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Abstract

Hot mix asphalt (HMA) pavements that have been poorly designed, compacted and/or constructed have higher chances of experiencing moisture-related damage. This research evaluates the interrelationship between field/laboratory permeability and other mechanical and physical pavement characteristics. Eight sites in Eastern Ontario were selected for evaluating the pavement's field permeability and core extraction. Laboratory specimens of the same mixes studied in the field were prepared using the Superpave gyratory compactor (SGC). The relative density (RD), lab permeability, and indirect tensile strength (IDT) tests were for the field-recovered cores and SGC specimens. Permeability, RD, and IDT were found to be related such that as RD and/or IDT decreases, the permeability increases exponentially. The strength of these relationships varied for the three test settings (SGC, field-recovered cores, and field measurements). The coefficients of field permeability and laboratory permeability using field-recovered cores were statistically different, with a fair relationship between these two test settings.

Key words: Field Permeability, Laboratory Permeability, Hydraulic Conductivity, Asphalt Pavement, Moisture-Induced Damage, Relative Density, and Indirect Tensile Strength.

1 INTRODUCTION

The Superior Performing Asphalt Pavements (Superpave[®]) system was initiated in late 1980s by the Strategic Highway Research Program (SHRP) to provide engineers, technicians and highway jurisdictions with a robust philosophy and procedures for designing hot-mix asphalt (HMA) pavement. One of the fundamental objectives of the Superpave[®] system is to build high quality asphalt road pavements with maximum durability, and better long term performance under different environmental and traffic loading challenges over the pavement lifespan (Kennedy et al. 1994). However, despite more than 20 years since the Superpave[®] products have been adopted in the pavement industry, it is still common to observe various premature pavement failures that could be attributed to inadequate mixture design, poor quality construction materials, unsuitable compaction equipment, repeated traffic loads, and environmental effects. One of the most serious distresses leading to asphalt pavement failures is the phenomenon known as the moisture-induced damage, which is a distress that occurs due to the presence of water within the pavement system and results in destroying the bond within the asphalt mix (Howson et al. 2009; Caro et al. 2010).

The existence of trapped water within a pavement structure leads to negative consequences by shortening the road service life or increasing the pavement maintenance and rehabilitation costs. Asphalt pavements that have been poorly designed, compacted and/or constructed have higher chances of experiencing moisture-related damage which adversely affects the asphalt strength and durability. The possible results of the reported early distress problems are moisture-induced cohesive and adhesive damage, fatigue cracking, potholes resulting from freeze-thaw cycles and/or permanent deformation (Umiliaco and Benedetto 2013). These concerns have been well investigated by numerous researchers to quantify the adverse

effects of different distress problems (Chen et al. 2004; Kim et al. 2004; Pang 2012). Moisture-induced damage can be prevented through controlling the amount of water infiltrating through the pavement structure, which depends on the pavement permeability. In fact, permeability was found to be a better indicator of pavement durability compared to relative density alone, the most widely used acceptance parameter in quantifying the HMA compaction (McLaughlin and Goetz 1955). This is because higher permeability is more closely related to moisture-induced damage, which is considered one of the main mechanisms causing stripping.

Previous studies have concluded that the most prominent factor that influences pavement permeability is the content of interconnected air voids (Zube 1962; Mallick et al. 2003; Brown et al. 2004). The air voids content and relative density are inversely related such that as the air voids content increases, the relative density decreases and vice versa. However, unlike the interconnected air voids, the isolated voids do not correlate with high permeability coefficient as there are no flow channels where the water can penetrate through as illustrated in **Error! Reference source not found.a** and **Error! Reference source not found.b**. Another significant factor that affects the permeability coefficient is surface cracks. An impermeable surface can be achieved if surface cracks are eliminated as shown in **Error! Reference source not found.c** and **Error! Reference source not found.d**. In other words, a pavement structure has the potential to be impervious if it does not have surface cracks even when having some air voids within it.

While Zube (1962) suggested that the dense-graded asphalt pavement experiences an excessively high permeability rates at air voids more than 8%, or a relative density value less than 92% of the theoretical maximum density, others concluded that high permeability coefficient exists even when providing acceptable air voids content in the field ranging from 5% to 7% (Brown et al. 2004). Studies showed that the as-built density for dense-graded asphalt

mixtures should not be more than 97% and not less than 92% of the theoretical maximum density (Roberts et al. 1996). Very high as-built density, which is usually caused by improper mix proportions, contributes to rutting and shoving. Alternatively, low as-built density, which is the result of inadequate compaction, allows more water and air to infiltrate through the pavement structure. This excessive infiltration is considered a major contributing factor to raveling, cracking, moisture damages, and oxidation (Brown et al. 2004).

In contrast, the coarse-graded asphalt mixtures behaved differently in a study to identify the percentage of air voids at which the pavement structure becomes excessively permeable. It was found that sometimes the coarse-graded mixes experience high permeability rates even when the air voids are below 8% (Choubane et al. 1998). Earlier studies concluded that the coarse-graded mixes have higher permeability coefficients than the fine-graded mixes for a particular air void content (Roberts et al. 1996). This is likely the result of the different content of interconnected air voids in both types of mixes where coarse-graded mixes will likely have more interconnected air voids than fine-graded mixes.

In recent years, numerous research works have been performed in a number of states in an attempt to study the permeability characteristic and ultimately recommend a reliable test method or acceptance permeability criteria (Choubane et al. 1998; Maupin 2000; Cooley et al. 2001; Mogawer et al. 2002; Brandon et al. 2004; Owusu-Ababio and Schmitt 2009; Tarefder and Ahmad 2015). Other studies have attempted to propose permeability limits to be added to the current quality assurance (QA) and quality control (QC) (Williams et al. 2009; Williams, 2011; Chen et al. 2013). Despite this growing concern of HMA permeability, little efforts were devoted to understand the interrelationship between permeability, in the field and laboratory, and other important mechanical and physical pavement characteristics. If these relationships are

investigated and quantified, the possibility of incorporating the permeability within the mix design procedure will not only be highlighted and addressed, but also field permeability prediction based on laboratory procedure can be ultimately achieved.

2 OBJECTIVES

The main objective of this paper is to investigate if pavement permeability can be used as a pavement construction quality control/quality (QC/QA) assurance criterion by exploring the relationship between pavement permeability and the pavement's resistance to loading, which is evaluated using the mechanical characteristic indirect tensile strength (IDT), and current pavement construction QC/QA criteria, the most important of which is the physical characteristic relative density (RD). Furthermore, the paper investigates the variability of pavement permeability with the test setting (field and laboratory) and the variability of the mechanical and physical pavement characteristics across the pavement lane width.

3 DATA COLLECTION AND STUDY SCOPE

The experimental program in this study consisted of two major phases; the field and laboratory as illustrated in **Error! Reference source not found..** The field phase dealt with measuring the field permeability as well as recovering field cores from the exact location where the field permeability test was conducted. In the laboratory phase, several laboratory specimens were prepared using the same mixtures studied in the field. In addition, different laboratory tests including the RD, laboratory permeability, and IDT were carried out on both the laboratory-prepared SGC specimens and field-recovered cores.

The site selection for inspection and sampling included both highway projects and in-house field trials located in Ontario's Eastern Region. The term "in-house" is used in this paper

to refer to non-highway field projects performed at controlled locations/sections under the supervision of the construction firm R.W. Tomlinson Limited. In addition, the site selection of this study incorporated both newly constructed asphalt pavement surfaces and other in-service roads. The term “in-service” refers to sites that were compacted and tested in a previous year. These in-service sections were evaluated to quantify the short-term effect of traffic densification on the field permeability of the road surface. In total, 130 field permeability tests were carried out, 88 field cores were recovered, and 33 laboratory samples were prepared. The full study plan implemented in this research is summarized in Table 1. It should be noted that the layer thickness shown in Table 1 was estimated based on the extracted/recovered core thickness. The HMA pavements in this research were all Superpave mixes with a nominal maximum aggregate size (NMAS) of 12.5 mm.

At each test site, a total of five testing locations were selected along the cross-section of a roadway lane to examine the variability in pavement physical and mechanical characteristics with the change of lateral location of the testing location. For each testing location (diameter = 150 mm), a pavement core was then recovered and transported to the Civil Engineering Laboratory at Carleton University for further experimental investigations as explained earlier. **Error! Reference source not found.** illustrates the testing locations incorporated in this research and their corresponding distances from the edge of the paved lane.

4 EXPERIMENTAL PROGRAM

4.1 Field and Laboratory Tests

As explained in the previous section, the research scope incorporated four different experiments including one field and three laboratory tests which are setup as shown in **Error! Reference source not found.** Firstly, the field permeability of the selected HMA pavement

sites was evaluated using the National Center for Asphalt Technology (NCAT) field permeameter shown in **Error! Reference source not found.a**. The test instructions outlined in the operating manual of the NCAT permeameter AP-1B were followed (NCAT 2015). Secondly, the bulk specific gravity (G_{mb}) or bulk relative density (BRD) of a compacted HMA samples was determined using the saturated surface dry (SSD) method outlined in the ASTM D2726/D2726M-14 (ASTM 2014) as presented in **Error! Reference source not found.b**. Relative density (RD) was then calculated as the ratio of the BRD to the maximum relative density (MRD). Upon completion of the RD test, the laboratory permeability test was carried out using the Karol-Warner Asphalt permeameter (**Error! Reference source not found.c**) and according to the Florida Test Method FM 5-565 (Florida DOT 2012). Finally, the IDT test was conducted in accordance with ASTM D6931 standard test method for IDT of bituminous mixtures (ASTM 2012) as **Error! Reference source not found.d** depicts. It is worth noting that the permeability or hydraulic conductivity, an important characteristic of pavement materials, was measured and represented by the permeability coefficient (k) in mm/sec in both testing setups; field and lab.

4.2 The Superpave Gyratory Compactor (SGC)

The SGC was used to compact loose mixes provided by the MTO at different compaction levels to simulate different densities achieved in the field. Before the compaction stage using the SGC, four parameters were considered and calibrated (according to the SGC user's manual) including the specimen height, consolidation pressure, ram speed, and turntable RPM. During compaction, the consolidation pressure was set at 600 kPa, with an angular velocity of 30 gyrations/min, and gyratory angle of 1.25°. Four different loose asphalt mixtures corresponding to the same mixes studied in the field were used to prepare the SGC specimens. It should be

noted that SGC specimens were prepared using the asphalt mixtures of the four highway projects (Highway 15, 16, 17, and 417) while there was no loose mixture available for any of the in-house sites. The mix designs for each mix are shown in Table 2.

Several trials or iterations were performed in order to quantify the amount of loose mixture required to produce SGC specimens with the targeted compaction levels. After producing a SGC specimen of anticipated compaction level, RD of that specimen was checked. If RD did not fall within the level specification range, a new specimen was prepared. This iterative process was performed until the desirable amount of material to reach each desired compaction level was determined. The four compaction levels, A to D, are described in Table 3.

For the last three compaction levels (B, C, and D), the weight of loose mix as well as the specimen height were entered while not specifying the number of gyrations. This means that the numbers of gyrations for the compaction levels B, C, and D were varied and the SGC selected the appropriate number of gyrations needed for each level. It is important to note that as the compaction effort decreased, the specimen height had to be reduced to avoid having loosely bound specimens with incoherent edges. Therefore, Table 3 shows the specified specimen height decreasing with the decrease in compaction effort and is lowest for level D. This difference in specimen height did not affect the results because the calculations for permeability coefficient and IDT consider the specimen dimensions including height.

On the other hand, for compaction level A, the number of gyrations was set to the maximum number which is 998 gyrations for all mixes rather than the maximum number of gyrations ($N_{\max}$) for each mix. Subsequently, the specimen height, which was not defined as an input, was measured after compaction and was found to range from 103 to 110 mm depending on the mixture type. RD for compaction level A specimens produced in this way ranged from 97%

to 99%. It is important to note that due to the limited quantities of loose asphalt mixture of Highways 15, 16 and 17, only seven specimens were produced at different compaction levels while twelve specimens were prepared using Highway 417 mix.

5 RESULTS AND DISCUSSIONS

5.1 Field Observations

During the field testing, an important observation was noted on several test locations where the water penetrated the surface into the body of the asphalt mix and appears to have moved sideways within the layer and returned upward outside the test region (**Error! Reference source not found.a** and **Error! Reference source not found.b**). This observation suggests two findings. First, the vast majority of the air voids within the finished paved lane were mostly interconnected forming a channel leading the water back again to the surface. Second, the water underneath the testing location flows in a three-dimensional pattern. These two findings are most likely the main important factors to explain the mechanism behind the development of potholes.

5.2 RD-IDT Relationship

The relationship between RD and IDT was explored for the field-recovered cores and SGC specimens. Non-linear regression analysis was carried out using SPSS 20.0 software to develop the RD-IDT relationship. For the SGC specimens, a very strong relationship was observed in each of the four mixes as the coefficient of determination (R^2) varies between 0.96 and 0.99 as shown in **Error! Reference source not found.a**. In general, the presented relationships suggest that as RD increases, IDT increases and vice versa. A similar trend was observed for the field-recovered cores as shown in **Error! Reference source not found.b**; however, the relationships resulted in R^2 coefficients ranging between 0.01 (practically no relationship) and 0.68 indicating a weaker relationship compared to the SGC trend. Thus, it can

be stated that very good estimates of the pavement's mechanical properties in the lab can be reached using RD. The quality of this estimation deteriorates for the mechanical properties of the actual pavement project in the field, but fair estimates can still be made using RD.

5.3 RD-Permeability Relationship

The relationship between RD and pavement permeability was examined using the three different measurements of the permeability coefficient which are laboratory measurement of SGC specimens, laboratory measurement of field-recovered cores, and field measurements. First, the relationship was explored for each mix separately based on the results of the 33 laboratory-prepared SGC specimens as presented in **Error! Reference source not found.a**. As can be seen, the plotted trend lines follow a strong exponential trend ($0.80 < R^2 < 0.97$) for all four mixes in this research. The general trend shows that as the achieved RD level decreases, the permeability coefficient increases. This trend is expected since higher RD values means lower air void content and thus less chances of having interconnected paths for water to move through. Furthermore, any interconnected air voids at high RD would likely have narrow channels where water cannot flow easily, thereby reducing permeability. However, the trends also show that the permeability coefficient increases at a slow rate with the decrease in RD until a certain transition zone (from 92% to 90%) where the permeability values start to increase rapidly with further decreases in RD. This suggests that below a specific relative density level, the asphalt pavement will likely become excessively permeable. The relationships based on the field-recovered cores in **Error! Reference source not found.b** had a similar trend, yet with moderate R^2 values ($0.34 < R^2 < 0.69$). Finally, the relationships based on field measurements in **Error! Reference source not found.c** exhibited the weakest relationship between RD and permeability coefficient as the R^2 values were between 0.05 and 0.32. The results indicate that variations in RD alone cannot explain the

variability in field permeability or pavement's tensile strength even though the relationships are very strong in the lab test setting.

5.4 IDT-Permeability Relationship

The previous relationships between RD and both IDT and permeability varied in their strength depending mainly on the test setting for measuring the permeability coefficient. It was therefore expected to observe the same difference in the IDT-permeability relationship at the three different permeability test settings. **Error! Reference source not found.**a depicts the relationship between the lab permeability and IDT for the SGC specimens of different asphalt mixes. In all mixes, it is obvious that a strong relationship exists between the permeability coefficient and IDT as R^2 ranges between 0.77 and 0.93. This could be attributed to the fact that stronger bonds between the aggregate and asphalt binder (cohesion) as well as stronger bonds within the binder itself (adhesion) exist in any given specimen of high IDT value. In general, higher RD values (or less air voids content) will likely contribute to a stronger internal structure. This reduction in air voids content occurs as the asphalt binder content filling the air void space. These structural changes caused by increasing RD or IDT will likely reduce the possibility of having interconnected paths and increase the isolated voids content. Consequently, lower permeability is expected since it is highly dependent upon the interconnected air voids content. For the second test setting based on the field-recovered cores, fair relationships ($0.33 < R^2 < 0.78$) were observed between the IDT and the permeability coefficient as presented in **Error! Reference source not found.**b; however, the relationships were not as strong as the relationships based on the SGC specimens. It can be seen also in both **Error! Reference source not found.**b and **Error! Reference source not found.**b that the variability in lab permeability is better explained by the IDT ($0.33 < R^2 < 0.78$) as opposed to RD ($0.34 < R^2 < 0.69$). After a closer look at

the two figures (**Error! Reference source not found.b** and **Error! Reference source not found.b**), it can be seen that as the values on the x-axis increase, IDT values exhibit stronger correlations when compared to the RD values. Finally, the permeability test setting based on field measurements exhibited (**Error! Reference source not found.c**) the lowest R^2 values, except for only one site, which confirms the previously presented poor relationships in **Error! Reference source not found.c**.

Finally, comparing **Error! Reference source not found.a** and **Error! Reference source not found.b** shows that the field-recovered cores and laboratory-prepared SGC specimens of the same mix design have different IDT values. The SGC specimens have almost twice the strength of the field-recovered cores. It should be noted that the SGC was developed to better simulate pavement compaction in the field, by utilizing a combination of pressure and kneading actions compared to the hammering action in Marshall compactor. Therefore, the difference in compaction mechanism between the lab and field is likely the source of this considerable difference in IDT. The difference cannot be explained by air voids or relative density. The constructed pavement in the field has a reduced resistance to loading compared to laboratory-prepared samples with the same air voids. This difference can be explained by the presence of construction-induced cracks which are observed in the field but not in the SGC specimens produced in the lab (Abd El Halim and Mostafa 2006; Abd El Halim et al. 2009; Abd El Halim et al. 2013).

5.5 Field-Lab Permeability Relationship

The previous analysis suggested that although field and lab measurements of the permeability coefficient follow similar trends, their level of association to other mix properties (such as RD and IDT) can vary considerably. It is therefore important to understand the

relationship between the field and lab permeability coefficients. First, a t -test at 5% level of significance was carried out to examine if there is a significant difference between the permeability coefficient as determined in the two test settings: field measurement and laboratory measurement of field-recovered cores. For each site, the null (H_0) and alternative (H_1) hypotheses were as follows:

$$H_0 = \mu_{\text{field permeability}} = \mu_{\text{lab permeability}}$$

$$H_1 = \mu_{\text{field permeability}} \neq \mu_{\text{lab permeability}}$$

The p -value for three different sites where the field and lab measurements of the field-recovered cores were available (Highway 16, 17 and 417) were 0.012, <0.001, and 0.046, respectively. These p -values indicate that there is a statistically significant difference between the field and lab measurements at 5% level of significance.

The relationship between field permeability measurements and laboratory permeability of field-recovered cores was subsequently examined using results obtained from the three projects with common measurements. In total, 45 points were plotted in a scatter diagram, and a linear relationship was developed. According to **Error! Reference source not found.**, a moderate linear relationship ($R^2=0.40$) exists between the field and laboratory measurements. In addition, the vast majority of field permeability measurements were below the 1:1 line which indicates that the field permeability was higher than the laboratory permeability nearly all the time.

The significant difference between the field and lab permeability could be attributed to several reasons. First, each device has its own measurement mechanism to estimate the permeability coefficient despite the fact that both of them are based on the falling head principle. More specifically, in the NCAT permeameter the water has the flexibility to diffuse in vertical

and lateral directions within the pavement structure. However, the permeability calculation using the NCAT device assumes that the water will flow in one dimension (vertically down) through the 150 mm diameter test area which is not an accurate assumption. In other words, the measured permeability is likely a combination of two directional permeability; the vertical and horizontal. On the other hand, the measurement mechanism of the Karol-Warner Asphalt permeameter forces the water to move only through the pavement thickness by applying a confining pressure of 68.9 ± 3.4 kPa to the attached rubber membrane. This setup is more consistent with the theoretical basis for calculating the permeability coefficient according to Darcy's law. In particular, the steady state flow condition as well as the saturation can be easily met. In fact, one can control the specimen saturation condition in the laboratory to reach a specific level in order not to violate Darcy's law; this is not possible during the field permeability test. In reality, however, the accumulated water on HMA surfaces caused by rainfalls will fall on the whole pavement surface, and for it to penetrate the surface and then move into the pavement structure, it will most likely flow in one direction downward. Thereby, the HMA permeability based on laboratory measurements will likely reflect and simulate the actual field condition.

Several prediction models relating the field permeability to the laboratory permeability of field-recovered cores have been developed in the literature. Table 4 summarizes the developed model by each study, the associated coefficient of determination (R^2), and the regression model type. The existing models were compared to the developed linear model in this study and the actual field-laboratory data as shown in **Error! Reference source not found.**. The plotted data suggests that for a specific range of field permeability coefficient (20 mm/sec to 100 mm/sec), Prowell and Dudley's model is the closest model to the data and developed model in this study followed by William's model and Kantipong Model's. All four models were below the 1:1 line

indicating that all models predict field permeability to be greater than the laboratory permeability for the same reasons previously discussed in the preceding subsection. Although the four models successfully explained almost half of the actual field data, some of the actual field data points tend to be slightly higher than the four models. In other words, the four models fall closer to the 1:1 line as opposed to some of the actual field data points.

5.6 Effect of Testing Location, Project Level, and Short-Term Compaction due to Traffic

The impact of two different independent factors, termed as the testing location and project level, on each pavement characteristic (response variable) was examined using a two-way analysis of variance (ANOVA) test at 5% level of significance. The term project level refers to the different pavement projects or highways investigated in this study. Before conducting any of the statistical tests, the Levene's test of homogeneity of variances was performed to check whether the examined datasets have equal variance or not. In case of not meeting the homogeneity of variances assumption, the results assuming unequal variances were considered. Summary of the two-way ANOVA results is shown in Table 5. As shown in the table, the project level has a significant effect for the four pavement characteristics as all p -values were less than 5%. For the testing location factor, all pavement characteristics had insignificant effect, except for the laboratory permeability of field-recovered cores. This indicates that the Karol-Warner Asphalt permeameter showed a difference in permeability coefficient for the various testing locations. Also, the laboratory permeability was the only pavement characteristic that had a significant two-way interaction effect. This implies that the effect of the project level on the lab permeability depends significantly on the testing location and vice versa.

The short-term effect of age and traffic on field permeability was also studied separately in this research. The field permeability measurements were available for two consecutive years

(the as-built and one year later) for three sites. A t -test at 5% level of significance was used to examine the difference between the measurements of the two years. The t -test results summarized in Table 6 indicate that in two out of three sites, statistically insignificant difference was noticed at 5% level of significance.

6 CONCLUSIONS

The main objective of the paper was to explore the relationship between important pavement characteristics, which are RD, IDT, and permeability in both lab and field test settings. First, RD was related to the permeability to examine the strength of both the RD-field permeability and RD-lab permeability relationships. It was found that RD has a strong relationship to lab permeability of SGC specimens but the strength of this relationship decreases when lab permeability is measured for field-recovered cores and is very weak when the permeability is measured in the field. The same trend was found for the relationship between IDT and permeability. The agreement of the trends of relationship between permeability and both RD (a good indicator of the physical characteristics) and IDT (a good indicator of the mechanical characteristics) affirms the difference between field and lab permeability. This difference, which can explain why some pavements fail prematurely even though they perform well in the lab, was tested statistically and was found to be significant at 5% level of significance. Finally, it was observed that a moderate relationship existed between RD and IDT of field-recovered cores which suggests that RD can be a reasonable predictor of IDT (and thus short-term pavement performance). On the other hand, both RD and IDT had weak relationships with field permeability, which indicates that neither characteristic can be a good predictor of field permeability (and thus long-term pavement performance). Therefore, measuring the pavement permeability in the field can help in evaluating the expected long-term performance of

a pavement project. Given that field permeability is measured using a fairly easy, nondestructive test, it can be valuable tool in QC/QA of hot-mix asphalt pavement projects.

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9 TABLES

Table 1: The Research Experimental Plan

Site Specifications					Field Investigations		Laboratory Investigations			
Name	Testing Date	Mix Type	Layer Thickness (mm)	Design AC (%)	Field Permeability (n)	FR Cores (n)	SGC Samples (n)	RD	Lab Permeability	IDT
Tomlinson In-house	Nov 10, 2012	SP12.5 RAP	55	5.00	7	10	-	FR	✖	FR
Thousand Islands Parkway	Oct 26, 2012	SP 12.5	45	5.10	7	5	-	FR	✖	FR
Highway 28	Sep 21, 2012	SP 12.5	40	4.70	10	10	-	FR	✖	FR
Tomlinson In-house	Nov 21, 2013	SP12.5 RAP	55	5.00	8	0	-	✖	✖	✖
Thousand Islands Parkway	Sep 19, 2013	SP 12.5	45	5.10	9	0	-	✖	✖	✖
Highway 28	May 30, 2013	SP 12.5	40	4.70	14	0	-	✖	✖	✖
Highway 16	Sep 27, 2013	12.5 FC2 RAP	50	4.80	15	15	7	FR & SGC	FR & SGC	FR & SGC
Highway 17	Sep 25, 2013	SP 12.5	50	4.48	15	15	7	FR & SGC	FR & SGC	FR & SGC
Highway 417	Sep 29, 2013	12.5 FC2	45	4.80	15	15	12	FR & SGC	FR & SGC	FR & SGC
Highway 15 (i)	Oct 2, 2013	12.5 FC1	90	5.00	10	10	7	SGC	SGC	SGC
Highway 15 (ii)	Oct 29, 2013	12.5 FC1	90	5.00	10	0	-	✖	✖	✖
Greenbelt Yard	Oct 15, 2014	12.5 FC2	50	5.00	3	8	-	FR	FR	FR
Total	-	-	-	-	130	88	33	78 FR 33 SGC	53 FR 33 SGC	78 FR 33 SGC

where: (FR) Field-Recovered Cores; (SGC) Superpave Gyratory Compactor Specimens; (✖) The test was not performed; (n) number of sample.

Table 2: Superpave Mix Designs for the Four Considered Mixes

Site Name	Highway 15	Highway 16	Highway 17	Highway 417
Number of Prepared Specimens	7	7	7	12
NMAS (mm)	12.5	12.5	12.5	12.5
Asphalt Binder Content (%)	5	4.8	5	4.8
VMA (%)	14.6	14.6	14.4	14.2
VFA (%)	72.6	72.6	72.2	71.8
Air Void @ N _{design} (%)	4	4	4	4
A/C Type	58-34	64-34P	58-34P	64-34
Hot Mix Type	12.5 FC1 RAP	12.5 FC2 RAP	SP 12.5	12.5 FC2
Maximum Relative Density (G _{mm})	2.521	2.497	2.477	2.500
Traffic Category	D	E	C	E
Sieve Size (mm)	Job Mix Formula (JMF) - Gradation Percentage Passing (%)			
25	100	100	100	100
19	100	100	100	100
12.5	96.0	98	97.9	97.4
9.5	83.8	89.8	84.5	87.4
4.75	57.1	61.9	53.4	63.5
2.36	42.1	47.1	39.5	46.3
1.18	30.2	36.8	28.7	36.3
0.6	22.0	28.6	21.1	28.0
0.3	11.9	15.3	13.9	14.1
0.15	6.1	7.9	7.6	6.6
0.075	3.3	4.1	4.3	3.3

Table 3: Compaction Levels of SGC Specimens

Compaction Level	RD Ranges	Total No. of Specimens	Input Variables		Loose Mix Weight (g)	Compaction Temperature (°C)	Final Height (mm)
			Height (mm)	No. of Gyrations			
A	94<RD	6	-	998	4602	145	103-110
B	92<RD<94	9	90	-	3260	145	78
C	89<RD<92	9	90	-	3081	145	78
D	RD<89	9	80	-	2320	145	63

Table 4: Summary of the Existing Field-Lab Permeability Models

Study	Model	R^2	Type
Prowell and Dudley 2002	$F = 7.2178 L^{0.6851}$	0.68	Power
Kanitpong et al. 2005	$F = 8.34 e^{0.055L}$	0.80	Exponential
Williams 2009	$F = \left(\frac{L}{0.4549} \right)$	0.91	Linear
Current Study	$F = \left(\frac{L + 4.829}{0.4183} \right)$	0.40	Linear

where: (F) Field Permeability Coefficient; (L) Laboratory Permeability Coefficient

Table 5: Summary of the Two-Way ANOVA Results

Factor	Response Variables			
	Field Permeability	Lab Permeability	RD	IDT
Project Level	<0.001	<0.001	<0.001	<0.001
Testing Location	0.529	0.001	0.466	0.128
Testing Location * Project Level	0.563	0.004	0.218	0.248

Table 6: Summary of the *t*-test Results for Effect of Age and Traffic on Field Permeability

Site Name	<i>F</i>	<i>p</i> -value
Highway 28	8.838	0.007
Thousand Islands Parkway	2.988	0.106
Tomlinson	0.667	0.429

10 FIGURE CAPTIONS

Figure 1: Effect of Interconnected Air Voids and Surface Cracks on Permeability (Not to Scale)
Figure 1(a) : Isolated Air Voids
Figure 1(b) : Interconnected Air Voids
Figure 1(c) : No Surface Cracks
Figure 1(d) : With Surface Cracks
Figure 2: Experimental Program Plan
Figure 3: Field Permeability Testing Layout
Figure 4: Setup Configuration of Field and Laboratory Tests
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Figure 4(b) : Bulk Specific Gravity
Figure 4(c) : Karol-Warner Asphalt Permeameter
Figure 4(d) : IDT
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Figure 6: RD-IDT Relationship
Figure 6(a) : SGC Specimens
Figure 6(b) : Field-Recovered Cores
Figure 7: RD-Permeability Coefficient Relationship.
Figure 7(a): SGC Specimens
Figure 7(b): Field-Recovered Cores
Figure 7(c): Field Measurements
Figure 8: IDT-Permeability Coefficient Relationship.
Figure 8(a): SGC Specimens
Figure 8(b): Field-Recovered Cores
Figure 8(c): Field Measurements
Figure 9: Relationship between Field and Laboratory Permeability Coefficients of Field-Recovered Cores.
Figure 10: The Examined Existing Models against the Developed Model/Actual Data.

(a)

(b)

(c)

(d)

Field Permeability Testing Layout

279x215mm (300 x 300 DPI)

(a)

(b)

(c)

(d)

(a)

(b)

Draft

(a)

(b)

(a)

(b)

(c)