Extending the Service Life of Asphalt Pavements Through the Prevention of Construction Cracks

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Recent research work based on the concept of relative rigidity has indicated that the use of steel rollers of present design will result in the initiation of surface cracks that may lead to premature failure of newly constructed asphalt overlays. A new compactor, the asphalt multi-integrated roller, or AMIR, has been developed to prevent the construction-induced cracks. Two prototype models were built and used to compact asphalt concrete for field and laboratory evaluation. Early results of field trials carried out in Egypt confirmed the findings of analytical and experimental investigations of previous research work. The results of the laboratory testing program showed that the AMIR compactor will prevent the formation of construction cracks, resulting in up to 40 percent higher tensile strength and up to 65 percent higher strain energy in comparison with asphalt concrete compacted with steel rollers currently in use.

Pavements in cold areas are subjected to high tensile stresses during contraction as temperatures fall below about –25°C. Transverse cracking occurs in the pavement at spacings that depend on the stiffness of the asphalt mix, the stress relaxation properties of the asphalt cement, the coefficient of contraction, the rate of temperature drop, base restraint, and other factors such as the integrity of the asphalt mix (*1–3*).

Attention to reducing the incidence of transverse cracks has been concentrated so far on the temperature-susceptibility aspects of the asphalt cement binder. However, none of these studies (*4–6*) have adequately explained why transverse cracks continue to appear at closer and closer spacings as the pavement ages. In fact, transverse cracks spaced at less than 1 m apart have often been observed. If the only cause of these closely spaced transverse cracks were low temperature contraction, longitudinal cracks at the same spacing would also be likely to be observed. However, only a few cases of map cracking of this type, in old pavements, have been observed.

Recent studies of crack growth mechanisms (*7*) show that cracks propagate at flaws, as a result of repeated tensile stresses such as those caused by temperature cycling.

Transverse flaws are observed in asphalt pavements at the time of construction in the form of "hair checking." Hair checking appears as a series of hair-thin parallel transverse cracks spaced 1 to 2 cm apart. Some of these are 10 cm long, some are shorter, and some are longer, but none continues across the width of the pavement. Hair checking is created mainly during the initial compaction process when steel wheel rollers are used. By introducing heavy pneumatic rubber tire intermediate rollers, it is believed possible to heal the hair checking. Light pneumatic tire rollers may or may not have the same effect. There is, in fact, no way of measuring whether hair checking is really eliminated by such treatment. Flaws may still exist under the surface of the pavement, especially as the pavement is cooling.

Once transverse cracks develop they are subject to penetration by water and traffic forces that can create spalling and result in deterioration caused by pumping. The pavement depresses at crack (cupping) and often tents upward during the winter (lipping) as water freezes and ice builds up under the pavement. Secondary parallel transverse cracks form in the spring as the softened base ceases to provide adequate support near the crack, and these may progress to conditions such as alligatoring and potholing.

If construction flaws during compaction can be eliminated, there is a high expectation that the appearance of transverse cracks through temperature cycling will also be reduced, if not eliminated.

A description is given in this paper of how the elimination of transverse hair checking during compaction is accomplished with the asphalt multi-integrated roller (AMIR). The principles of relative rigidity (*8*) form the basis for the design of AMIR (*9–14*). The effect of hair checking of asphalt samples compacted in the laboratory and in the field is compared with that of samples compacted by different versions of the AMIR, in terms of densities attained and tensile strengths.

DEVELOPMENT OF THE AMIR ROLLER

The principles of relative rigidity, when applied to the process of loading the hot asphalt layer with a conventional steel roller drum, reveal two problems: the small curvature of the drum and the large difference in relative stiffness between the steel and the soft asphalt mix. For these reasons, hair checking of the asphalt mix is inevitable (*9–11*).

Use of the AMIR compactor (protected by international patents) resolves these incompatibilities because a rubber belt is inserted between the soft asphalt mat and the steel roller, and

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a surface of infinite curvature is ensured because the rubber belt is supported between two steel drums. The AMIR compactor consists of two large steel drums encompassed by a multilayer rubber belt, which integrates them into one flat roller. Additional smaller supporting rollers between the larger drums keep the bottom surface of the rubber belt flat and ensure uniform stress distribution across the entire flat area of the rubber belt. The presence of the rubber belt between the steel and asphalt mix produces a modular ratio close to unity and, with the flat compaction surface, satisfies the principles of relative rigidity. Thus compaction is accomplished without cracking.

Even though the contact pressure of AMIR is much lower than that of the steel wheel roller, the time of its passage over any point is much longer. This longer contact time allows the rubber belt to warm up more rapidly than would rubber tire rollers; asphalt pickup is thus avoided. As will be demonstrated, the compacted densities of AMIR are comparable with those produced by traditional steel wheel compaction.

A full-scale AMIR compactor, built by the Egyptian Corps of Engineers and undergoing testing in Egypt, is shown in Figure 1. For experiments reported here, two different versions of AMIR were built. For field-compacted mixes a Wacker VGP-160 plate vibrator was fitted with a rubber belt attached to the bottom of its plate (see Figure 2). The second version is a laboratory AMIR model, which consists of two 150-mm steel drums and a rubber belt integrating them into a flat roller (see Figure 3). To distinguish between the two types, the plate vibrator with the rubber is called AMIR-Plate and the small laboratory model is referred to as AMIR-LAB throughout the paper.

EXPERIMENTAL INVESTIGATION

The main objective of this research is to conduct a testing program to compare and evaluate the effect of the compaction method on the engineering properties of the asphalt concrete mix. Specifically, the objectives of this study are to

1. Evaluate the influence of the compacting device on the construction-induced cracks;

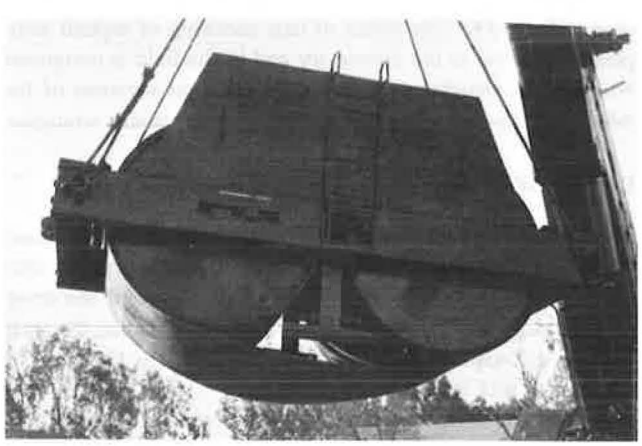

FIGURE 1 Full-scale AMIR prototype.

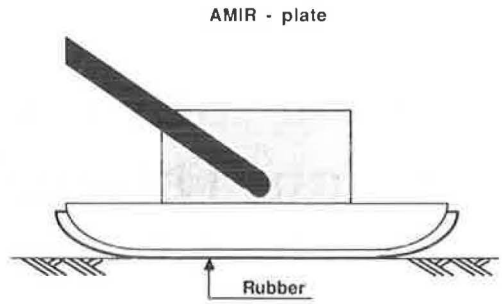

FIGURE 2 AMIR-Plate.

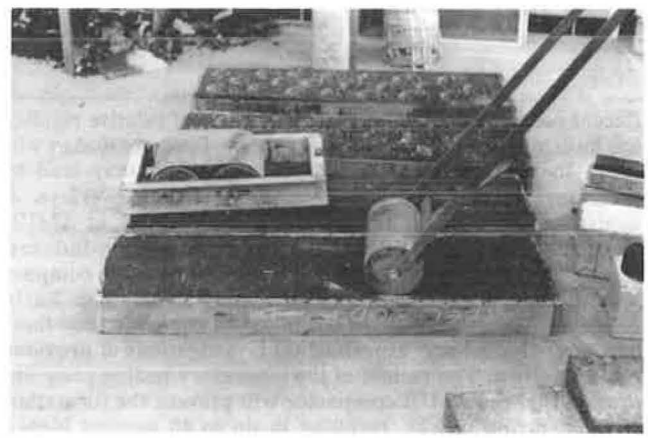

FIGURE 3 Laboratory models of AMIR-LAB and steel drum.

2. Determine the ability of the AMIR compactor to achieve densities similar to the ones obtained by steel plates and rollers currently used;
3. Evaluate the effect of the construction cracks on the tensile strength of the steel-compacted pavements; and
4. Evaluate the impact of the new compaction method on the long-term performance of the asphalt overlays.

The following sections present details of the testing program conducted to meet these objectives.

Testing Program

The testing framework designed was divided into two major testing programs. The first was to measure the densities obtained from each compaction method. Asphalt cores with 100-mm diam, 85-mm thickness, 57-mm diam, and 75-mm thickness were obtained from field- and laboratory-compacted asphalt slabs (HL-3 mix), respectively.

The second testing program was designed to evaluate the tensile strength of relatively large-sized asphalt samples. The selection of dimensions and size of the test specimens was to ensure that the construction-induced cracks would exist within the tested asphalt samples. Thus, asphalt slabs having 500-mm length by 225-mm width and variable thickness were selected. An outline of the experimental investigation is given in Table 1.

TABLE 1 OUTLINE OF EXPERIMENTAL INVESTIGATION

Mix Type	Size of Slab (length × width × depth) (mm)	Compaction Method	Type of Test
HL-2 plant	1250 × 300 × 38	Steel drum	Tensile strength
	1250 × 300 × 38	AMIR-LAB	Tensile strength
HL-3 plant	2000 × 900 × 75	Steel plate	Tensile strength and density
	2000 × 900 × 75	AMIR-Plate	Tensile strength and density
	1250 × 300 × 75	Steel drum	Density
	1250 × 300 × 75	AMIR-LAB	Density
HL-4 laboratory	1250 × 300 × 85	Steel drum	Tensile strength and density
	1250 × 300 × 85	AMIR-LAB	Tensile strength and density

Construction of Asphalt Slabs

Three different types of asphalt mixes were employed in the experimental investigation. Two mixes (HL-2 and HL-3) were obtained from the hot mix plant of an Ottawa-based construction company, and the third mix (HL-4) was prepared at the laboratory at Carleton University in Ottawa. The three mixes were prepared according to the standards of the Ontario Ministry of Transportation and Commmunication (see Table 2).

TABLE 2 SIEVE ANALYSIS OF ASPHALT MIXES

Mesh Size (sieve #)	Percentage Passing by Dry Weight		
	HL-2	HL-3	HL-4
16 mm (5/8)	100	100	100
13.2 (1/2)	100	100	93
9.6 (3/8)	100	88	77
4.76 (4)	92	73	53
2.36 (8)	76	53	42
1.18 (16)	60	39	34
600 (30)	38	28	30
300 (50)	19	18	8
150 (100)	7	4	3
75 (200)	4	2	0

NOTE: For Mixes HL-2, HL-3, and HL-4: percent asphalt = 8.0, 6.5, and 8.0, respectively; temperature of construction = 138°C, 140°C, and 150°C, respectively; asphalt gradation for all mixes is 85/100.

Field-Compacted Slabs

Two plywood forms, 2000 mm long by 900 mm wide and 75 mm deep, were built and used for placing the asphalt hot mix at the plant site. The asphalt mix (HL-3) was placed in each form in two lifts and each lift was compacted according to the specifications. Equal numbers of passes (3 passes/lift) of the steel plate or AMIR-Plate compactors were made on top of the asphalt slabs. Thus, the surface conditions and densities of the finished asphalt samples could be compared under the same compaction effort. It should be noted that, for the purpose of comparison, only one type of plate compactor (AMIR-Plate) was used on one slab, whereas the other plate compactor (steel) was used on the second slab. The temperature of the mix at time of compaction was about 140°C.

After the completion of compaction, the two asphalt slabs were left in the field for 1 week. The following week, each of the two 2000 × 900 slabs was cut into 16 smaller slabs, each 500 mm long by 225 mm wide by 75 mm deep. Thus, a total of 32 asphalt concrete specimens were obtained from the two field-compacted larger slabs. The specimens were then transported, along with the underlying plywood base, to the laboratory for testing.

Laboratory-Compacted Slabs

In addition to the slabs compacted by the plates in the field, smaller laboratory roller models were employed to compact asphalt samples placed in plywood forms 1250 mm long by 300 mm wide with varied depths, as given in Table 1. The compaction effort for these specimens was controlled by the final depth of the compacted mix. For each form, an equal weight of asphalt mix was placed and compacted until the desired slab depth was reached. A total of 16 slabs were constructed using the plant mix HL-2, 4 slabs using the plant mix HL-3, and 4 slabs using the laboratory-prepared asphalt mix HL-4.

Testing Facility

In order to evaluate the effect of the construction-induced cracks on the tensile strength of the pavement slabs, the asphalt specimen must be of a relatively large size. The direct tensile test apparatus was therefore designed and built to

1. Have a horizontal constant rate of displacement,
2. Conduct direct tensile strength on asphalt slabs as large as 750 mm long and 375 mm wide,
3. Allow different slab thicknesses to be tested,
4. Enable direct measurements to be recorded, and
5. Monitor the crack history.

In order to meet these objectives, the testing facility consists of two steel plates, one fixed and the other movable. Both plates are placed horizontally on a rigid steel table. The movable plate is connected to a loading mechanism consisting of a load cell with 22 kN capacity, a displacement transducer fixed on the edge of the moving steel plate, and an electric motor with transmitting gear to provide the constant rate of displacement desired. Continuous monitoring of load displacement is provided by a data-acquisition system equipped with an *x–y* plotter. The main components of this test facility are illustrated in Figure 4.

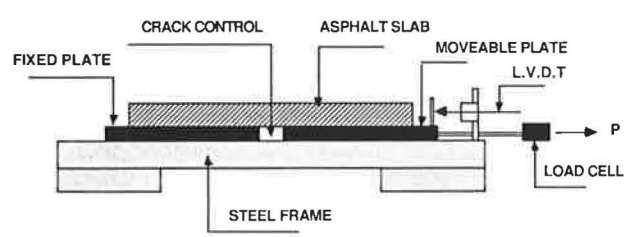

FIGURE 4 Main components of direct tensile strength test facility.

TEST RESULTS

The results of this investigation, although favoring the AMIR compacting method, should be considered conservative. The steel compactors used in the construction of the asphalt samples represent a technology that has reached its limit. However, the AMIR types used in this program represent the first step for developing a new technology and therefore have not reached an optimum design.

Densities

Results of tests carried out on 97 core specimens to measure the effect of the compaction method on void ratios and bulk density are given in Table 3 and showed the following:

1. Regardless of the mix type used in the test, there were quite small differences in the measured bulk densities of asphalt cores compacted by steel or the AMIR, although the AMIR type of compaction tended to be more consistent, as indicated by the calculated values of the coefficient of variation. For example, the coefficient of variation for the AMIR method was 0.06, whereas it was 0.30 for the steel-compacted samples in the case of HL-4.
2. Void ratios obtained from the AMIR compaction method were slightly higher than the void ratios of cores compacted with steel rollers. As given in Table 3, the difference is less than 1 percent.
3. Regardless of the compaction method, densities were higher for the laboratory-compacted samples. Measurements of the void ratios of the laboratory specimens from the HL-4 mix were significantly less than the void ratios of cores taken from the HL-3 plant mix.

In addition to these measurements, the surface conditions of the compacted asphalt slabs were evaluated and recorded. Observations of the finished surfaces are summarized as follows:

1. Asphalt slabs compacted using a steel plate in the field or a steel laboratory roller in the laboratory were surface cracked. The steel plate gave less but more severe crack intensity in comparison with the steel roller. The surfaces of the compacted slabs were more deformed in the case of the steel roller compared with the steel plate. These observations are in agreement with the results of previous research work (*9, 10*).
2. The use of the AMIR roller or plate resulted in a much-improved surface. Crack-free and flat surfaces were obtained when either was employed. Clearly, the AMIR method provides a flat shape in both cases, in addition to the elimination of the stiffer steel material from the compaction process, as discussed previously. These results and observations are significant because the main objective of the research was to evaluate the effect of the construction-induced cracks on the overall strength of the asphalt material. Density of asphalt pavement has been the most important factor in accepting or rejecting field projects.

TABLE 4 TYPICAL RESULTS OF THE DIRECT TENSILE TESTS

Mix Type	Slab No.[a]	Tensile Strength (MPa)	Strain Energy (N.m)	Ratio: Tensile Strength (%)	Ratio: Strain Energy (%)
HL-3					
	ST-6	169.62	15.54	138	166
	AM-6	234.43	25.79		
	ST-11	212.37	26.95	107	104
	AM-11	226.16	28.22		
	ST-16	155.14	6.61	165	168
	AM-16	257.18	11.19		
HL-4					
	ST-20	344.06	28.48	138	134
	AM-20	476.47	38.08		
HL-2					
	ST-24	98.60	1.24	124	133
	AM-24	121.35	1.65		
	ST-25	105.49	1.65	126	139
	AM-25	133.07	2.30		

[a]Serial number.

Results of Direct Tensile Strength Tests

Asphalt slabs made of the three mixes previously discussed were employed in this test. Tests were performed with the

TABLE 3 SUMMARY RESULTS OF DENSITIES AND VOID RATIOS

Type of Mix	Method of Compaction	No. of Cores	Average Bulk Density	Difference AMIR–Steel (%)	Average Void Ratio	Difference AMIR–Steel (%)
HL-3: 100-mm diameter	AMIR-Plate	17	20.63 (0.39)[a]	−1.7	10.7 (6.31)[a]	+0.3
	Steel-plate	18	20.80 (0.60)[a]		10.4 (5.07)[a]	
HL-3: 60-mm diameter	AMIR-LAB	16	20.88 (0.43)[a]	+0.3	11.7 (8.46)[a]	0.0
	Steel roller	16	20.85 (0.30)[a]		11.7 (9.67)[a]	
HL-4: 60-mm diameter	AMIR-LAB	16	22.97 (0.06)[a]	+0.8	5.3 (1.35)[a]	+0.8
	Steel roller	14	22.89 (0.30)[a]		4.5 (1.59)[a]	

[a]Coefficient of variation.

horizontal load applied in the same direction as that of the rolling. This was to simulate the effect of longitudinal movement of an underlying cracked layer as a result of thermal stresses. The results of the direct tensile strength tests are summarized in Tables 4 and 5. The effect of the compaction

TABLE 5 SUMMARY OF THE RESULTS OF THE DIRECT TENSILE TESTS

Mix Type	No. of Tested Slabs	Average Tensile Strength (MPa)	Average Strain Energy (N.m)	Ratio (%) Tensile Strength	Ratio (%) Strain Energy
HL-3					
Steel	7	167.55	15.64	125	137
AMIR	7	208.92	21.48		
HL-4					
Steel	2	349.58	26.78	136	120
AMIR	2	474.38	32.21		
HL-2					
Steel	7	93.77	1.34	129	137
AMIR	7	121.35	1.83		

method is readily apparent. On the average, the maximum tensile strength of slabs compacted by the AMIR method is 35 percent higher than the tensile strength obtained in the other compaction method. In addition to the higher strength obtained in the case of AMIR, the calculated energy required to cause total propagation of the first crack is 65 percent higher in the case of the new compaction method. Figures 5 and 6 illustrate typical results obtained from the tests.

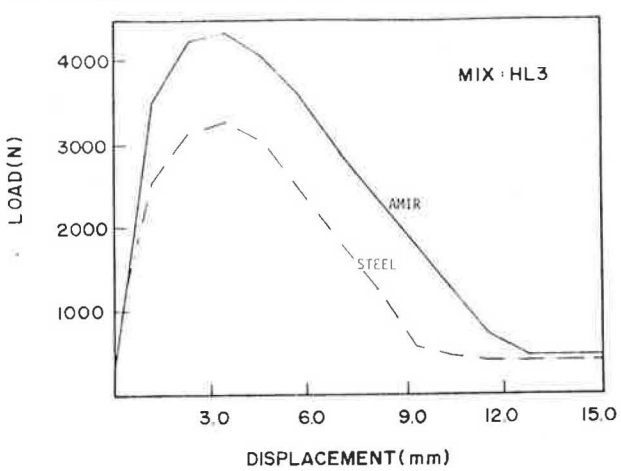

FIGURE 5 Typical results of direct tensile strength tests.

The recorded test data for steel and AMIR samples taken from similar locations within the larger compacted slabs can be seen in Figure 5, which shows that the maximum tensile strength of the AMIR compacted slab is 33 percent higher than the strength obtained from the steel-compacted one. It should be noted that the dimensions of both slabs are the same and therefore the load value can be used instead of the stress value. Also, the differences between the two curves after reaching their peak values indicate the higher amount of energy required to propagate the crack in the AMIR-compacted slab in comparison with the crack in the case of the steel-compacted

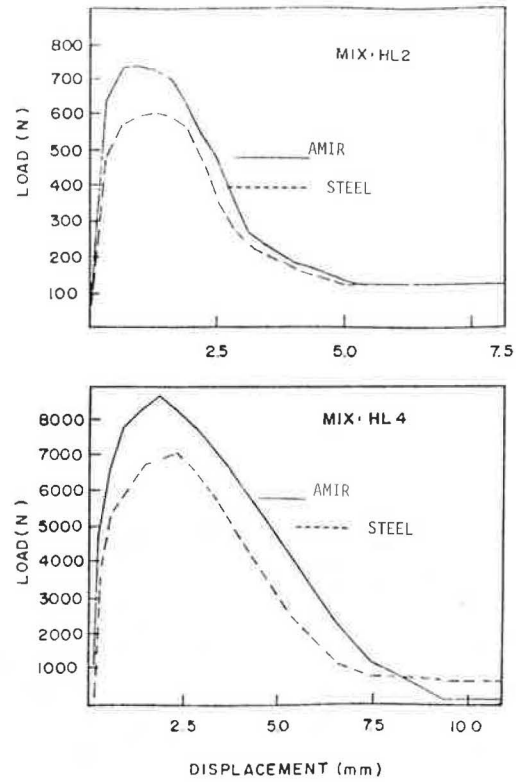

FIGURE 6 Test results of HL-2 and HL-4 mixes.

sample. Similar results were obtained when tests were performed on different mixes or compacted with the laboratory rollers, or both, as can be seen in Figure 6. The effect of the mix type is demonstrated by the maximum strength values obtained from the tests, as shown in Table 5.

In addition to these important results, observations of the tested samples indicated that the earlier-than-expected failure of new pavements can be explained by the presence of the construction cracks. Illustrated in Figure 7 is a side view of a steel-compacted test sample, which shows that secondary cracks originated from the top of the slab but did not extend through the entire depth of the specimen. This phenomenon was consistently repeated with the steel-compacted slabs regardless of the mix type or size of the specimen. On the other hand, this phenomenon was not observed in the case of the AMIR-compacted slabs, as can be seen in Figure 8. This can be explained as occurring as the result of crack propagation at hairline surface cracks, for example, in construction-induced cracks.

FIELD TRIALS

The first full-scale AMIR prototype was designed and built by the Egyptian Corps of Engineers under a cooperative research program with Ain Shams University and Carleton University. The project originated in the summer of 1985 and its first phase was completed by the end of 1986. The main objective of this first phase was to build a full-scale version of the AMIR compactor. It was decided at the beginning of the project to design the full-scale prototype to be as simple as possible and to concentrate on the quality of the compaction before dealing with mechanical aspects such as steering and uniform belt

FIGURE 7 Tested steel-compacted slab.

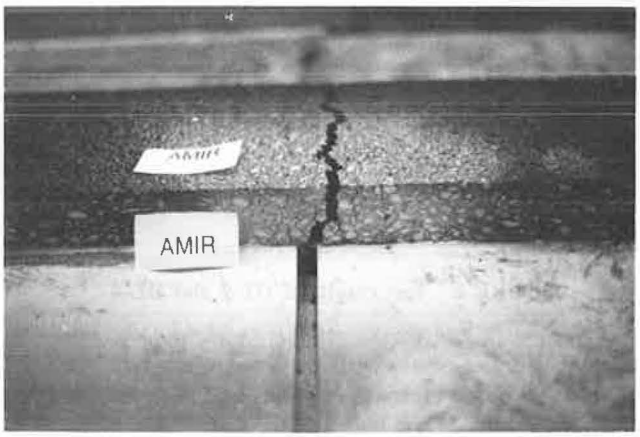

FIGURE 8 Tested AMIR-compacted slab.

loading. The finished version consisted of the following major components:

1. Two standard steel drums, each 2250 mm in diam and 1300 mm wide. The empty weight of each drum was 2250 kg.
2. A 19-mm thick multilayer rubber belt produced according to specifications defined by the involved parties.
3. Tension mechanism to apply the required tension on the rubber belt.
4. Additional smaller rollers placed between the two main drums to ensure that the rubber belt is in constant contact with the compacted surface. See Figure 1 for a photograph of the AMIR full-scale prototype.

The AMIR prototype was operated in the field using a set of ropes, pulleys, and two trucks positioned at opposite ends of the compactor. The compactor was then employed to carry out the second phase of the project. The main objectives of this second phase were as follows:

1. To conduct a large-scale field trial to confirm that, as suggested by the principle of relative rigidity, only modular ratio and curvature would have any significant influence on the formation of the construction-induced cracks, and the temperature and type of asphalt mix used would not matter. Although this conclusion was confirmed in previous laboratory investigations (*11*), further testing is needed to verify these results.
2. To validate the analytical and experimental results of earlier research work. It has been shown both analytically and in the laboratory that the AMIR compaction method will prevent the construction cracks. Clearly, this conclusion needs to be substantiated under actual field conditions.
3. To evaluate the long-term performance of asphalt pavements compacted by the new roller and to compare it with the performance of similar sections compacted by the current methods.

With these objectives in mind, the second phase of the project started at the beginning of 1987 and was expected to be completed by the end of that year. In February 1987 two field trials were carried out; they are described in the following paragraphs.

Field Trial 1

In order to meet the first objective, a 150-mm layer of sand was compacted on top of a hard-rock access road. Two different types of steel rollers were used to compact a given section of the sandy layer. The first was a static steel roller, and the second was a steel wheel vibratory compactor. The results of using either compactor confirmed the conclusions stated in Objective 1 already mentioned. Shown in Figure 9 is a photograph of the surface of the compacted sand with the construction cracks readily visible. This photograph is more visual proof that the principle of relative rigidity applies to all materials. The theory can be applied to predict the formation of construction cracks in the sand by steel wheel rollers.

FIGURE 9 Construction cracks of steel-compacted sand.

When the AMIR compactor was employed on the same test section, the results were quite different. As shown in Figure 10, the finished surface of the compacted sand was clearly crack free. This result led to the conduct of the second field trial in which the AMIR compactor was used to compact a 30-m test section of open-graded asphalt overlay.

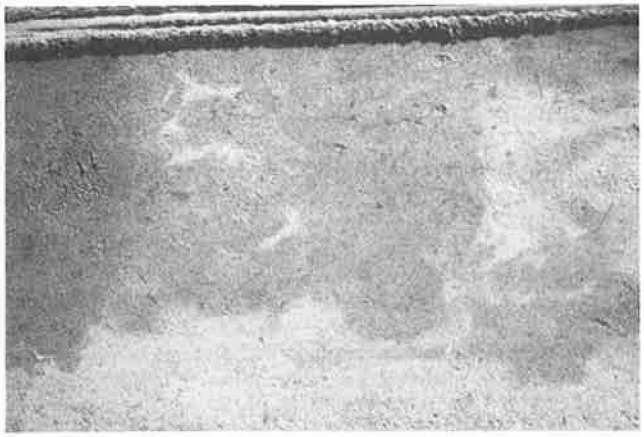

FIGURE 10 Crack-free surface of AMIR-compacted sand.

FIGURE 12 Surface cracks of steel-compacted asphalt (field trial in Egypt).

Field Trial 2

This field trial was conducted mainly to examine the potential of the new compaction method to provide a crack-free asphalt structure and to evaluate the operational functions of the new prototype. Preliminary results and observations reported from this test section are summarized as follows:

1. The AMIR compactor was successful in producing a 30-m asphalt pavement test section that was crack free, as can be seen in Figure 11. This observation can be appreciated when the surface given in Figure 11 is compared with the steel-compacted surface shown in Figure 12. It should be noted that the only difference shown between the two photographs is the compaction method used.
2. Use of the AMIR compactor resulted in better surface texture and a more even surface than current compaction methods.

In summary, these preliminary field trials confirmed the observations of previous studies. However, the long-term performance of the test sections will not be known before 1989.

FIGURE 11 Crack-free surface of AMIR-compacted asphalt (field trial in Egypt).

SUMMARY AND CONCLUSIONS

The major conclusions of this investigation may be summarized as follows:

1. The mechanical properties of asphalt pavements are significantly influenced by the compaction method used. It was shown that up to 65 percent higher tensile strength and 68 percent improvement in the calculated strain energy could be achieved using the new compaction method AMIR.
2. The current density criterion for accepting or rejecting field asphalt pavement projects is shown to be inadequate. The results of the testing program have shown that density alone is not a reliable criterion for asphalt evaluation. As has been shown in this paper, the tests were performed on asphalt specimens having the same densities, yet the measured mechanical properties were quite different.
3. It is important to note that although the tested asphalt samples have the same densities, the same geometry, the same mix type, and the same compaction effort, the final product of each compaction method is completely different. Clearly, the only logical explanation for this phenomenon is that the construction-induced cracks in the case of the steel compaction method resulted in reducing the effective thickness of the structure. As a result, the ability of the tested samples to resist the applied loads was significantly affected.
4. Clearly, the reduction in the strength of the compacted asphalt mixes using current methods will cause the pavements to fail earlier than anticipated. Also, the presence of the construction cracks plays a major role in speeding up the process of this unexpected deterioration. As was shown earlier by the tests, the energy required to propagate an existing crack is about 65 percent less than in the case of a crack-free structure. It is reasonable to assume that, based on these results, construction-induced cracks resulting in a significant loss of the tensile strength of new pavement are a major factor in its subsequent performance. These cracks provide ideal conditions for water seepage through the asphalt mix, which leads to stripping of the asphalt and perhaps softening of the foundations.

Freezing and thawing cycles compound the effect of traffic loads, and the result is how pavements behave today in cold areas. Can extended pavement life be attained by a different construction procedure? These laboratory results would tend to strongly suggest that this is so.

The results and conclusions presented in this paper can be used to explain why most of the current solutions for arresting or delaying crack propagation are so ineffective. As was shown in Figures 6 and 11, construction-induced cracks were propagating downward at the same time that the major crack was propagating in the opposite direction. Thus, any solution such as reinforcement or slip layers designed to stop the major crack from propagating upward is clearly insufficient to prevent surface deterioration. The construction-induced cracks will negate the effect of any solution that ignores their existence. Finally, it is noteworthy to indicate that the preliminary results of the full-scale field trials using the AMIR method supported the basic assumption of this investigation. As more data and information about long-term performance become available, the economic benefits of extending the service life of new asphalt overlays through the use of the new AMIR method could be realized.

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