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A Protection of the Environment Through the Prevention of Surface Cracking

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Abstract: One of the main objectives of the top asphalt layer is to provide a protective surface against water penetration and other harmful liquids such as chemicals. However, current construction equipments do not provide finished asphalt surfaces that meet this quality and therefore, allowing the intrusion of several liquids through the asphalt layers and deeper into the underlying soils. Subsequently, the result is often polluted soils and possibly seepage of the chemicals to rivers and underground water endangering the environment, plants, animals and ultimately humans. Results of recent research proved that current steel drum rollers induce surface cracks that provide path for surface water to intrude into the pavement layer. The development of a new compactor, asphalt multi-integrated roller (AMIR), produces asphalt layers with tight surface texture which demonstrate very low values of permeability when compared with similar asphalt compactor using current rollers. The results of field measurements of permeability on four asphalt sections compactor using AMIR and steel rollers showed that AMIR compacted surfaces will significantly improve the tightness of the surface and will reduce the permeability by a factor of up to 10 to 1, when compared with measured permeability on surfaces compacted using steel rollers. The results are used to discuss the role of better compaction in the protection of the environment and reduction of possible harmful pollution of water and soils.

INTRODUCTION

There is no doubt that asphalt pavements have helped in shapeing the economic and industrial development of the first world nations. More than 85% of road networks in the world are asphalt pavements. The main objective of the top asphalt layer is to protect the subsequent pavement layers against water and other liquid penetrations, such as harmful chemicals. However, since the construction of asphalt pavements started in the early 20th century, no solution has been found to provide crack-free surfaces that would prevent the intrusion of such harmful liquids into the pavement layers and subsequently into the underlying soils.

The pavement industry has invested millions of dollars in search of remedies for pavement distress. These remedies included the improvements in the design of asphalt mixes, development of new and engineered asphalt binders, using new materials, and establishment of new research efforts. These remedies were successful in improving the properties of asphalt materials in the laboratories. However, these improvements did not appear in the field performance of the asphalt roads. The research performed to attempt to solve pavement distress problems did, however, result in a number of significant solutions and initiatives such as the Strategic Highway Research Program (SHRP), which in part deals with the characterization of asphalt materials and their performance under a wide range of in-service conditions, and the adoption of gyratory compaction as the main laboratory device for designing asphalt mixes. In addition, new advanced materials are currently being used to reinforce asphalt layers and to improve their tensile and shear strengths such as non-metallic polymeric grid and polymer modified asphalt binders. There is no doubt on the significant technical and economic affect of these improvements. However, such initiatives can be considered more affective and advanced when addressing and solving the initial cause of asphalt pavement deterioration [1].

The presence of surface cracks significantly reduces the life of the asphalt pavements. This is because surface cracks are one of the main contributors in the development of other different types of cracks in the asphalt layers. They accelerate the development of cracking, which would ultimately lead to the early failure of the pavement [2].

One of the main contributors to surface cracking is the current practice of asphalt compaction that has been used for the past century without any significant change or improvement. Construction cracks have been traditionally recognized to be due to deficiencies in the base stability, the mix temperature during compaction, operator error, or due to the design of the asphalt mix itself. To remedy these surface cracks, the practice was to use pneumatic rubber-tired rollers.

However, even though pavements are normally designed to last 15 to 20 years, the compaction procedure has helped to reduce this fatigue life by more than 50% [2-4]. Studies by Abd El Halim *et al.* [5-7] have proven that the compaction procedure is the main factor behind the reduction in service life of pavements and behind the appearance of surface cracks. These studies also proved that the solutions of these

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problems would not be through using pneumatic rubber-tired rollers, but rather to change the methodology concept of compaction. These studies introduced a new concept in compaction by the invention of the asphalt multi-integrated roller (AMIR), which caused a revolution in the research of asphalt pavements.

This paper presents the role of compaction in the protection of the environment and reduction of possible harmful pollution of water and soils. A comparison is made between the effect of the traditional steel drum rollers and the AMIR compactor on inducing surface cracks. The results of field measurements of permeability of four asphalt sections compacted using AMIR and the steel drum rollers, are also presented.

CONSTRUCTION INDUCED SURFACE CRACKS

Compaction has been recognized as one of the main factors affecting the performance of asphalt pavements by many researchers [8-12]. Hughes (1989) pointed out that better compaction would result in higher strength, durability, resistance to deformation and moisture damage, impermeability, and skid resistance of the asphalt pavement. Bell *et al.* pointed out that better compaction would result in extending the service life of the asphalt pavement [13].

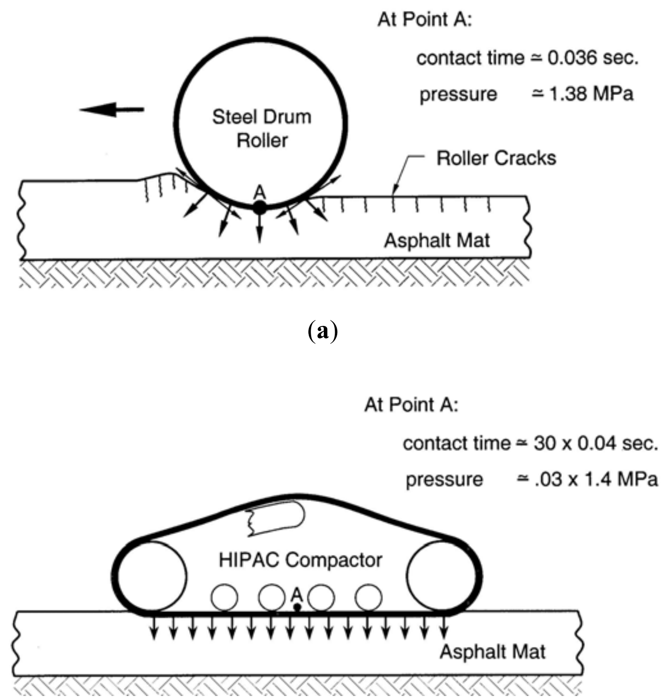
All these statements are true, however the approach of applying them in the past 50 years is not. Past research has assumed that any problems of compaction are related to the mix properties, and that increasing the performance of the pavement would be realized by increasing the density and reducing the percentage of air voids in asphalt mixes. Hughes (1989), for example, stated that the aggregate and asphalt properties as well as their mixture properties affect the ability to achieve the proper compaction level [12]. Therefore, problems due to compaction were often remedied through improving the asphalt mix. Geller (1982) stated that the problems that occur in the asphalt pavements are not due to compaction deficiencies, but rather due to the inability to predict the behavior of the asphalt mixture [9].

However, this section will attempt to describe the process of formation of the surface cracks and will prove that these cracks are in fact attributed to the compaction process itself.

Formation of Construction Cracks

Asphalt pavements are constructed by placing the hot asphalt mix over either the base course or an existing road surface. Compaction is then performed by first using heavy vibratory steel rollers to reach the desired density. Then, multi wheeled pneumatic rubber rollers followed by a light steel roller are used to smooth out the surface. The addition of the pneumatic rubber rollers was considered one of the main achievements in the compaction industry, in the last 50 years [7].

The interface between the surface of the compacted asphalt mix and that of the compacting device is a key factor in the quality of the compacted product. In case of the typical steel drum roller, the contact between the asphalt mix and the roller drum is a rectangular area 5 to 10 cm long and its width equals to the width of the drum. Although this could be considered as a rectangular area, it actually takes the shape of a cylindrical drum which is the shape of the roller drum. The applied force has both radial and tangential components due to the small curved contact area as shown in Fig. (**1** (**a**)). At a normal rolling speed of 10 km /h, the contact time between the roller and the mix is approximately 0.03 seconds. The small contact area and load time combine to apply an intense pressure impulse, typically 1.38 MPa, to the asphalt surface. Therefore, conventional compaction equipment presents forces that are both rapidly applied and held for merely a fraction of second [7].



(**b**)

Fig. (1). Schematic of (**a**) Conventional Steel Drum Roller and (**b**) AMIR Compactor.

Effects of Compaction Procedure

Two major negative effects result from this compaction procedure. First, loads applied rapidly for a short duration time causing asphalt to respond with a high elastic stiffness with relatively small plastic deformation. In order to overcome the increased asphalt stiffness, conventional equipment seeks to increase the applied load or to use vibration. This may cause breakage of the aggregate particles. The second negative effect is that the small contact area causes the application of horizontal forces which causes shoving of the asphalt layer. Both radial and tangential forces applied by the steel roller contain horizontal components, as shown in Fig. (**1**). As the roller travels, the horizontal forces push and pull the asphalt in front of and behind the drum respectively, inducing hairline surface cracking, often referred to as "roller checking" with an interrelated dissipation of a significant portion of the applied compaction energy. The initiation of surface cracking at this stage of construction reduces the strength and fatigue resistance of the asphalt layer, and facilitates the development of cracking, which can ultimately lead to the premature failure of the newly constructed pavement. This process has been extensively described in other references of the first author [2-7]. Abd El Halim [5-7] also showed that the pneumatic-rubber rollers do not eliminate these surfaces cracks, and that these cracks are detrimental to long term performance of asphalt pavements.

IMPLICATIONS OF CONSTRUCTION CRACKS ON THE ENVIRONMENT

Although the presence of surface cracks developed during construction is not the only reason for the development of the different types of cracking in asphalt pavements, these surface cracks serve as catalysts, which accelerate the development of cracking and ultimately the failure of the pavements [2]. One of the main negative effects of construction cracks is the moisture induced damage or stripping in asphalt pavements. Newly constructed asphalt pavements are designed to have air voids between 3 to 5%. It is usually constructed at higher air voids content that may reach between 8 to 10%. In addition to the high air void content, the surface cracks caused by the conventional steel drum rollers used for compaction enable the infiltration of water through the pavement layers. Stripping of the asphalt material from the surface of the aggregate or loss of adhesion is one of the most common types of pavement distresses known in the asphalt pavement field and is subjected to wide research efforts [3, 14-16]. It often accelerates the pavement deterioration and reduces its life.

Asphalt layers are expected to serve as waterproofing layer for the entire pavement structure. Thus, one of the main functions of the asphalt layer is the protection of the base and sub-base layers in addition to the prevention of the infiltration of salts, oils and other chemical that may exist on the road surface. However, the presence of surface cracks leads to higher surface permeability. Subsequently, these cracks will allow water and other harmful fluids to penetrate the top layer into the main body of the highway structure. These fluids would eventually become pollutants to the soil and water resources adjacent to the paved roads. Polluted water and soil can be harmful to people, animals and plants. Clearly, this would have adverse effects on the environment and could threaten the well being of the communities.

Therefore, it is important to control the construction induced cracks not only for the structural integrity of the pavement, but also to ensure that the finished asphalt layer meets the environmental adequacy in terms of the proper protection of the underlying layers. An exponential relationship was found between permeability and air voids. Consequently, when the asphalt pavements are properly compacted, cracks are eliminated and air voids could be reduced to less than 7%, which would reduce the intrusion of water into the asphalt pavements. In addition to the direct effect on the environment, the construction induced cracks result in serious deterioration of the pavement which lead to early failure and waste of initial investment. Hence, rehabilitation and/or new construction of the damaged road will require new materials which are in short supply.

THE NEW CONCEPT: AMIR COMPACTOR

The relative rigidity parameter (R) influences the transfer of stresses in pavement systems between the loading compactor and the various components of the multi-phase elastic material or the multi-component elastic structure. Abd El Halim [5] pointed out the importance of understanding the relationship between the numerical value of the parameter R and the physical terms contained in the equation of relative rigidity using the theory of relative rigidity. The application of the equation in the asphalt pavement field provided a new mechanistic approach for the prediction of construction-induced cracks. This approach was the main inspiration that led to the development of the AMIR roller.

The reason for surface cracking has been attributed to the incompatibility between the geometry and relative rigidity of the soft, flat asphalt layer and the hard, cylindrical steel drums of conventional rollers [5]. The Asphalt Multi-Integrated Roller (AMIR) prototype shown in Fig. (**2**) was designed and fabricated by Carleton University and the National Research Council of Canada in 1989 to overcome these incompatibilities. AMIR uses a multi-layered belt composed of specialized rubber compounds to create a single flat contact plate of approximately 3 m^2 for compaction. In addition, the rubber belt is flexible, providing a closer match in rigidity to the asphalt surface. Due to the large contact area, the stress applied to the asphalt mat is relatively low at 41.6 Kpa. This is compared with stresses of 1.38 MPa applied by typical steel drum rollers. However, for the same rolling speed, the AMIR load duration is 30 times longer than conventional steel rollers. Fig. (**1** (**b**)) shows a schematic drawing of the belt and the forces acting on the asphalt pavement. The AMIR prototype is well described in the following references [4-7].

Based on AMIR technology, the HIPAC compactor was designed and fabricated by Pioneer Road Services in Australia, in early 1998. Significant operational modifications were implemented to the HIPAC device in order to produce a regular production, and commercially available compactor. The HIPAC is double-belted and has greater maneuvrability than the AMIR compactor. A more descriptive development program of HIPAC is available in other references [17]. A photo of the HIPAC compactor is shown in Fig. (**3**).

Fig. (2). Photo of AMIR Prototype.

The compaction pressure of the device is low and is applied gradually over a long duration, in order to keep the initial stiffness response of the asphalt, low. The applied stress from the compactor is more efficiently utilized, because it is not "fighting" against a large initial damped elastic stiffness response that occurs with rapid, short duration loading. The long load duration also compensates for the low applied pressure by allowing visco-plastic flow of the asphalt, providing efficient particle contact and expulsion of entrained air. Furthermore, the large contact area minimizes horizontal forces applied to the asphalt mat and provides a high degree of confinement during compaction. This, in turn, eliminates roller induced cracking, reduces surface permeability, and increases tensile strength and resistance to fatigue damage. The elimination of surface cracking also permits the full compaction energy to be applied to the pavement layer. Fig. (**4** (**a**)) shows the construction cracks formed by compaction using the steel drum roller, while construction cracks are significantly reduced when asphalt is compacted by the AMIR roller in Fig. (**4** (**b**)). Fig. (**5** (**a**)) shows the surface cracks formed on s and using the steel drum roller, while Fig. (**5** (**b**)) shows how these surface cracks are significantly reduced when the AMIR roller is used. This further proves that surface cracks are actually a function of the type of compaction used rather than the type of material being compacted.

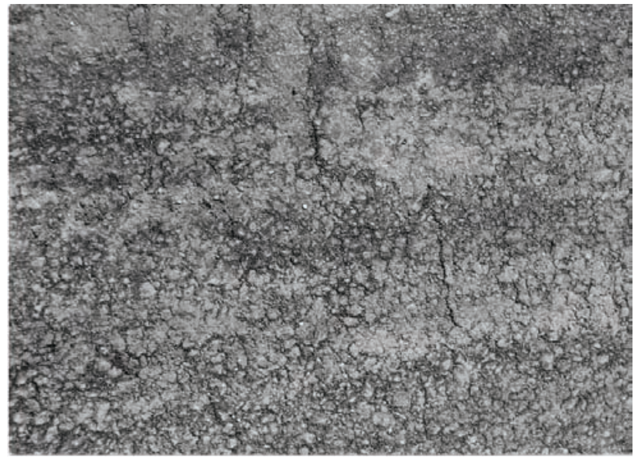
(**a**)

(**b**)

Fig. 3 (a, b). Photos of HIPAC Prototype.

EXPERIMENTAL INVESTIGATION: EFFECT OF COMPACTION ON PAVEMENT PERMEABILITY

As explained previously, an experiment was designed to test the effect of compaction on preventing surface cracking, and therefore protecting the environment. The experiment presented here was described previously in detail in a previous publication [18]. However, a summary of the results is shown here to further demonstrate the methodology of protecting the environment from the adverse effect of permeability in asphalt pavements.

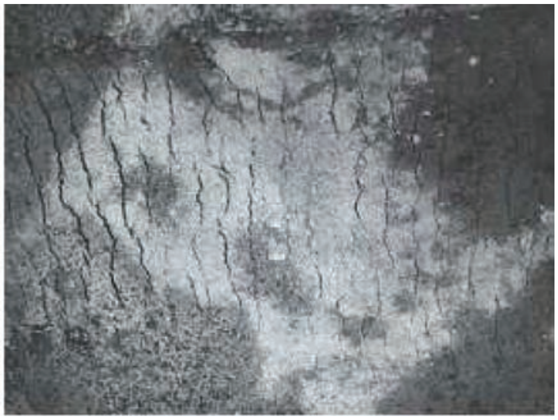


(**a**)

(**b**)

Fig. (4). Asphalt Compacted by (**a**) Steel Drum Roller and (**b**) AMIR Roller.

The hydraulic conductivity of the compacted layer is a common parameter used to measure the susceptibility of an asphalt pavement to moisture infiltration and its possible damage. In-situ permeability of an asphalt pavement could be measured by using a field permeameter, shown in Fig. **6**, which was designed by the National Center for Asphalt Technology. This device records the drop in water level in a standpipe over a given period of time. The permeameter is divided into four parts. The base is the largest section, and the top is the smallest. The bottom level is used when the asphalt mix is in high permeable pavement, and the top level is used when the asphalt mix is relatively less permeable. Three tests were conducted for each of the three sites. For each test, three individual measurements of the permeability coefficients were calculated using Equation 1, and the average value was taken.



(**a**)

(**b**)

Fig. (5). Sand Compacted by (**a**) Steel Drum Roller and (**b**) AMIR Roller.

$$K = (a*L/A_t) * ln\ (h_1/h_2) \quad (1)$$

Where, K = coefficient of permeability (cm/sec); a= inner cross-section area of standpipe, cm^2; L = thickness of the asphalt layer, cm; A = cross-sectional area that in contact with water during the test, cm^2; h_1 = initial head, cm; h_2 = final head, cm.

Field Experiments

Abd El Halim and Mostafa (2006) [15] performed field measurements of permeability on pavement sections, compacted by the AMIR compactor and the conventional steel drum roller. To facilitate the comparison, three independent tests were performed at three different sites and a total of four sections were tested as follows:

1. Site A: composed of two different mix types, HL-3 and HL-4.
2. Site B: constructed using an HL-3 asphalt mix.
3. Site C: constructed using HL-3 asphalt mix.

The test section at Site A was designed and compacted in 1990, and was the fist field test conducted to evaluate the AMIR compactor. Two mix types were investigated at this site, HL-3 and HL-4 Ontario mixers. The results of this experiment and the details on the construction of these mixes are found in other publications [2, 4], and [18]. Six specimens were extracted from this site in 2004, which is 14 years after the construction of this pavement. The results showed that the HL-3 asphalt mix compacted by the AMIR compactor was 11 times less permeable than the same mix compacted by the steel drum roller. The results are shown in Table **1**.

(**a**)

(**b**)

Fig. (6). Permeability Readings Using the Permeameter for Asphalt Compacted by (**a**) Steel Drum Roller and (**b**) AMIR Roller.

Table 1. Summary of Mix Properties and Permeability Measurements (Reproduced from Abd El Halim and Mostafa 2006) [15]

Year S	ite	Compactor	Thickness (cm)	AV (%)	AC (%)	Average K (cm/sec $*10^{-4}$)	Permeability Ratio (Steel Roller/AMIR Roller)
2003-2004	Site A	AMIR 6.	20	5.00	5.1	0.37833	11.30
		STEEL 6.	40	6.10	5.1	4.27667	
	Site B	AMIR 5.	15	5.15	5.0	0.08500	45.61
		STEEL 5.	25	5.25	5.0	3.87667	
	Site C	AMIR 5.	10	5.10	5.3	0.44700	7.70
		STEEL 5.	20	5.19	5.3	3.44333	
2005	Site A	AMIR 6.	20	5.00	5.1	0.00689	8.68
		STEEL 6.	40	6.10	5.1	0.05975	
	Site B	AMIR 5.	15	5.15	5.0	0.01516	12.85
		STEEL 5.	25	5.25	5.0	0.19485	
	Site C	AMIR 5.	10	5.10	5.3	0.04178	6.27
		STEEL 5.	20	5.19	5.3	0.26178	

Site B was constructed in November 2003. Similar to the first site, six specimens were extracted from the asphalt pavement to test the effect of compaction on permeability. It was found that the section compacted using the AMIR roller was 45 times less permeable than the same mix compacted using the steel drum rollers. The results are also presented in Table **1**.

Finally, Site C was constructed in September 2004. Again, six specimens were extracted. The results shown in Table **1** shows that the mix compacted using AMIR roller was found to be 8 times less permeable than the same mix compacted by the steel drum roller.

The surfaces compacted using AMIR were generally found to have tighter textures and no visible surface cracks. This resulted in the big difference in the permeability between the sections compacted using AMIR compactor and the others using the conventional methods. This is further illustrated in Fig. (**6**). In Fig. (**6** (**a**)), it is obvious that due to high permeability of the asphalt surface compacted the conventional roller, the final head in the permeameter is much lower than the initial head. However, in Fig. (**6** (**b**)), the difference between the initial and final head is minor due to the lower permeability of the asphalt surface compacted by AMIR. Therefore, it could be concluded that the compaction method does in fact affect the permeability characteristics of the pavement structure. In addition, mixes compacted using AMIR had less air void content than those compacted by the conventional roller.

These two results show the major improvement in the asphalt pavement characteristics in terms of permeability and air voids by changing the compaction method from the conventional steel drum rollers to the AMIR compactor. This outcome has significant economic and environmental impacts that will be discussed in a following section.

In order to test the effect of time and traffic loading on the permeability characteristics of the asphalt sections, a second field test was performed on the following year in 2005. The results are also shown in Table **1**. Three specimens were extracted at each location. The results showed that the specimens taken at Site A showed that the AMIR compacted sections maintained lower permeability than the steel drum compacted sections even after 15 years, since the initial construction. The AMIR compacted sections were in less visible distress as compared to the steel drum compacted sections and in better field condition. Results shown in Table **1** show that the permeability of AMIR compacted sections in all three sites remain lower than the conventionally compacted sections by a ratio of 8, 13, and 16 for the sections at Sites A, B, and C, respectively.

EXPERIMENTAL INVESTIGATION 2: EFFECT OF COMPACTION ON INFILTRATED WATER

Due to significant results of the first experiment explained previously, a further experimental investigation was carried out in order to measure the effect of compaction on the characteristics of infiltrated water through the pavement layers. An experiment was conducted at the Civil and Environmental Engineering Laboratory of Carleton University in August 2008, where two sets of sections were prepared. The first pavement section was compacted using the conventional steel drum roller and the second was compacted using AMIR compactor. For each section, three samples were taken, and a series of experiments to measure the environmental effects of the compaction procedure were then performed on these samples.

A permeability test similar to the procedure explained earlier was performed. Results of the permeability test are shown in Fig. (**7**). The results show very low permeability of the pavement section compacted using AMIR roller as compared to that using the conventional steel drum roller. In addition, the permeability values of the pavement sections compacted using the AMIR roller remained with a low permeability value for a long time.

To further substantiate the positive environmental effects of the AMIR roller, the water was used in the permeability test and infiltrated through the pavement sections, was tested before and after the permeability test to find the effect of the pavement compaction on infiltrated fluids through pavement sections. In this test procedure, three levels of salinity were used for the distilled water samples used in the permeability test. The first sample was infiltrated with water with no salinity and the second contained 50 g/L of salt. Six measurements were taken for the water samples: pH values, turbidity, conductivity, total carbon dissolved in mg/L, total organic carbon, and total inorganic carbon. The results are shown in Table **2**. It should be noted that the results measured for the samples compacted by the AMIR roller were taken after an average of 50 hours as compared to 0.64 hours for samples compacted using the steel drum rollers.

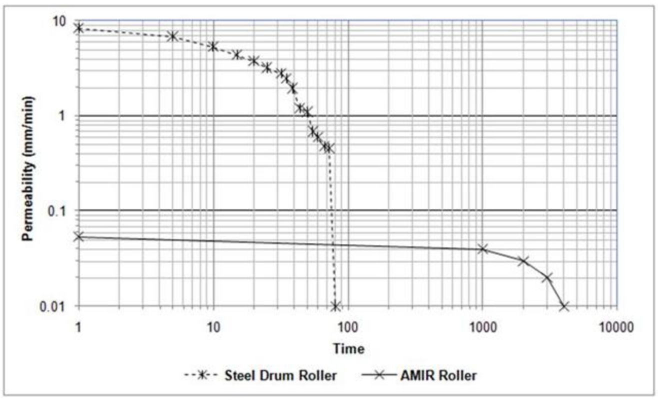


Fig. (7). Permeability Results for Asphalt Compacted by (**a**) Steel Drum Roller and (**b**) AMIR Roller.

The results of the table show that the pH value and turbidity were not significantly affected by the type of compaction. On the other hand, due to the long duration after which the samples are taken for the AMIR compacted samples, the values of conductivity and amounts of total carbon in the water sample are higher. This is a logical result, since the samples infiltrated through the pavement sections after 58 and 44 hours , respectively. However, the results show the resistance of the AMIR compacted samples in infiltrating water through it, which is a main benefit of this type of compaction.

Therefore, to ensure the benefit of using AMIR for pavement surfaces, and since it was unfair to compare the results of AMIR with the steel roller since two different time frames were used, the test was repeated for the AMIR compacted sections, where the water samples were taken during the test, rather that after the test, finished after 40 and 50 hours as before. The results of the second run for the AMIR compacted samples are shown in Table **3**.

The results show the greater benefit of using the AMIR to the environment. As apparent from Table **3**, the water samples were taken after 3 hours of the test rather than 40 hours. In this case, the values of turbidity, conductivity, and total carbon (both organic and inorganic) are much less than the values of the first run. In addition, the values are also very close to the values for the water before entering the pavement sections. This shows the less detrimental effect of using the AMIR to the underlying soil layers below the pavement.

IMPLICATIONS OF PREVENTING SURFACE CRACKS ON THE ENVIRONMENT

It was discussed earlier that the AMIR compactor successfully prevented surface cracks from appearing on asphalt pavement surfaces during compaction. It also had a great effect in reducing the permeability of the asphalt pavement. These results are significant and will have considerable positive economic impacts in terms of reducing the pavement distresses and therefore, extending the life of the pavement. This would save billions of dollars to the pavement industry that would otherwise be lost in capital invested in the pavement structure.

The environmental benefits of preventing surface cracks are even more significant. The pavement network is a very long structure that extends thousands of kilometer in many nations. This structure is often exposed to severe environmental conditions and different weather conditions. In winters, especially in cold countries, temperatures could reach –40 ℃. Then in summers the pavement surface could reach 60℃ due to hot weather conditions in addition to traffic flow. The change in temperature along with precipitation has the following adverse effects:

1. This big difference in temperature accompanied with precipitation in the form of rain or snow could cause severe deterioration to the asphalt surface.

Table 2. Comparison of the Chemical Analysis of Water Infiltrated Through AMIR Compacted and Steel Compacted Pavement Sections

Salinity	Sample	Duration to Measurement (Hours)	pH	Turbidity	Conductivity (ms/cm)	Total Carbon (mg/L)	Total Organic Carbon mg/L	Total Inorganic Carbon mg/L
No Salt	Water Inflow	0.00	7.22	0	3.22	1.09	0.42	0.67
	Steel (outflow)	0.83	6.58	0.11	11.42	4.70	2.36	2.34
	AMIR (outflow)	57.94	7.30	0.30	263.90	12.57	8.4	4.17
50 g/L	Water Inflow	0.00	9.68	2.00	330.00	9.25	6.85	2.40
	Steel (outflow)	0.45	9.48	0.41	313.33	12.47	9.62	2.85
	AMIR (outflow)	43.54	8.58	1.13	329.50	20.86	13.09	7.76

Table 3. Second Run of the Chemical Analysis of Water Infiltrated Through AMIR Compacted Sections

Salinity S	ample	Duration to Measurement (hours)	pH T	urbidity	Conductivity (ms/cm)	Total Carbon (mg/L)	Total Organic Carbon mg/L	Total Inorganic Carbon mg/L
No Salt	Water Inflow	0.00	7.22	0.00	50.8	2.79	1.57	1.20
	AMIR (outflow)	3.63	7.30	0.00	19.75	2.67	1.79	0.88
25 g/L	Water Inflow	0.00	9.10	1.20	57.9	6.60	5.15	1.46
	AMIR (outflow)	3.32	9.00	0.40	44.50	7.24	5.63	1.61

2. Due to the thermal cycle of rise and fall of temperature, the pavement surface like any other structure or material expands when exposed to high temperatures and contracts when exposed to low temperatures. This, coupled with the previously compaction induced surface cracks, causes severe continuation of pavement cracking resulting in severe pavement distresses.

3. The frost action is known to be very detrimental to the pavement structure. The crystallization of ice within the air voids and the subsequent formation of ice lenses would cause the soil and pavement to "heave" upwards inducing and increasing the already existing cracks.

Along with these adverse effects that cause deterioration to the pavement structure, there are environmental effects. The liquids that enter the pavement surface, whether in the form of snow or rain, seep through the cracks on the surface to the inner pavement layers. The water first washes the surface of the pavement and reacts with the components and particles on it. These particles could be asphalt residues that are stripped off the surface of the pavement due to the traffic flow and the great number of repetitions of rubber tires on the pavement. They could also include oil-based treatments used to increase the structural strength of the pavement or to prevent other unwanted characteristics. This residue accompanied with the cycle of low and high temperature could lead to the dissolving of these harmful and toxic materials into the liquid, which in turn infiltrates to the inner layers and subgrade of the road. Then, the contaminated mixture of water and toxic substances could find its way through the subgrade to the groundwater or to other water bodies such as rivers, lakes, or seas. This has very harmful and drastic effects on the environment, as these water bodies are sources of life to plants, animals, and drinking source of human beings.

The experimental investigation presented earlier proved that sections compacted using the AMIR compactor suffer less percentage of air voids, less permeability, and less surface cracks than other conventionally compacted sections. In addition, due to the low permeability of samples compacted using AMIR roller, the water infiltration through the pavement structure was very slow, proving the resistance of AMIR compacted pavements to liquid infiltration. This was proven through the higher conductivity, total dissolved solids, and total carbon amounts in the samples compacted using the AMIR roller.

Therefore, without doubt, using the AMIR compactor would also result in less drastic environmental effects of asphalt pavements. First, due to the lower percentage of air voids, there would be less formation of ice lenses within the pavement layers, since there are less air voids for them to form in. Second, the lower permeability of the pavement structure would reduce the infiltration of the contaminated liquids into the inner pavement layers and subgrade, and ultimately into the ground water. Finally, and obviously the most significant contribution, is the reduction of surface cracks which is known to trigger other types of cracks. Reducing surface cracks would hence prevent or reduce substantially contaminated water infiltration into the pavement layers and ground water.

CONCLUSION

This paper presented a summary of a long term research work performed through the last 20 years. It showed how proper compaction of fresh asphalt mixes using the new AMIR compactor, along with its many advantages, is able to protect the environment from the severe and detrimental effects of surface cracking to our environment. AMIR compactor has been proven to successfully prevent surface cracks that are induced due to the conventional method of compaction. This in turn has significantly lowered the air voids content and permeability of asphalt pavements. Due to the fact that AMIR is successful in preventing surface cracks, the adverse effects accompanied with surface cracks are also prevented. Infiltration of harmful material that are washed by precipitation and dissolved into it, is substantially reduced. This result not only has a significant economic effect in terms of saving losses in capital invested in pavement structures, but also has important environmental effects. This is even more significant as it would result in less destruction to our soil and water resources. It would ultimately reduce sources of ground and water pollutions in addition to sustain the resources and assets of the society for generations to come.

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REFERENCES

[1] A. O. Abd El Halim and R. Haas, " Process and case illustration of construction innovation: From concept to commercial realization", *J. ASCE Construct. Eng. Manag.*, vol. 130, Issue 4, pp. 570-575, July/August 2004.

[2] A. O. Abd El Halim, W. Phang, and R. C. Haas, "Unwanted legacy of asphalt pavement compaction", *J. Transp. Eng.*, vol. 119, No. 6, pp. 914-932, November/December 1993.

[3] A. Mostafa and A. O. Abd El Halim, "Evaluating the effect of surface cracks on moisture induced damage using different standard test methods for airfield asphalt pavement mixes" in Canadian Technical Asphalt Association 49th Annual Conference, Montreal, QC, November 2004, pp. 318-339.

[4] A. O. Abd El Halim, R. Haas, and O. J. Svec, "Improved asphalt pavement performance through a new method of compaction". In 17th *ARRB* Conference, Part 3, 1994, pp. 175-191.

[5] A. O. Abd El Halim, "Influence of relative rigidity on the problem on reflection cracking", *Transp. Res. Rec.,* vol. 1007, pp. 53-58, USA, 1985.

[6] A. O. Abd El Halim and G. E. Bauer, "Premature failure of asphalt overlays at time of construction", *J. Transport. Forum*, vol. 3, 2 September pp. 52-58, 1986.

[7] A. O. Abd El Halim, W. Phang, and R. C. Haas, "Realizing Structural Design Objectives Through Minimizing Of Construction Induced Cracking", In Sixth International Conference on Structural Design of Asphalt Pavements, Ann Arbor, USA, July 13-16, 1987, vol. 1, pp. 965-970.

[8] F. N. Finn and J. A. Epps, "Compaction of hot mix asphalt concrete", *Res. Rep. 214-21,* Texas Transportation Institute, College Station, Tex., 1980.

[9] M. Geller, "Compaction equipment for asphalt mixtures", *Placement and compaction of asphalt mixtures: ASTM STP 829,* American Society for Testing and Materials, Philadelphia, Pa, 1980.

[10] V. Marker, "Construction methods--symposium on thick lift construction", *Proc. Assoc. Asphalt Paving Technol.,* vol. 41, pp. 101-354, 1972.

[11] F. N. Finn, "Factors involved in the design of asphaltic pavement surfaces", *NCHRP Rep. 39.* Transportation Research Board, National Research Council, Washington, D. C., 1967.

[12] C. S. Hughes, "Compaction of asphalt pavement", *NCHRP Rep. 152.* Transportation Research Board, National Research Council, Washington, D. C., 1989.

[13] C. A. Bell, G. Hicks, and J. Wilson, "Effect of percent compaction on asphalt mixture life", *Placement and compaction of asphalt mixtures: ASTM STP 829,* American Society for Testing and Materials, Philadelphia, Pa, 1982.

[14] A. Mostafa, " The Stripping Susceptibility of Airfield Asphalt Mixes: The Development of Guidelines for a Laboratory Test Method", a Ph.D. thesis. Carleton University, Ottawa, Canada, February 2005.

[15] A. O. Abd El Halim and A. Mostafa, " Asphalt Multi-Integrated Rollers and Steel Drum Compactors, Evaluating Effect of Compaction on Permeability of Asphalt Pavements," *Transportation Research Record: J. Transp. Res. Board,* No. TRB, Washington D. C., 1967, pp. 173-189, 2006.

[16] A. B. Brown, J. W. Sparks, and G. Marsh, "Objective appraisal of stripping of asphalt from aggregate mixtures" *STP 240. Am. Soc. Testing and Materials*, Philadelphia, Pa, pp. 59-74, 1999.

[17] Rickards, S. Goodman, J. Pagiani, A. Abd El Halim, and R. Haas, "Practical realization of a new concept for asphalt compaction", *Transp. Res. Rec.,* No. 1654, pp. 27-35, 1999.

[18] E. H. Mohamed and A. O. Abd El Halim, "Differential thermal expansion and contraction: A mechanistic approach to adhesion in asphalt concrete", *Can. J. Civil. Eng.,* vol. 20, No.3, pp. 366-373, 1993.

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