Effects of Field Compaction Method on Water Permeability and Performance of Asphalt Concrete Pavements

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Abstract This paper presents the results of field studies of hot mix asphalt pavements compaction using conventional compaction technologies (train of vibratory steel drum, pneumatic tired roller) and the Asphalt Multi-Integrated Roller (AMIR) to examine the effects of different compaction methods on the water permeability of asphalt concrete pavements as a surrogate measure of durability and eventual long-term performance. Nine different pavement construction projects were used in this paper where laboratory and field properties of pavements compacted using conventional and AMIR compaction were measured and evaluated. Field measurements of water permeability showed higher mean value and higher variation of the permeability coefficient for conventional compaction than the AMIR-compacted pavements, even though the air voids and relative compaction were almost the same. Compared to the conventional compaction, statistical analysis showed that AMIR compaction reduced water permeability of compacted surfaces on stiff bases (such as an overlay on top of a milled asphalt concrete pavement) and also reduced the rate of permeability increase due to increase in air voids.

Keywords Asphalt concrete pavement · Compaction · Permeability · Pavement performance

1 Introduction

The structural performance and durability of asphalt concrete pavements are controlled by a number of factors including proper mix design and adequate compaction. Hughes (1989) suggested that neither of these two factors alone can guarantee a satisfactorily performing pavement. Properties such as strength, resistance to ageing, resistance to deformation, resistance to moisture damage, permeability, and

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skid resistance are stated to be affected by compaction (Hughes 1989). Most highway jurisdictions emphasize the quality of pavement compaction through setting a minimum compaction level or relative compaction (the percentage of compaction achieved in the field relative to maximum compaction of the mix) expected of the contractor. Such requirements are based on the premise that a higher relative compaction would ensure better performing and more durable pavements. As these requirements focus on the end result, less emphasis is placed on the method of pavement construction. However, research findings have shown that the different compaction methods impart different properties to the asphalt concrete with some more prone to distresses than others at comparable compaction levels (Tarefder and Ahmad 2016; Airey and Collop 2016). Therefore, this paper examines the effects of asphalt pavement compaction on the expected pavement's long-term performance. The paper uses the results of field trials involving two compaction methods: the conventional compaction using a train of vibratory steel, pneumatic, and static steel rollers and compaction using AMIR (Asphalt Multi-Integrated Roller) as a single roller. The pavements in the study are compared based on relative compaction, air voids, and water permeability.

2 Background of Asphalt Pavement Field Compaction

From the late 19th century when the first steam roller was invented till the late 1950s, compaction of asphalt concrete was performed by the static steel drum roller with different axle configurations (Hughes 1989; Geller 1984; Parker 1960). The 1960s saw the introduction of the vibratory steel drum roller, and the oscillatory steel drum roller was introduced between 1980s and 1990s to improve the efficiency of field compaction and provide better performing asphalt concrete pavements. Figure 1 shows the three main technologies of rotary steel drum compactors according to Kearney (2006). However, neither the shape nor the material of the drum has fundamentally changed among these three steel drum roller types (Hughes 1989; Parker 1960; Geller 1984). Hence, the current compaction technology is referred to in this paper as conventional compaction.

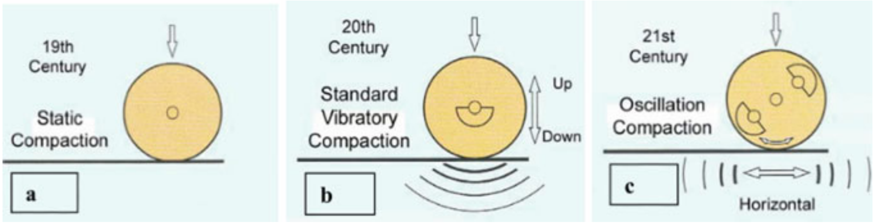

Fig. 1 Different types of rotary steel drum compaction (Kearney 2006)

For over a century now, the problems of "bow wave" phenomenon, pavement surface irregularities and transverse cracks otherwise known as roller checking, have been well documented in the literature (Hughes 1989; Parker 1960; Geller 1984; Ramezani et al. 2018). Researchers such as Geller (1984) and Parker (1960) attributed these problems to mix instability, and hence emphasized the importance of training and discipline of roller operators. Increasing the roller drum radius was also recommended to address these problems. But on the shape of the compactor equipment, Eq. (1), according to Parker (1960), shows that an infinite radius of the drum roller is required to eliminate the drawbar pull, which is a considerable factor contributing to the construction problems. Obviously, this indicates that a circular roller drum will always generate a drawbar pull and, in turn, much of the associated compaction problems.

$$P = \frac{WG}{R - H} \tag{1}$$

Where $\boldsymbol{P}$ = drawbar pull which is the engine track force that drives the roller, $\boldsymbol{W}$ = roller weight, $\boldsymbol{G}$ = the horizontal distance of the roller-pavement contact, $\boldsymbol{R}$ = drum radius, and H = depth of drum penetration into the hot asphalt during compaction.

Figure 2 shows the illustration of the roller drum dimensions, roller drum-pavement contact area, and the drawbar pull (Parker 1960).

F = resultant force

$$tan\theta = \frac{G}{R - H} = \frac{P}{W}$$

Based on tensile strength testing of field-compacted slabs, Ramezani et al. (2018) concluded that construction cracks at the top of a pavement layer would make the top portion of the layer weaker than the lower portion. Several other problems associated with the current conventional compaction of asphalt pavements have been reported in the literature including lower tensile strength in the roller direction (hence perpendicular to construction cracks) and higher susceptibility to moisture damage and other forms of asphalt pavement distress (Abd El Halim et al. 2015; Abd El Halim et al.

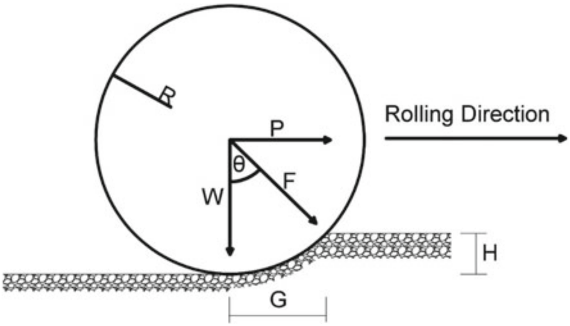

Fig. 2 Influence of roller drum radius on surface irregularities (Parker 1960)

1994; Abd El Halim and Haas 2004). A recent study concluded that the formation of bumps in asphalt concrete pavements increases with greater vibration and steeper downgrade in the direction of rolling (Shuler 2017). Unfortunately, most highway jurisdictions have not considered in their job acceptance schemes the method of compaction used in asphalt pavement construction. It is generally believed that once the required compaction level has been achieved, other properties and long-term performance of the asphalt pavement would be assured regardless of the method of compaction. However, findings by Williams (2011), Kandhal and Mallick (2007), and Fleckenstein et al. (2002) reported that the performance of asphalt pavements does not depend on the level of compaction alone but rather on other characteristics, such as permeability.

As mentioned earlier, Eq. (1) indicated that removal of the effect of the drawbar pull, which causes surface cracks, entails having an infinite radius of the steel drum roller. This condition can be achieved by replacing the drum with a flat surface such that the pavement is compacted without initiating cracks. The Asphalt Multi-Integrated Roller (AMIR) compaction technology has been developed under this premise to solve the problems of asphalt surface cracking during compaction operations. As shown in Fig. 3, AMIR changes the two parameters that have been fixed features of all steel rollers. First, the radius of the compaction equipment is changed from a finite radius in all other rollers to a flat surface or infinite radius. Second, the roller material in direct contact with the pavement is changed to rubber, which is considerably closer to the stiffness of the hot asphalt concrete than the steel used in conventional rollers. AMIR's flat rubber belt provides a greater contact area and time of compaction allowing proper densification of the mat using considerably less vertical pressure exerted on the pavement surface (Abd El Halim and Mostafa 2006; El Hussein et al. 1993). AMIR efficiently compacts asphalt concrete pavements and produces surfaces that are free of cracks and irregularities, with lower

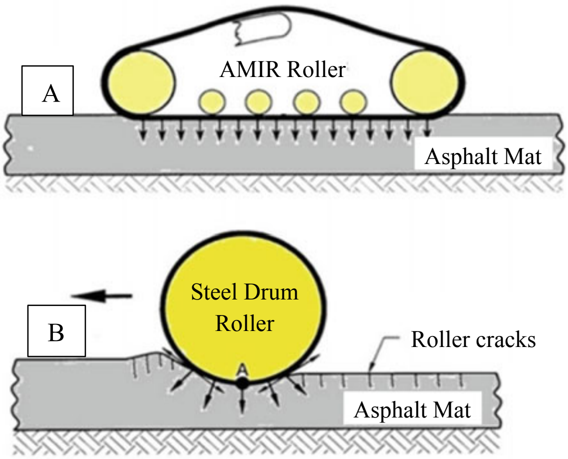

Fig. 3 The schematic diagram of **a** AMIR and **b** Steel drum rollers

water permeability, and with improved engineering properties; all of which lead to better durability and long-term performance (Abd El Halim et al. 2013; Abd El Halim et al. 1988).

3 Research Methodology

To study the comparative effects of the conventional and AMIR compaction methods on the properties of asphalt concrete, data were collected from several construction projects. The data included parameters related to the quality of the finished pavement such as density and water permeability measured in the field (referred to as field permeability) as well as parameters related to the compaction process such as compaction level, base type (compacted granular base, Portland cement concrete, or milled asphalt concrete surface), roller type, and number of roller passes. The data used in this paper comprise information from 162 cores collected from nine paving projects across Eastern Ontario, Canada. All sites have similar climatic conditions, and all fall within the same zone for performance grade requirement of asphalt cement (OHMPA 1999). The test locations were on relatively straight sections with moderate grades.

The cores were extracted at the same points where field permeability measurements were taken on the pavement surface. The cores were transported to Carleton University, where they underwent tests to determine the volumetric parameters (namely, density and air voids) and the unconditioned indirect tensile strength of each core. The volumetric properties were determined using the saturated surface dry method according to AASHTO T166 (AASHTO 2016), while the unconditioned indirect tensile strength was determined as part of AASHTO T283 method (AASHTO 2014) using an INSTRON series 5583 loading machine at 50.8 mm/minute loading rate. Field permeability tests were performed using the NCAT permeameter according to the operating manual provided by the manufacturer (Gilson 2013). Thus, a database was established for the coefficient of water permeability as measured in the field (referred to as permeability coefficient) along with other pavement characteristics for the same location of permeability measurement.

Mix types for all projects were the Ministry of Transportation Ontario's (MTO) Superpave 12.5 Nominal Maximum Aggregate Size (NMAS) with different designs for the projects. The binder content for these projects ranged from 4.7 to 5.1%. Paving operations followed the relevant MTO standards with mixing temperature and compaction temperature around 165 and 147 °C, respectively, and lift thickness of about 50 mm. Eight of the nine projects involved two side-by-side test sections at each site that corresponded to the conventional and AMIR compaction. A nuclear density gauge was used to monitor the density during compaction and ensure that enough compaction has been applied to each section to achieve the required compaction level. At the end of compaction, the two sections in each project had achieved approximately the same relative compaction. However, the conventional compaction required 22–24 passes of different rollers to achieve the required compaction, while

AMIR achieved the same compaction level in 4–8 passes by a single roller depending on the project and layer thickness.

The ninth project (Site 9) was conducted in the yard of a local contractor and involved using each of the conventional and AMIR compaction to apply varying compaction efforts on three sections for each compaction method in the yard of a local contractor. The number of roller passes for each AMIR section was one-third that of the corresponding conventional compaction section. More specifically, the three AMIR-compacted sections A1, A2, and A3 were compacted using 4, 6, and 8 passes, respectively. On the other hand, the three conventional compaction sections S1, S2, and S3 were compacted using 12, 18, and 24 total roller passes, respectively. All other parameters, including mix design and construction process, were similar to the other eight projects. A total of 30 field permeability measurements were performed, and 30 cores were recovered from the test sections of Site 9.

4 Results

First, Fig. 4 shows the compaction and permeability for Site 9 for the three AMIR-compacted sections (A1–A3) and the corresponding conventional compaction sections (C1–C3). It could be seen that the conventional compaction yielded marginally higher mean relative compaction, which was achieved with three times the number of roller passes of AMIR. However, each section of A1–A3 had a lower mean permeability coefficient and lower variance than the corresponding values of C1–C3.

To investigate the effects of the two compaction methods on the properties of asphalt pavement, regression analysis was used with the dependent variable being the coefficient of permeability (K) as the performance indicator variable, while the independent variables are those commonly used in quality control including maximum theoretical specific gravity (Gmm), relative compaction ($Comp$), bulk specific

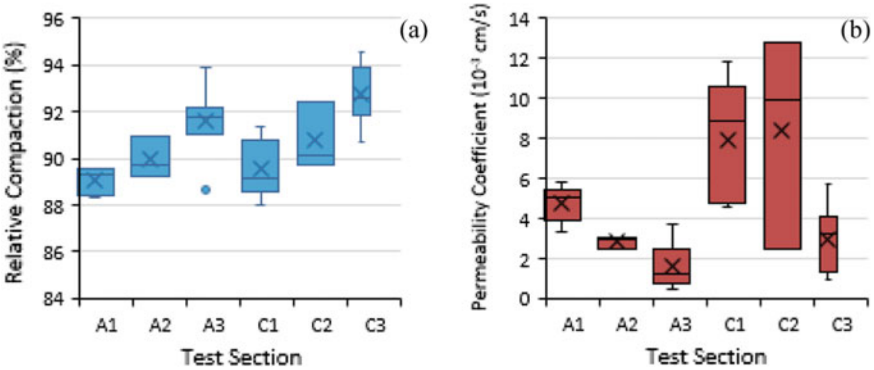

Fig. 4 Summary of relative compaction (**a**) and Permeability (**b**) Test results at site 9

gravity (*Gmb*), air voids (*Va*), indirect tensile strength (*IDS*), base type (*Pavt*: granular base = 0; milled/concrete base = 1), number of roller passes (*Pass*), lift thickness (*Thick*), roller or compaction type (*Rol*: conventional = 0; AMIR = 1), and project site. Compared to the results presented by Igboke et al. (2018), this paper adds the data from the ninth control project to provide better insight on the effect of compaction effort (*Pass*) and interaction with the other variables.

First, Table 1 shows a summary of the main characteristics of pavements compacted by the two compaction methods for all sites. As shown in the table, the relative compaction and air voids were very close for both compaction types as the construction controlled for this variable. That is, compaction continued with the conventional rollers until an acceptable compaction level was achieved. Despite the almost similar air voids and density, AMIR-compacted pavements had lower permeability with less variability (in terms of standard deviation).

Table 2 summarizes the main variables used in the regression analysis. In addition to these variables, to account for the potential of site-specific conditions that could have affected the pavement's permeability, nine dummy variables (Site 1 to Site 9) were used to represent the nine project sites. Each of these variables was set equal to 1 for the data belonging to this site, and all other site variables were set equal to 0. Finally, the interaction of the different variables was considered using independent variables that are the multiplication of two or more variables. These interaction variables account for the multiplicative effects of the independent variables on *K*.

Table 1 Permeability and compaction values of two roller types

Compaction type		*Comp* (%)	*Va* (%)	*K* (10^{-3} cm/sec)
AMIR	Mean	92.60	7.40	3.97
	Std deviation	2.89	2.89	5.47
Conventional	Mean	92.11	7.89	4.49
	Std deviation	1.92	1.92	7.90

Table 2 Summary of the main dependent and independent variables (number of samples = 162)

Variable	Mean	Std deviation	Minimum	Maximum
K (10^{-3} cm/sec)	4.28	7.00	0.005	45.3
Comp (%)	92.35	2.41	86.18	98.23
Va (%)	7.65	2.41	1.77	13.82
Gmm	2.53	0.049	2.38	2.66
Gmb	2.34	0.055	2.17	2.48
IDS (kPa)	267.23	186.37	42.25	1024.21
Pavt	0.093	0.29	0	1
Rol	0.41	0.49	0	1
Pass	15.84	7.13	4	24
Thick (mm)	52.43	7.39	42	95

Table 3 Summary of regression analysis

Variable	Regression coefficient	Standard error	p-value	Standard estimate
Intercept	0.0070	0.0013	<.0001	0
Comp	−0.00070	0.00022	0.0022	−0.24
Pavt	0.0063	0.0022	0.0041	0.263
Pass	−0.000202	0.000067	0.0028	−0.21
VaRol	−0.00070	0.00028	0.013	−0.23
PavtRol	−0.011	0.0040	0.0053	−0.302
sqVaRolPavt	−0.00027	0.00011	0.019	−0.21
Site 2	−0.0026	0.0010	0.013	−0.12
Site 7	0.02040	0.0028	<.0001	0.74

Table 3 summarizes the results of the significant model accounting for the independent variables and their interaction. The regression model had an F-statistic value of 38.29 (p-value < 0.001) indicating that the model is significant at 5% level of significance. The model's coefficient of determination (R^2) is 0.667 indicating that the model explained 66.7% of the observed variation in the permeability coefficient of the test sections.

As shown in the table, relative compaction (*Comp*), base type (*Pavt*), and number of passes (*Pass*) are significant variables at 5% level of significance. Expectedly, K decreases with the increase of *Comp* and *Pass*. Compared to a pavement layer over an aggregate base, K would increase for overlays on top of a stiff base of milled asphalt concrete or Portland cement concrete. Two sites (2 and 7) were also found to be significant with lower K at Site 2 and higher K at Site 7 compared to pavements with the same characteristics at all other sites. Three interaction terms involving *Rol*, *Pavt*, and *Va* were also significant with negative regression coefficients. First, *VaRol* (interaction term for *Va* and *Rol*) indicates that an increase in the pavement's air voids would cause a smaller increment in K if the pavement is compacted with AMIR than the case of conventional compaction. Similarly, *PavtRol* (interaction term for *Pavt* and *Rol*) indicates that the increase in K over a stiff base is lower for AMIR compaction than conventional compaction. Finally, *sqVaRolPavt* (interaction term for square of *Va*, *Rol*, and *Pavt*) indicates a further reduced rate of increase in K for AMIR-compacted pavements compared to conventional compaction when the percentage of air voids increases and/or overlay over a stiff base.

5 Conclusions

This paper has explored the influence of conventional vibratory steel drum compaction train and the AMIR single roller compaction technology on the asphalt pavement properties using field permeability as the property of interest to study the effect of the conventional and AMIR compaction methods on asphalt pavement properties. Based on the findings of this paper, the following conclusions are made. Field compaction equipment and its process are important factors that control the resulting properties of asphalt concrete regardless of mix design. That compaction level alone is inadequate to ensure the performance and durability of the asphalt pavement system without consideration to the process of compaction used and other related properties and benchmarked with other compaction types. Major factors such as relative compaction, stiffness of the underlain base, type of field compactor and number of rollers passes affect properties of asphalt pavement such as permeability. The major conclusions of the foregoing results are that proper compaction improves and enhances the mechanical and physical properties of asphalt pavement. Also, as-constructed asphalt concrete quality should not be based on density alone, and that the inclusion of permeability testing as part of a quality control scheme is expedient conditioned on the process of compaction used.

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