# Effect of Field Compaction Method on Fatigue Life of Asphalt Pavements

ABD EL HALIM OMAR ABD EL HALIM AND RALPH HAAS

Field compaction of asphalt mixes has long been recognized as a major factor in the performance of the pavement. It has generally been concluded that the effect of compaction lies in the resulting density, air voids, and their variance, instead of in effects such as construction induced cracking or "checking." Indeed, the assumption has been that the effect of construction-induced cracks is more unsightly than physically detrimental to performance. This research demonstrated in numerous field trials that steel roller compaction is responsible for construction-induced cracks and that this is because of an incompatibility between the geometry of the roller and the mat and their relative rigidities. It has also demonstrated that a new type of flat plate compactor, the asphalt multi-integrated roller (AMIR), overcomes this problem and results in a smooth-textured mat, free of cracks. A series of fatigue tests were conducted on mixes from two Ottawa, Canada, field trials in which the major variables were steel roller versus AMIR compaction, direction of test loading, and type of mix. The results showed that AMIR compaction, for either type of mix, resulted in approximately double the fatigue life, all other factors being constant. Also, the direction of rolling in the field had negligible effect on the fatigue life of the AMIR compacted mixes but a very significant effect on the steel roller–compacted mixes in that the fatigue resistance to transverse cracking was much lower than the resistance to longitudinal cracking. The key conclusions are that construction-induced cracks as the result of the use of steel rollers can substantially reduce fatigue life, that direction of rolling in the field has a substantial effect, and that a new type of compactor, the AMIR, can overcome these problems.

Compaction of asphalt mixes during construction has been recognized by many experts as one of the most important factors affecting asphalt pavement performance. It has been suggested (*1*) that proper compaction of asphalt concrete is one of the most critical factors associated with performance, and indeed it has been stated, "Compaction has always been emphasized as perhaps the single most important factor for achieving satisfactory service life" (*2*, p. 28). The former chief engineer of the Asphalt Institute (*3*, p. 354) concluded that compaction is the most important construction operation in the ultimate performance of the finished pavement.

It has been shown (*4*) that better compaction can extend the service life of the pavement by up to a factor of seven. These observations are all based on the assumption that increasing density and reducing the percentage of air voids in asphalt mixes will have a positive effect on the performance of the pavement.

However, the mechanisms of this vital process are not fully understood. Any problems of compaction are usually assigned or related to mix properties. The importance of aggregate properties, asphalt cement properties, and mix properties on the ability to achieve the proper level of compaction has been emphasized (*5*). As a result, when problems are encountered during compaction, attempts are made to correct them by improving the asphalt mix. It has been stated

> Although certain types of pavement problems are likely to occur in the future, they will not be new problems but rather the same problems continuing to reoccur as they have over 70 years. These are types of compaction problems caused by our inability to predict mix behaviour during the compaction process, but they are not compactor problems. (2)

This statement reflects the school of thought that exists today in the pavement industry. Although it recognizes that the problems experienced today are the same ones observed 70 years ago, it fails to identify the main causes of the compaction problems.

Construction-induced cracks, known as checking, are generally ignored unless they are severe and unsightly. Pavement engineers and researchers usually attribute the causes of these cracks to properties of the asphalt mix, temperature during compaction, weak support, or poor operators. Attempts to assess their effects on the performance of asphalt pavements apparently have not been carried out, according to the literature. There is a strong belief in the industry that using pneumatic rubber rollers after the heavy steel compactors will seal the surface and cure any such construction-induced cracks. For example, it has been stated, "As for advantages and unsubstantiated claims, these comments taken from Geller are pertinent: Pneumatic tire rollers do have the advantages of being able to eliminate hairline cracks and checks, which are probably more unsightly than physically detrimental" (*5*). It is interesting to note that both observations reported in this statement were never verified. The assumption that construction cracks can be eliminated by pneumatic rollers is based on visual observations instead of on any systematic experimental evidence. More serious is the observation that the construction cracks are "probably" more unsightly than physically detrimental.

It has been shown (*6–8*) that widely used, conventional cylindrical rigid wheel rollers, although certainly capable of achieving the specified density, induce hairline cracks during compaction. The results of a concentrated research effort in the field of compaction of asphalt mixtures (*9–11*) have shown that currently used compaction equipment has a number of serious deficiencies. The cylindrical shape of the drum or wheel, coupled with the higher stiffness of its steel material, resulted in a mismatch in the order of relative rigidities of the compacting device (the roller) and the compacted structure (hot asphalt mixture). It has been shown analytically that this mismatch in the rigidities will cause the well-known phenomenon of construction-induced cracks or checking. The analytical results were verified in the laboratory by using small scale models of steel rollers (*8*). To prevent the occurrence of construction cracks and provide asphalt structure without flaws, the deficiencies of the existing drum-based

A. O. Abd El Halim, Department of Civil and Environmental Engineering Carleton University, 1125 Colonel By Drive, Ottawa, K1S 5B6, Ontario, Canada. R. Haas, Department of Civil Engineering, University of Waterloo, 200 University Ave., Waterloo, N2L 3G1, Ontario, Canada.

rollers have to be overcome. The geometry of the drum (i.e., cylindrical shape) has to be replaced with the geometry of a flat plate. In addition, the stiffer steel material must be separated from the immediate contact with the asphalt material during compaction. To meet both requirements, a new compactor called asphalt multi-integrated roller (AMIR) was designed. The AMIR compactor consists of at least two larger drums with a special thick rubber belt integrating both drums into one flat surface. Smaller rollers are added on top of the rubber belt between the two main drums to ensure that a more uniform pressure distribution is achieved at the belt/asphalt interface, as shown in Figure 1. Two large scale AMIR prototypes were built and used in large scale field trials in Egypt and Canada.

The main objectives are to show that (a) construction cracks are a result of compaction by current cylindrical steel wheel rollers, and (b) construction cracks are detrimental to long-term performance of asphalt pavements.

## FIELD INVESTIGATION OF CONSTRUCTION CRACKS

The roller-checking phenomenon is described as short transverse cracks 25 to 76 mm apart that occur in the asphalt concrete during compaction (*12*). These cracks do not extend completely through the depth of the asphalt mat but normally are between 6 to 10 mm deep. The causes of this phenomenon were explained as excessive deflection of the pavement structure under the compaction equipment and a deficiency in the asphalt concrete mix design (*12*).

Further, it was suggested that replacing a static steel wheel roller by a vibratory roller or pneumatic tire roller can minimize the problem until the mix design is altered. Regarding the suggested causes of cracks as excessive bending of the pavement layers, one should expect that cracks would also develop at the bottom of the compacted layer. It is not clear why replacing the static steel roller with a vibratory or pneumatic roller would minimize the problem, especially when in many cases the weight of either roller is higher than that of the static steel wheel roller.

The phenomenon of construction cracks can be better understood by considering the interaction between the roller and the asphalt mat during compaction. An analytical model, supported with laboratory simulation, has shown that the cracks are mainly a result of the geometry and material of the drum (*7–9*). It was also concluded that the type of asphalt mixture, strength of the structure under the asphalt layer, temperature of the mix, and experience of the operator of the roller play very little role in the occurrence of cracking. These parameters contribute to the severity of the phenomenon instead of to its initiation.

To verify the analytical results and conclusions presented, 10 field trials were carried out in the Toronto and Ottawa, Canada, areas. The AMIR compactor was used side by side with presently used rollers (static steel roller, vibratory and rubber tired rollers) to compact a number of the Ministry of Transportation of Ontario standard hot asphalt mixes and special large aggregate asphalt mixes. The results of these field trials have been reported before (*10–14*). Only the main findings of these field trials are summarized as follows:

- The use of a static or vibratory steel wheel roller induced surface cracks over the entire area of compaction. In some cases the cracks were up to 4.0 mm wide.
- The AMIR compactor provided a crack-free surface with a smooth texture.
- The influence of temperature, type of mix, effect of paver, roller operator, and strength of subgrade on the initiation of surface cracks during compaction is questionable because none was observed on the AMIR-compacted sections.
- Surface cracking and crushed aggregate were observed when the large aggregate asphalt mixture was compacted with the steel wheel roller. The AMIR compactor provided a finished surface without cracking or crushing.
- The use of the pneumatic roller failed to eliminate any of the cracks left by the vibratory roller. In some cases the pneumatic roller made more than 14 passes on the same spot without any noticeable change in the condition of the cracks.

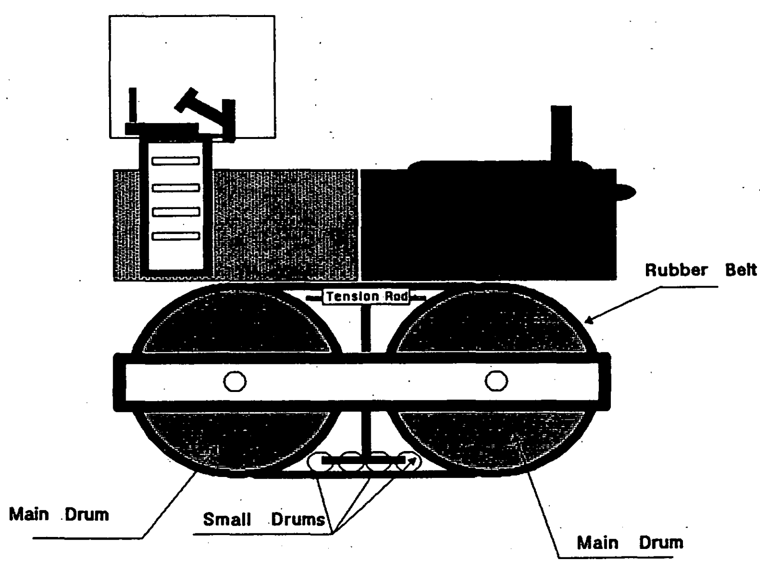


**FIGURE 1 Sketch of AMIR compactor.**

These results and observations were consistently repeated throughout the 10 field trials carried out from 1989 to 1991.

## EFFECTS OF CONSTRUCTION-INDUCED CRACKS

Although the presence of the construction cracks has been recognized for many decades, the influence of these cracks on the mechanical properties and the long-term performance of asphalt pavements has received limited attention. Statements such as the one previously noted, "hairline cracks are probably more unsightly than physically detrimental," may have led pavement researchers and engineers to neglect the effects of these cracks. However, premature deterioration of newly constructed asphalt pavements is a serious problem facing the industry. For example, there are extreme cases of stripping of asphalt mixes in the field occurring within weeks after construction. Also, reflection cracking has been noted on the surfaces of new asphalt overlays 1 to 2 years after the pavement is constructed. These observations suggest that there is a relationship between the observed deterioration and the condition of the pavement after construction. Because most finished pavements are expected to meet the current compaction specifications, one can assume that density should not be the major cause leading to the reported early deterioration. Also, the reported cases of early deterioration include different types of pavement structures, asphalt mixes, a wide range of climatic conditions, and traffic loadings. The only common parameter appears to be the rollers used. Therefore, the next phase of the research reported here was to quantify the effect of construction cracks on the performance of the asphalt pavements.

## OUTLINE OF EXPERIMENTAL INVESTIGATION

The observations and data collected from the field trials confirmed that current compaction equipment is the main cause of the construction-induced cracks. Furthermore, it proved that the new AMIR compactor will prevent those cracks. Subsequently, it was essential to investigate the effect of the construction cracks on the mechanical properties of the compacted asphalt pavement. To achieve this objective, a comprehensive experimental program (*10–15*) was planned and carried out as follows:

1. Asphalt cores, slabs, and beams were recovered from the field trials. All samples were marked with a line indicating the direction of compaction in the field.
2. Density and air voids measurements were performed on core samples. Air voids tests were not performed on asphalt cores used in the fatigue tests.
3. Recovered specimens were tested to determine indirect and direct tensile strengths, flexural strengths, and stripping and fatigue resistance.
4. All laboratory testing was performed on the recovered samples with the loads applied along the direction of rolling or perpendicular to it.

The following is a brief description of the field trials that were used to recover 162 asphalt cores specifically for the fatigue testing program.

### Ottawa Field Trial (August 1989)

The first field test carried out in Ottawa was performed on an existing paved service road on the campus of the National Research Council. The test strip consisted of two 150-m-long by 3.0-m-wide sections. An HL-4 hot asphalt mix (*15*) was placed on top of the existing pavement. One 150-m section was compacted using the AMIR prototype, and the other 150-m section was compacted using a vibratory roller followed by a pneumatic multiwheel roller.

### Ottawa Field Trial (May 1991)

The last field test was completed in May 1991. The test section included the use of HL-3 asphalt mix (*15*) to overlay an existing 60-m × 3.0-m asphalt strip. The 3.0-m lane was laid by the paver, and one-half was compacted using the AMIR roller while the other half was compacted using vibratory and pneumatic rollers.

The two field trials were carried out by two different paving contractors from the Ottawa region. The static weight of the vibratory steel roller was 12,000 kg; that of the pneumatic roller was 14,000 kg. The AMIR roller does not have any vibratory abilities; its weight during the field trials was 8,200 kg. The site of the first Ottawa field trial (August 1989) was closed to traffic for two consecutive winters. The closing of this test section was to prevent damage to the asphalt test sections due to traffic loads. Thus, only the effect of the cold temperatures of the winter on the compacted pavements can be evaluated.

### Indirect Tensile Fatigue Tests

The fatigue resistance of asphalt mixes is a key tool in predicting the long-term performance of the constructed asphalt pavement. Tests are performed on asphalt cores subject to cyclic stress or strain until failure. The testing program adopted in this study used a stress-controlled indirect tensile fatigue testing method similar to the one developed at the University of Texas at Austin (*16*). Different stress levels were used at room temperature. For each stress level, 12 asphalt core specimens (95 mm in diameter), six from the AMIR-compacted section and the other six from the vibratory and pneumatic rollers compacted section, were tested.

### Effect of Direction of Rolling

Generally, compaction in the field is carried out along the longitudinal axis of the paved lanes. As a result, interlock and bond between the aggregates and the asphalt cement of the compacted mix will be higher in the longitudinal direction (parallel to the direction of rolling). Subsequently, one would expect that a crack-free finished asphalt mat should have higher tensile strength, or resistance, to transverse cracks than to cracking in the longitudinal direction.

Clearly, current rollers have a relatively smaller area of contact with the asphalt mat during compaction. This feature is due to the cylindrical shape of the compacting wheel or drum, which is known to result in an area not larger than 100 mm by the width of the drums. This small area of contact ensures that, given that the finished pavement is crack-free, the tensile resistance to transverse cracking must always be higher than the tensile resistance to longitudinal cracking. Therefore, if two asphalt cores taken from the field

were loaded, one to measure the tensile resistance to transverse cracking and the other to measure the tensile resistance to longitudinal cracking, the number of load cycles to failure should be higher for the first core.

Accordingly, asphalt cores (representing each compaction method) were subdivided into two groups. One group was loaded to determine the fatigue tensile resistance to transverse cracking (referred to as the transverse resistance or strength). Thus, the test load was applied perpendicular to the rolling direction. The second group was loaded parallel to the direction of rolling to determine the fatigue tensile resistance to longitudinal cracking (referred to as the longitudinal resistance or strength).

### Effect of Cold Temperature

The effect of the cold temperature on the phenomenon of construction cracks was evaluated for the HL-4 field trial. Asphalt core specimens were recovered from the test sections 3 weeks after construction (September 1989). Each core was marked (compaction method, location in the field, and direction of rolling) and kept in a plastic bag at room temperature until the date of testing (July 1990). These asphalt cores are referred to as "HL-4 Summer." As mentioned, the test site was closed to traffic for two consecutive winters. One winter after construction, additional asphalt core specimens were taken from the same test sections (May 1990) and kept in plastic bags at the laboratory until the date of testing (July 1990). These cores are referred to as "HL-4 Winter."

### Reference Specimens

Because of the time required to perform fatigue tests, all asphalt core specimens from the HL-3 test sections were recovered in June 1991. Part of these core specimens, termed HL-3 (a), were tested in July 1991 and the remainder of the core specimens, termed HL-3 (b), were tested a year later. Clearly, the test results of the HL-3 (a) served to ensure that the time between recovering of the cores of the HL-3 (b) and their actual testing plays no significant role in the results of both tests.

## TEST RESULTS AND ANALYSIS

The details of the test data and results are given in Tables 1 to 8 and Figures 2 to 4.

### Effect of Compaction Method

The test results showed that the fatigue life of AMIR-compacted asphalt sections was consistently higher than that of the same asphalt mix when compacted with current equipment. This result was reported for both asphalt mixes, all stress levels, for both transverse and longitudinal resistances, and for the summer and winter asphalt cores.

Results of statistical significance analysis performed on the mean values given in Tables 1, 2, 3, and 5 show the following:

**TABLE 1 Results of Indirect Tensile Strength Fatigue Test for HL-4 Summer Cores**

| Stress (KPa) | AMIR | | | Vibratory and Pneumatic | | |
|---|---|---|---|---|---|---|
| | 200 | 270 | 400 | 200 | 270 | 400 |
| *Longitudinal Fatigue Resistance:* | | | | | | |
| Number of Load Repetitions | 29435<br>23461<br>31872 | 11215<br>16545<br>20127 | 2501<br>5493<br>2380 | 17435<br>18478<br>15186 | 8715<br>6148<br>8358 | 1060<br>1980<br>1704 |
| **Mean** | **28256** | **15962** | **3458** | **17033** | **7740** | **1581** |
| *Transverse Fatigue Resistance:* | | | | | | |
| Number of Load Repetitions | 29429<br>40285<br>50545 | 21361<br>36158<br>21351 | 3702<br>4389<br>4675 | 15995<br>3156<br>10376 | 918<br>5535<br>1279 | 485<br>419<br>361 |
| **Mean** | **40086** | **26290** | **4255** | **9842** | **2578** | **422** |
| *Average Fatigue Resistance:* | | | | | | |
| Mean | 34154 | 21126 | 3857 | 13437 | 5159 | 1002 |
| St. Dv. | 9709 | 8322 | 1239 | 5763 | 3377 | 703 |
| C.O.V. | 28.4% | 39.4% | 32.0% | 43.0% | 65.0% | 70.0% |

**TABLE 2 Results of Indirect Tensile Strength Fatigue Test for HL-4 Winter Cores**

| Stress (KPa) | AMIR | | | Vibratory and Pneumatic | | |
|---|---|---|---|---|---|---|
| | 200 | 270 | 400 | 200 | 270 | 400 |
| *Longitudinal Fatigue Resistance:* | | | | | | |
| Number of Load Repetitions | 36780<br>36829<br>37502 | 18359<br>11566<br>11111 | 2310<br>1546<br>2176 | 22031<br>12752<br>18082 | 7411<br>10198<br>5237 | 1502<br>1323<br>1105 |
| **Mean** | **37037** | **13679** | **2010** | **17622** | **7615** | **1310** |
| *Transverse Fatigue Resistance:* | | | | | | |
| Number of Load Repetitions | 31264<br>31654<br>25125 | 13265<br>13458<br>10277 | 2463<br>2988<br>2910 | 24416<br>11442<br>15632 | 5388<br>2507<br>5850 | 1948<br>1817<br>1515 |
| **Mean** | **29348** | **12333** | **2787** | **17163** | **4582** | **1760** |
| *Average Fatigue Resistance:* | | | | | | |
| Mean | 33192 | 13006 | 2399 | 17392 | 6099 | 1535 |
| St. Dv. | 4813 | 2900 | 529 | 5126 | 2559 | 310 |
| C.O.V. | 14.5% | 22.3% | 22.1% | 29.5% | 42.0% | 20.0% |

**TABLE 3 Results of Indirect Tensile Strength Fatigue Test for HL-3 (a)**

| Stress (KPa) | AMIR | | | Vibratory/Pneumatic | | |
|---|---|---|---|---|---|---|
| | 200 | 400 | 600 | 200 | 400 | 600 |
| Number of Load Repetitions | 3990<br>3503<br>2457<br>2035<br>2983<br>3237 | 410<br>491<br>416<br>429<br>411<br>445 | 192<br>173<br>159<br>142<br>165<br>211 | 2862<br>2160<br>2729<br>1080<br>1099<br>1158 | 398<br>192<br>332<br>282<br>282<br>258 | 91<br>72<br>106<br>95<br>127<br>180 |
| **Mean** | **3034** | **434** | **174** | **1848** | **291** | **112** |
| **St. Dev.** | **708** | **31** | **25** | **840** | **70** | **38** |
| **C.O.V.** | **23%** | **7%** | **14%** | **45%** | **24%** | **34%** |

**TABLE 4 Results of Effect of Direction of Rolling on Indirect Tensile Strength Fatigue Test for HL-3 (a)**

| | AMIR | | Vibratory/Pneumatic | |
|---|---|---|---|---|
| | Transverse | Longitudinal | Transverse | Longitudinal |
| Number of Load Repetitions (Stress: 400 KPa) | 498<br>525<br>349 | 416<br>534<br>335 | 109<br>333<br>281 | 291<br>344<br>255 |
| **Mean** | **457** | **428** | **241** | **297** |
| **Ratio** | **107%** | | **81%** | |

**TABLE 5 Results of Indirect Tensile Strength Fatigue Test for HL-3 (b)**

| Stress (KPa) | AMIR 70 | AMIR 200 | AMIR 270 | AMIR 400 | Vibratory and Pneumatic 70 | Vibratory and Pneumatic 200 | Vibratory and Pneumatic 270 | Vibratory and Pneumatic 400 |
|---|---|---|---|---|---|---|---|---|
| *Longitudinal Fatigue Resistance:* | | | | | | | | |
| Number of Load Repetitions | 36452<br>31715<br>35398 | 4358<br>3777<br>3120 | 2496<br>1754<br>1866 | 715<br>978<br>1151 | 29961<br>22615<br>21745 | 4111<br>2917<br>1756 | 1711<br>1299<br>1479 | 595<br>689<br>499 |
| Mean | 34521 | 3752 | 2039 | 948 | 24774 | 2928 | 1496 | 594 |
| *Transverse Fatigue Resistance:* | | | | | | | | |
| Number of Load Repetitions | 48600<br>47306<br>32262 | 3053<br>5293<br>4884 | 1307<br>2064<br>2010 | 1080<br>807<br>1349 | 18623<br>10141<br>18150 | 1835<br>1629<br>1268 | 1307<br>931<br>1150 | 227<br>583<br>352 |
| Mean | 42723 | 4410 | 1794 | 1079 | 15638 | 1577 | 1129 | 387 |
| *Average Fatigue Resistance:* | | | | | | | | |
| Mean | 38622 | 4081 | 1916 | 1013 | 20206 | 2253 | 1313 | 491 |
| St.Dev. | 7460 | 923 | 392 | 231 | 6502 | 1065 | 268 | 172 |
| C.O.V. | 19.3% | 22.6% | 20.5% | 22.8% | 32.2% | 47.0% | 20.4% | 35.0% |

**TABLE 6 Effect of Compaction on Fatigue Test Results ($N_{fA}/N_{fC}$)**

| Mix Type | Stress Level (KPa) 70 | 200 | 270 | 400 | 600 | Mean |
|---|---|---|---|---|---|---|
| HL-4 Summer | | | | | | |
| Longitudinal | N/A | 1.7 | 2.1 | 2.2 | N/A | 2.0 |
| Transverse | N/A | 4.1 | 10.2 | 10.1 | N/A | 8.1 |
| Average | N/A | 2.8 | 4.1 | 3.9 | N/A | 3.6 |
| HL-4 Winter | | | | | | |
| Longitudinal | N/A | 2.1 | 1.8 | 1.5 | N/A | 1.8 |
| Transverse | N/A | 1.7 | 2.8 | 1.6 | N/A | 2.0 |
| Average | N/A | 1.9 | 2.1 | 1.6 | N/A | 1.9 |
| HL-3 (a) | | | | | | |
| Average | N/A | 1.6 | N/A | 1.5 | 1.6 | 1.5 |
| HL-3 (b) | | | | | | |
| Longitudinal | 1.4 | 1.3 | 1.4 | 1.6 | N/A | 1.4 |
| Transverse | 2.7 | 2.8 | 1.6 | 2.8 | N/A | 2.5 |
| Average | 1.9 | 1.8 | 1.5 | 2.1 | N/A | 1.8 |

$N_{fA}$ = Fatigue life of AMIR compacted core samples,

$N_{fC}$ = Fatigue life of core samples compacted using conventional rollers, and

N/A = Not Applicable

**TABLE 7 Effect of Direction of Rolling on Fatigue Test Results (No. for Longitudinal/No. for Transverse)**

| Mix Type | Compaction | Stress Level (KPa) 70 | 200 | 270 | 400 | Mean |
|---|---|---|---|---|---|---|
| HL-4 Sum. | AMIR<br>Vibratory | N/A<br>N/A | 0.70<br>1.73 | 0.61<br>3.00 | 0.81<br>3.75 | 0.71<br>2.83 |
| HL-4 Winter | AMIR<br>Vibratory | N/A<br>N/A | 1.26<br>1.03 | 1.11<br>1.66 | 0.72<br>0.74 | 1.03<br>1.14 |
| HL-3 (b) | AMIR<br>Vibratory | 0.81<br>1.58 | 0.85<br>1.86 | 1.14<br>1.33 | 0.88<br>1.53 | 0.92<br>1.58 |

**TABLE 8 Effect of One Winter on Fatigue Test Results (No. for Summer/No. for Winter)**

| Compaction Method | Stress Level (KPa) 200 | 270 | 400 | Mean |
|---|---|---|---|---|
| AMIR | | | | |
| Parallel | 0.76 | 1.17 | 1.72 | 1.22 |
| Perpendicular | 1.37 | 1.62 | 1.61 | 1.53 |
| Overall | 0.97 | 1.62 | 1.61 | 1.40 |
| Vibratory | | | | |
| Parallel | 0.97 | 1.02 | 1.21 | 1.07 |
| Perpendicular | 0.57 | 0.56 | 0.24 | 0.46 |
| Overall | 0.77 | 0.85 | 0.65 | 0.77 |

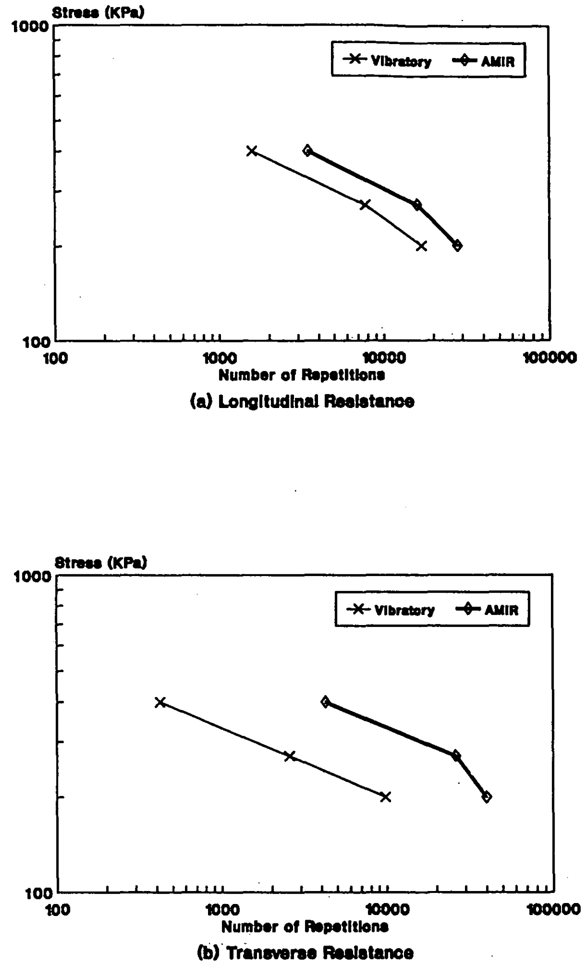


FIGURE 2 Fatigue test results (HL-4 summer cores).

- Fatigue test results of AMIR-compacted sections were significantly different (at $\alpha = 0.05$) from those of the same asphalt mixes compacted with the vibratory steel and pneumatic rollers.
- The coefficients of variation (COVs) of the AMIR-compacted samples are consistently lower than those calculated for the other compaction methods. As can be seen in Tables 1, 2, 3, and 5, the COVs of the AMIR test sections ranged from 7 to 39.4 percent. On the other hand, the COVs of the other sections ranged from 20 to 70 percent.

These results explain the often higher values of variation previously reported with fatigue tests performed on field asphalt specimens (*16*). There is a portion of the calculated variation that is due to the effect of the construction-induced cracks. This variation can be reduced by adopting the direction of rolling as a reference for applying the test loads.

- For both compaction methods, the HL-4 asphalt mix resulted in higher fatigue resistances than the relatively finer HL-3 asphalt mix.
- The results provided in Table 6 show that the fatigue resistance of the asphalt has been improved by a factor ranging from 1.4 to 8.1 because of the elimination of construction cracks.

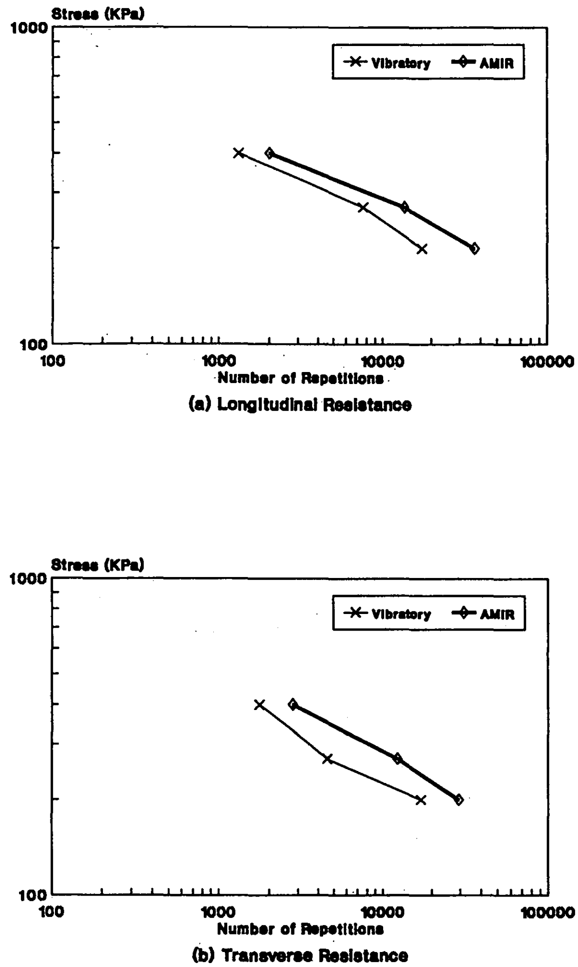


**FIGURE 3 Fatigue test results (HL-4 winter cores).**

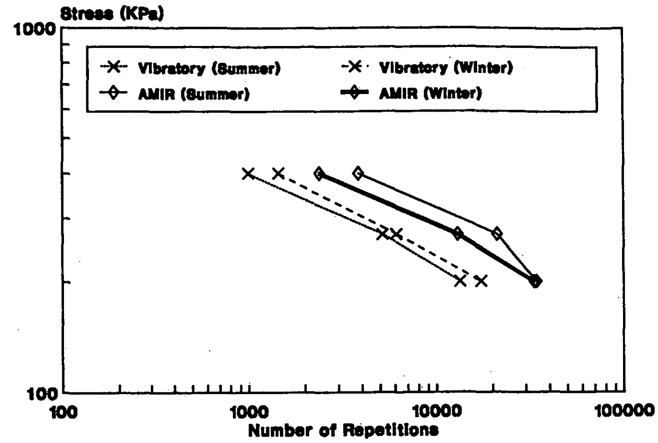


**FIGURE 4 Fatigue test results (HL-4 average resistance).**

## Effect of Construction Cracks

As explained earlier, the transverse strength of a crack-free asphalt mat must be higher than its longitudinal strength. The results of this testing program confirmed the field observations and conclusions reported earlier (*8,11,17*). Table 7 shows the following:

- The transverse tensile strength of the AMIR-compacted test sections followed the criterion of transverse and longitudinal resistances to cracking explained earlier. Note that only the AMIR winter samples, at a stress level of 200 KPa, violated this criterion. Obviously, the cold temperatures of the winter caused some weakening in the transverse direction, resulting in the reported result.
- In contrast to the results of the crack-free AMIR test sections, all the test results (with the exception of two stress levels for the winter cores) showed consistent violation of the criterion that states that transverse tensile strength must be higher than the longitudinal strength, especially when the asphalt mats were compacted with a drum.
- The mean values given in Table 7 clearly demonstrate the effect of the construction-induced cracks on the fatigue performance of the asphalt pavement. It showed that the construction cracks reversed the order of the fatigue resistance by a factor as high as 3.75.

These test results explain why transverse cracks are the main crack pattern observed on most asphalt surfaces across the world. Furthermore, these test results explain the phenomenon of the occurrence of transverse cracks year after year until the spacing between these cracks becomes much smaller than the uncracked width of the paved lane or lanes. The test results showed a ratio of almost 4 to 1 in favor of the longitudinal resistance. This can be interpreted as follows: (a) The transverse cracks may appear much earlier than the longitudinal cracks, or (b) the spacing between successive transverse cracks has to reach a ratio equal to one-fourth the width of the paved lane before longitudinal cracks start to appear.

## Effect of Cold Temperature of One Winter

The effect of subjecting the HL-4 field test to the cold winter of Ottawa (–30°C) showed the most interesting results. Figure 4 and Tables 6, 7, and 8 show the following:

- For each stress level, the fatigue resistance of the AMIR-compacted section was at least 50 percent higher than the fatigue resistance of the section compacted with current rollers. The mean values in Table 6 show an increase of 80 to 200 percent.
- For the AMIR-compacted section, except for stress level of 200 KPa for the longitudinal strength, the fatigue test results showed that the cold temperature of one winter can result in a loss of up to 72 percent of the fatigue resistance and mean values of 22 to 53 percent, as shown in Table 8.
- In contrast to those test results, the construction-induced cracks in the other test section appear to have gained more fatigue tensile strength, in comparison to its summer test results, under the same cold climate conditions. This is illustrated by the relative values given in Table 8. However, these results are not surprising because they can be explained by the following mechanism:
  - At the time of coring the winter core samples, a number of large transverse cracks were observed across the test section that was compacted using the vibratory and pneumatic rollers (*11,17*).
  - Clearly, when these large transverse cracks occur, the entire length of the asphalt mat between each two of these cracks will shrink as the result of cold temperatures.

–The shrinkage of the asphalt mat will then induce thermal compressive stresses, forcing the construction cracks to close during the winter season (cold welding), and as a result, the major cracks will exhibit crack widths wider than expected.

As a result of this mechanism, the construction-cracked core samples temporarily gained additional tensile strength, as shown in Table 8. However, this cycle is reversed in the summer, and as a result the major cracks close (not completely) while new transverse cracks appear in place of the cracks induced during compaction. Also, the adverse effect of traffic loadings in the winter may prevent the construction cracks from experiencing the benefit of this cold welding process due to bending and stress concentration at the edges of these cracks.

## CONCLUSIONS

The results of the fatigue tests support the following conclusions:

- Construction-induced cracks due to the use of steel rollers can reduce the service life of the pavement by a factor of 50 percent or more. This loss is not due to service loads or climatic conditions.
- The effect of construction cracks on the pattern of cracking that results during the life of the pavement is very significant. Fatigue lives of the steel-compacted test sections are significantly affected by the direction of the roller in the field. It was clear from the test results that these test sections are more susceptible to transverse cracking than to longitudinal cracking.
- The prevention of the construction cracks, as demonstrated by the test results of the AMIR-compacted sections, improved the fatigue performance of both types of asphalt mixes without any additional costs.
- The results of the AMIR and the conventional compaction methods provide an explanation for the often reported observations of failed pavements much earlier than expected.

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