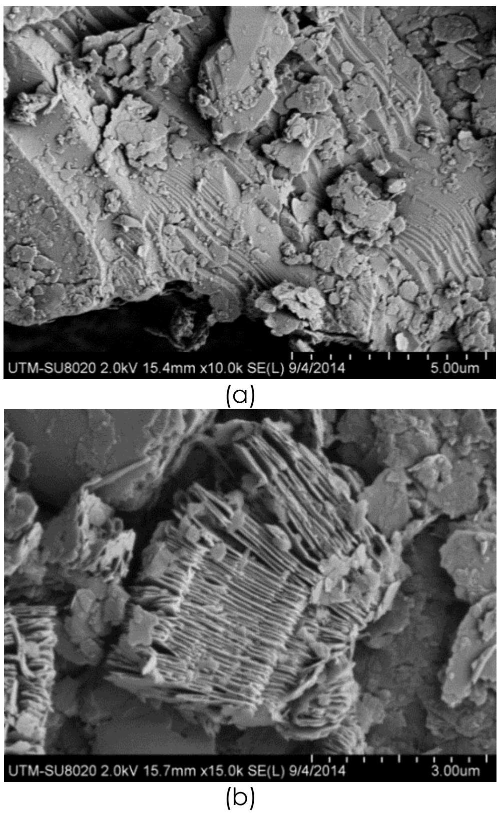


Figure 3 Surface texture for clogging materials at magnification of 5µm and 3 µm for (a) highway and (b) residential

2.2 Mixture Design and Sample Preparation

The samples were fabricated to achieve the target air void content of 20±1%. The optimum bitumen content (OBC) was determined by meeting the criteria of Cantabro, binder draindown test and target air voids content. The binder draindown test is used to quantify the sufficient quantity of bitumen film thickness to coat the aggregate particles. While Cantabro test is used to evaluate the mixture's resistivity against stripping or aggregate loss. The specimens were compacted using gyratory compactor with the loading pressure of 600 kPa. From these tests, the optimum bitumen content for the porous asphalt mixture was obtained at 5%. A few trials compaction were conducted at various number of gyrations i.e. 20, 40, 60 and 80. Based on Figure 4, the number of gyration to achieve the target of 20% air voids content is 58 gyrations.

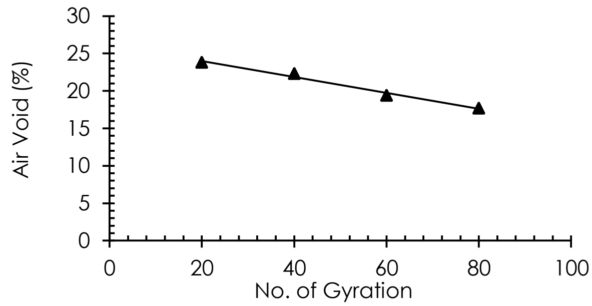


Figure 4 Determination number of gyration

2.3 X-ray CT and Image Analysis Technique

The internal structure properties of asphalt mixture can be investigated using image analysis technique. X-ray Computed Tomography (CT) is an advanced imaging technique which is used as a non-destructive method to capture images. In this study, this technology was used to investigate the air voids distribution within the samples. For porous asphalt, the air void characterization provides information regarding the air void distribution and its properties which reflect the voids interconnectivity within the compacted sample. The presence of interconnected air voids in the porous asphalt as wearing course layer allows water to infiltrate within the pavement layer and prevent water accumulation on the surface. Therefore, using this imaging technique the distribution of the air voids and the rest of the asphalt constituents can be assessed.

The compacted samples were scanned using a Micro Focus X-ray Computed Tomography (CT) system at Universiti Teknologi Petronas, Malaysia. The Shimadzu inspeXio SMX-225 CT is a top-of-the-line Micro Focus X-ray CT system, which features a high precision CT stage and sophisticated image processing software. The specimens were rotated at 360° generating multiple two dimensional image slices from top to the bottom sections of the sample at the interval approximately 0.10 mm as shown in Figure 5. The X-ray CT scan generates images in a form of 16-bit images which were later converted to 8-bit images. This particular image consists of 256 ranges of grey intensity, from 0 (darkest region) to 255 (brightest region) which refer to the different densities within the specimens. The images were then processed using imaging software, ImageJ. These images were combined in stack formations prior to image enhancement. The image processing is necessary to eliminate defects such as ring artifacts, beam hardening and noises. The images were filtered using Gaussian Blur and Median Filter, threshold and converted into binary images to analyse the air voids content. Details on the image acquisitions and enhancement regarding asphalt mixtures are further explained by previous researchers [4, 26-28].

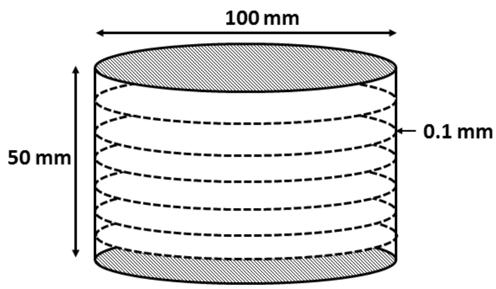


Figure 5 Schematic image of staged images for scanned images of X-ray CT scan

2.4 Permeability Test

The permeability test was conducted using a Falling-head Permeameter Test method at ambient temperature, 25°C according to ASTM D5084-10 as per Figure 6. A total of 30 gyratory compacted samples were tested with three replicates for each concentration and type of clogging materials. Each sample has dimensions of 100 mm diameter and 50 mm height and the air void content is approximately 20%. .

The coefficient of permeability, *k* is measured in terms of its discharge time in seconds, which was the time taken for a specified volume of water to permeate through the samples. In this study, permeability is measured in terms of the time taken for the water level to fall between two designated points from 60 mm to 20 mm within the permeameter tube. The permeability coefficient is calculated by using Equation 1 following the Darcy's Law.

Figure 6 Falling-head permeameter

For uncontaminated porous asphalt mixtures, the initial reading for the coefficient of permeability is 0.16 cm/s. The samples were then subjected to five different concentrations at five cycles of clogging material. The clogging materials were prepared at five different concentrations, 1.0, 2.0, 3.0, 4.0 and 5.0 g/L. Three replicates were prepared for each condition. After subjected to the clogging material, the samples were left to dry for about 24 hours at a temperature of 35.0°C to complete one cycle. Next, the clogging procedure was repeated for another four cycles to complete the clogging cycles.

$$k = \frac{al}{At} ln \frac{h_1}{h_2} \quad [1]$$

where,

k = Coefficient of water permeability, (cm/s)
a = Inside cross-sectional area of inlet standpipe, (cm^2)
l = Sample thickness, (cm)
A = Sample Cross-sectional area, (cm^2)
t = average elapsed time of water flow between timing marks, (s)
h_1 = hydraulic head on sample at time t_1, (cm) and,
h_2 = hydraulic head on sample at time t_2, (cm)

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Air Voids Distribution

The air voids distribution was analysed throughout the compacted samples. Figure 7 shows a two dimensional (2D) image slice obtained from X-ray CT scanner. The dark region in the image indicates low density materials which represent the air voids, and aggregates as the brightest region due to its high density.

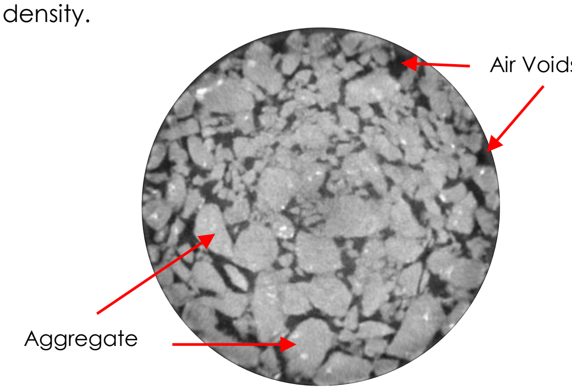
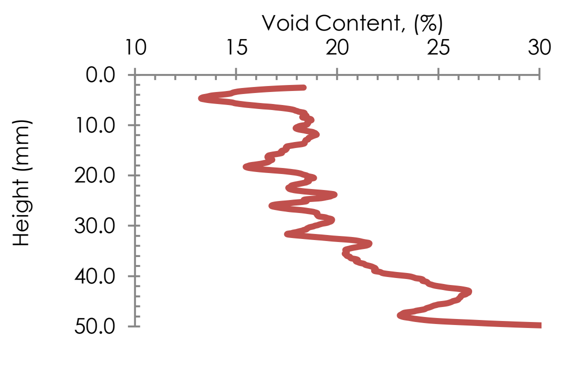


Figure 7 Two dimensional (2D) image of X-ray CT image for porous asphalt mixture

Figure 8 shows the distribution of air voids properties, voids content, voids number and average voids size for the porous asphalt mixture. These parameters can be used to describe the air voids connectivity within the sample which an important characteristic in the design of porous asphalt for the water infiltration. High air voids content and less number of voids at any specimen's height describe the high connectivity of voids (large void size) within the section. Based on the figure, the top section at the height of 0 is referred to the surface of the compacted sample that has a direct contact to the gyratory plate. It should be noted that a few slices at the top and bottom sections were excluded from the analysis due to high variation of the surface voids. It can be seen that, for this grading type, higher air void connectivity can be found at the bottom section compared to the top section. In particular, although the samples were fabricated to achieve air voids content approximately 20%, the air voids content was found to vary along the height which could affect the permeability rate. Based on this observation, low water infiltration can be expected at the top section and high permeability coefficient or rate for the water to be released from the bottom section of the sample.



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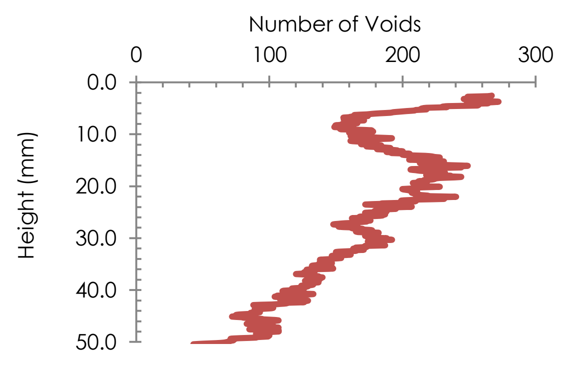

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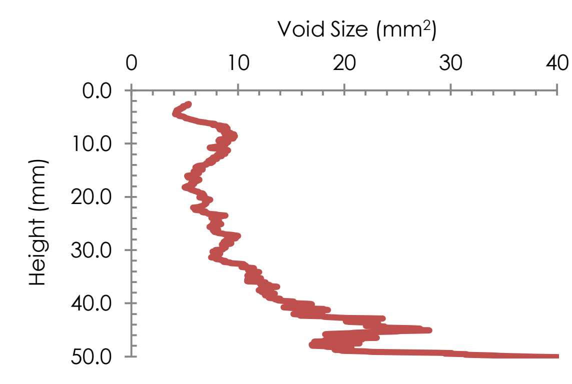

(c)

Figure 8 Air Voids Distribution For Porous Asphalt Mixtures (a) Voids content; (b) Voids Number; (c) Voids Size

3.2 Effects of Clogging on Permeability

Figure 9 and Figure 10 show the relationship between the permeability coefficient and clogging cycles for different concentrations of clogging materials. The initial permeability rate shows to be slightly different where the coefficient of permeability for each of the samples is fluctuating due to the minor differences in the voids interconnectivity. Even though there are slight variations in the air voids content and voids distribution within the sample that could affect the permeability rate between the samples, but it was verified using a number of replicates.

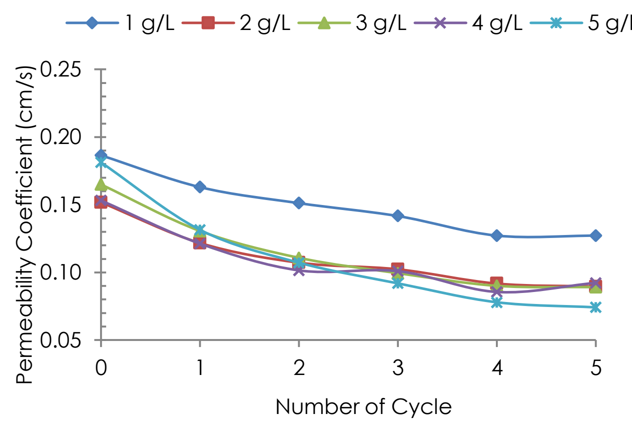

Figure 9 Relationship between permeability and number of cycles of clogging materials from highway

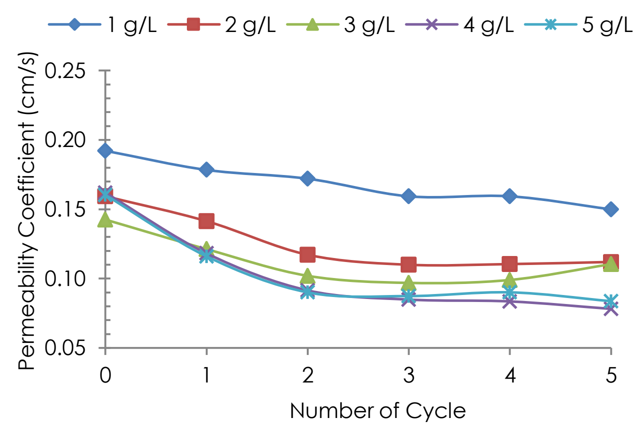

Figure 10 Relationship between permeability and number of cycles of clogging materials from residential area

The high permeability coefficient value indicates less discharge time and proves the samples have better voids interconnectivity. In general, the result shows that the permeability coefficient decreases as the clogging concentration and clogging cycle increases for both types of clogging materials. This indicates that the clogging materials remain in the sample and fill up the existing voids and subsequently reduce the voids connectivity within the porous asphalt mixtures. This is due to the cumulative particles that build up and clogged the air voids during each cycle. At the concentration of 2 g/L, the clogging materials have caused a major clogging problem which reduces the permeability rate. This can be clearly observed for the samples clogged with materials collected from the highway as they contain coarser sandy materials compared to those from residential area. The coarse particles tend to clog the void spaces severely causing the increase in discharge time of the subsequent cycles. In other words, the clogging material collected from highway is primarily consists of coarse sand and rough surface texture that resist the particles movement with water and tends to fill up the void spaces. For clogging material obtained from residential area, its composition consists of fines, including silt and clay which can easily stick to the mastic and aggregate particles and clog up the void spaces. From the graph it can be seen that the first two clogging cycles are considered critical based on the sudden drop in the permeability rate but later increasing at a slower rate until the fifth cycle. This implies that the rate of clogging is higher during the first few cycles compared to the remaining clogging cycles because during the initial cycles, more air voids are available for the entrapment of clogging materials.

4.0 CONCLUSION

From the study, it can be concluded that the clogging phenomenon affects the permeability behaviour of porous asphalt where it reduces the ability of porous asphalt to drain water from the pavement surface. Deterioration of air voids connectivity due to clogging problem was observed through the increment of discharge time from the permeability test. Porous asphalt experience the greatest voids deterioration during its initial clogging cycles, but less towards further cycles. This implies that clogging occurs mainly in the first few cycles of its service life and clogs at a slower rate beyond the initial cycles. Furthermore, the concentration of clogging materials used affects the discharge time. The increase in the concentration of clogging materials increases the water discharge time. The physical properties of the clogging materials determine their ability to move along with the water and clog the void spaces. Additionally, the air voids distribution and their characteristics analysed from X-ray CT images are able to describe the air voids formation within the mixture. Even though the mixture was produced with high air voids content, but the distribution of the air voids was found inhomogeneous throughout the sample with less interconnected voids formed within the mixture particularly at the top section.

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