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EFFECT OF COMPACTION METHODS ON THE IN-SITU PROPERTIES OF ASPHALT CONCRETE

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ABSTRACT

This paper describes the result of a comparative study that was conducted to evaluate the representability of different laboratory compaction methods to actual field compaction based on samples cored from the field. The compaction methods evaluated in this study were: i) Gyratory Shear Compaction (1.25 degree angle of gyration), ii) Gyratory Shear Compaction (6 degree angle of gyration), iii) Marshall Manual Impact Compaction, iv) Marshall Automatic Impact Compaction and v) California Kneading Compaction. The samples for this study were selected from four projects located at different locations in the Eastern Province of Saudi Arabia. The comparison of laboratory and field compaction was based on samples cored from the field following compaction without traffic densification and after four years of traffic densification. The ability of five compaction methods to simulate field compaction was evaluated by assessing the engineering properties, such as resilient modulus, air voids, indirect tensile strength, bulk density and static creep of the asphalt samples prepared in the laboratory and the core samples obtained from the field. Cores taken after traffic densification of 3 to 4 years were tested for resilient modulus and indirect tensile strength using Lottman method. The test results indicate the change in mix stiffness and the effect/damage of water with age based on the laboratory compaction methods. Overall the gyratory shear compactors demonstrated the ability to produce mixtures with engineering properties nearest to those determined from the field cores.

Keywords: *Asphalt Mix, Compaction Methods, Pavement, Engineering Properties, In-situ and Field Cores*

الملخص

تستعرض هذه الورقة دراسة مقارنة لتقييم مدى محاكاة طرق الدك المخبرية للدك في الحقل. حيث تم تقييم طرق الدك التالية: أ) دك القطع الدوار بزاوية ميل 1.25 درجة، ب) دك القطع الدوار بزاوية ميل 6 درجات، ج) طريق دك مارشال اليدوية، د) طرقة دك مارشال الآلية، هـ) طريقة عجن كاليفورنيا للدك. وقد تم تجميع عينات حقلية من أربعة مشاريع في مناطق مختلفة من المنطقة الشرقية من السعودية، وقد تمت عملية المقارنة لطرق الدك المخبرية مع الدك الحقلي من خلال عينات حقلية أخذت مباشرة بعد انتهاء الرصف وأخرى بعد أربع

سنوات من استخدام المقاطع .وتم اعتماد المقرنة من خلال الخصائص الهندسية مل معامل المرونة وحجم الفراغات، وقوة الشد غير المباشرة، والكثافة العامة، ومقدار التحطط الثابت .في حين تم اختبار العينات الحقلية لإيجاد معامل المرونة ومقدار الشد غير المباشر .وقد أظهرت النتائج أن الدك بطريقة القطع الدوار أظهرت المقدرة على إنتاج خلطات لها مواصفات هندسية أقرب ما يكون للعينات الحقلية.

1. INTRODUCTION

Asphalt concrete is major component of highway system in Saudi Arabia and worldwide. Saudi Arabia as well as other Arabian Gulf States have seen an unprecedented growth of urbanization and industrialization over the past three decades. Several highway systems linking the various parts of the country have been built to cope with the rapid development of the region. Over the last twenty-five years, the Kingdom of Saudi Arabia has invested more than 135 billion Saudi Riyals (36 billion US $) in road construction, to improve its highway network [Abdul Wahab et al., 1999]. This network includes more than 5000 kms of divided highway and more than 50,000 kms of paved roads [MOC, 1996]. Most of these roads have served for more than decades and number of them have started falling apart. Battered by harsh weather and increasing traffic loads many of the asphalt concrete pavements are wearing out much sooner than expected. The result is rough pavements, which endanger the safety of the user, high maintenance and rehabilitation expenses.

Compaction is a key step in the pavement construction process as the performance of pavement largely depends on quality of compaction. Compacting asphalt mixtures involves number of processes that can profoundly affect the life of the pavement. The quality of an asphalt pavement depends largely on the quality of the construction techniques used. An asphalt mix might be well designed and well produced, but if it is placed in the road in an improper way, the pavement performance will be poor. Therefore, next to mix design, construction and degree of compaction must be considered as the main quality parameters of a laid asphalt mixture. A well designed and well produced mixture performs better, and have better durability and mechanical properties when it is well compacted [Kumar and Goetz, 1974].

The difference in laboratory mix design methods and in-situ properties is not only the result of the evaluation procedure but is also the consequence of the compaction method employed in specimen fabrication. The goal of a mix design procedure is to combine aggregates and a binder in a proportion that is able to satisfy a desired level of performance. Realistic methods for evaluating the strength of bituminous mixtures are therefore quite important. There are several factors that affect the strength of bituminous mixtures; one of them is the method of forming a realistic test specimen in the laboratory that represents the structure of the paving mixture when placed in the field. Duplicating the composition of a field mixture in the laboratory presents some problems, but they are minor compared to producing in the laboratory a specimen that truly represents the mixture as it exists in the field [Goetz, 1989].

Top

2. OBJECTIVE AND SCOPE

From the earliest days of asphalt concrete construction, compaction has always been emphasized as perhaps the single most important factor for achieving satisfactory pavement service life. There are standards and procedures for designing asphalt mixtures and testing these designs in laboratory. There are standard procedures for testing the asphalt pavement after it has been compacted, to determine if its properties live up to the design expectation. However, there is little in the way of standard or data to measure the interrelationship between compaction, the mix behavior and existing environment in the field during the act of compaction. In recent years researchers have found that different compaction techniques produce asphalt concrete specimen with different particle orientations, different degree of resistance to permanent deformation and thus differing physical properties. When evaluating asphalt concrete mixtures in the laboratory, it is desirable to produce test specimens that duplicate, as nearly as possible, the compacted mixture as it exists (or will exist) in an actual pavement layer. Reproduction of the compacted mix in the laboratory and correlation of the compacted mix to the in-service properties of the material will provide useful data for improving mix design procedures.

The compaction methods used to simulate field construction conditions include direct compression, impact hammering, kneading action, gyratory shear, vibration, and simulated rolling. Standard mix design procedures are differentiated on their method of compaction, which are assumed to simulate field compaction. In the Marshall design method, specimens are prepared by impact compaction, while in the Hveem mix design method specimens are fabricated by kneading compaction. Recently, the Strategic Highway Research Program (SHRP) adopted the gyratory compaction method in Superpave mix design [NCAT, 1993].

The specific objective of this study was to compare and evaluate a variety of laboratory compaction methods that are widely used and/or resemble as closely as possible field compacted mixtures. A detailed comparative study was conducted to select the compaction technique best able to achieve material and engineering properties (such as air voids, resilient moduli, density, aggregate particle orientation and stiffness), which are similar to those of materials placed in the field using standard compaction practices. To identify the laboratory compaction method that creates an aggregate structure and other characteristics most similar to that obtained in field, specimens were prepared by compacting the field mix with the different compaction methods.

Asphalt mixtures sampled from the paver were compacted using the selected techniques. Field cores were extracted from a number of locations before the road was opened to traffic. The laboratory prepared specimens and the extracted field cores were evaluated using static creep, modulus of resilient, and Marshall stability. The particle orientation of both the laboratory and the field compacted specimens was analyzed. The laboratory compacted specimens were compared with the field cores to determine a compaction technique which is able to best reflect field compaction. Further, cores taken after traffic densification of 3 to 4 years were tested for Resilient Modulus and Indirect tensile strength with Lottman method to evaluate the change in mix stiffness and the effect/damage of water with age.

Top

3. RELATED RESEARCH

It is established that method of compaction asphaltic concrete mixtures in flexible pavements plays a major role in the performance of these pavements. Mix properties such as air voids, stiffness, aggregate structure etc. are highly dependent on the degree and the method of compaction. These properties, in turn, affect pavement performance indicators such as rutting and fatigue cracking. However, while evaluating asphalt concrete mixture in the laboratory, it is desirable to fabricate compacted specimens that have potential to mimic actual field compaction.

It is been long documented that different laboratory compaction methods can produce specimens with different degrees of resistance to permanent deformation and particle orientation. Several significant studies have been performed that focus on comparing the properties of mixtures compacted with different laboratory compaction devices. These studies include: [Van, 1986., Aunan et al., 1988., Quintus et al., 1988 and Sousa et al., 1990]. The consensus of these studies is that the response of a mixture to loading (mixture property) is affected by the laboratory compaction method used to prepare the specimens.

In a NCHRP study entitled “Asphalt-Aggregate Mixture Analysis System” by Quintus et al. [1988], the effects of five different laboratory compactors on the selected properties of compacted mixtures were investigated. Field cores and laboratory compacted samples were subjected to indirect tensile testing (strength, strain at failure, resilient modulus, and creep) and aggregate particle orientation was evaluated. On the basis of the pooled results of mechanical tests performed at three different temperatures, the authors reported the relative similarity between laboratory compaction technique and field compaction.

Sousa et al. [1990], under SHRP contract A-033A at the University of California at Berkeley, evaluated three compaction devices: Texas gyratory, kneading and rolling wheel. The purpose of the study was to determine the extent to which method of laboratory compaction affects fundamental mixture properties (permanent deformation and fatigue) related to pavement performance. The most important findings of the study were the following:

1. Samples prepared with Texas gyratory compactor are expected to be more sensitive to asphalt type (and binder content) than samples prepared by the kneading compactor.
2. Samples prepared using the kneading compaction device are more resistant to permanent deformation, primarily because of the development of a more complete inter particle contact “structure”, at least for densely graded aggregates: mixtures prepared under kneading compaction are more sensitive to aggregate angularity and surface texture.
3. Specimen prepared using the rolling wheel compactor were ranked between specimen prepared by kneading and gyratory methods in terms of their resistance to permanent deformation.

There are many factors affecting the degree of compaction of an asphaltic bound material. These include material temperature, thickness of the laid materials (lift thickness), binder content, and type and grading of the aggregates used in the asphaltic concrete mixture. [Scherocman and Acott. 1989] studied the effect of compaction in terms of a number of factors and rated these factors on the basis of the degree to which they contributed to the cause of each pavement distress: permanent deformation, fatigue cracking, low-temperature cracking, and moisture damage. It was concluded that several factors (environmental conditions, lift thickness, mix properties, type of compaction equipment, and roller operation) played a role in influencing the pavement performance indicators except in relation to low-temperature cracking.

In an another study [Consuergra et al., 1992] evaluated the ability of five compaction devices to simulate field compaction. The compaction devices evaluated were selected on the basis of their availability and on their uniqueness in mechanical manipulation of the mixture. The devices evaluated were (i) The Texas Gyratory Compactor, (ii) The California Kneading Compactor, (iii) The Marshall Impact Hammer, (iv) The Mobile Steel Wheel Simulator, and (v) The Arizona Vibratory Kneading Compactor. The results of their study showed that the Texas Gyratory Compactor was the best in terms of its ability to produce compacted mixtures with engineering properties similar to those produced in the field. The California Kneading Compactor was ranked second on the basis of its ability to replicate field conditions. Neither the Marshall Impact Hammer or the Arizona Vibratory Kneading Compactor were found to be very effective.

4 DESCRIPTION OF EXPERIMENTAL PROGRAM

In this study, the first step was to select four different sites from an area in the Eastern Province of Saudi Arabia. The site selection criterion was such, that the project must meet certain minimum standards ensuring that the variability of the following factors could be adequately controlled: compaction process, aggregate and gradation consistency, mixture placement temperature, consistency of mixing plant and air void. In this study the field core with and without traffic densification were compared to samples prepared by different laboratory compaction technique

4.1 Material Handling and Characterization

Asphalt cement with 60/70 penetration and locally available limestone aggregates were used in this study. A series of tests was conducted to evaluate the physical properties of the asphalt and the aggregate that are significant to an asphalt mix. Table 1 shows the physical properties of aggregates used in the four selected roads. Asphalt mixture samples were collected from the paver. The sampling of asphalt concrete mixtures for laboratory specimen preparation was performed to ensure random selection of trucks and to prevent segregation of mixtures. Properly sealed containers were used to transport mixtures and great care was taken to provide full mixture documentation regarding mix design and temperature history.

Top

4.2 Study Approach

Overall, 160 specimens were prepared by the different types of compaction methods from the asphalt mixes brought from all the four locations. In addition, eight field cores 102-mm (4-in) diameter were extracted from each location a day after compaction. Later, four cores 102-mm (4-in) diameter were also extracted after traffic densification of 3 to 4 years to evaluate the change in mix properties after traffic densification. The extent of the experimental program is summarized in Table 2.

4.3 Mix Design

The bituminous mixtures brought from the four different sites were designed by the standard Marshall Mix Design Method. For all the investigated mixtures, the aggregate type, quarry source, gradation, and nominal size were nearly identical. A summary of mix design properties for all the four projects is shown in Table 3. The mix from Road # 2 was a base course, while the mixes from the other roads were either wearing course or binder course. All the mixes had a different aggregate gradation and different optimum asphalt content.

Table 1. Physical Properties of aggregate

Physical Properties	**Road # 1**	**Road # 2**	**Road # 3**	**Road # 4**	**Specification**
Sand equivalent	67	62	64	59	Minimum 45
Loss angeles abrasion loss	28.6	27.5	19.9	24.9	Maximum 40
Sodium sulphate soundness	9.3	8.3	10.5	9.6	Maximum 20
Plasticity Index	N.P	N.P	N.P	N.P	Maximum 6
Clay Lump & Friable Particles	0.15	0.16	0.18	0.18	0.25
Flat and Elongated Particles	0.19	1.10	0.24	0.89	5

N.P: Non Plastic

Table 2. Experimental program

Compaction Method	**Number of specimens**			
	Road # 1	**Road # 2**	**Road # 3**	**Road # 4**
Marshall compaction (Automatic)	8	8	8	8
Marshall compaction (Manual)	8	8	8	8
California kneading compaction.	8	8	8	8
Gyratory shear compaction, 1.25^{0}	8	8	8	8
Gyratory shear compaction, 6^{0}	8	8	8	8
Field cores (One day after paving)	8	8	8	8
Field cores (After four years of traffic)	8	8	8	8

Top

Table 3. Summary of Mix Design Properties

Mix Properties	Road # 1	Road # 2	Road # 3	Road # 4
Optimum asphalt content (%)	5.23	5.12	4.96	4.7
Average bulk density gm/cm^2	2.309	2.35	2.337	2.374
Maximum theoretical sp. gravity	2.458	2.453	2.440	2.476
Percent air voids (%)	4.2	3.7	4.2	4.1
Voids filled (%)	71	76	73	-
Average stability (kg)	1258	1340	1456	1510
Average flow	3.05	3.3	3.04	3.14
Percent stability loss (%)	18.2	10.4	13.4	12.6

5. COMPACTION METHODS USED IN THIS STUDY

Historically, there have been three compaction methods that have been used in routine asphalt concrete mixture design: impact compaction, kneading compaction and the gyratory compaction. The mixes sampled from the various sites were kept in an oven at the same compaction temperature as that of the field, and each was compacted using one of the selected compaction methods. The compaction methods evaluated in this study were: i) Marshall Manual Impact Compaction, ii) Marshall Automatic Impact Compaction iii) California Kneading Compaction iv) Gyratory Shear Compaction (1.25 degree angle of gyration), and v) Gyratory Shear Compaction (6 degree angle of gyration).

Marshall Compaction, both automatic and manual, uses an impact hammer to achieve the desired level of compaction. All specimens for this study were prepared in accordance with the procedure presented in "Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus" (ASTM D1559-90) the test method. The compaction energy was controlled by the number of blows the specimen was subjected to in the compaction process. The sample mixes brought from all four sites were compacted using both an automatic and a manual Marshall hammer, with 75 blows per side applied to each sample. Eight specimens from each location were prepared for each type of compaction.

The California Kneading Compaction method was used in this study to simulate the kneading type of compaction which would allow inter-particle movement similar to that obtained under a rubber-tired roller. All specimens were compacted in accordance with the "Preparation of Test Specimens of Bituminous Mixtures by Means of the California Kneading Compactor" (ASTM D 3202-90) test method. In this type of compaction method, forces are applied to a portion of the free face of an otherwise confined asphalt concrete mix. Compaction forces are applied uniformly around the free face. The partial free face allows particles to move relative to each other. This creates a kneading action that densifies the mix. Further, 20 tamping blows were applied at 250 psi, followed by 150 tamping blows at 1,500 psi. Then, a 1,000 psi static leveling load was used to finish compacting the specimens. Overall, 32 specimens were prepared by this compaction method (eight for each location).

The major operational aspects of the gyratory compaction method have been thoroughly discussed in the literature [NCAT, 1993., Sousa et al., 1990 and ASTM D 4013-90]. The gyratory compaction method applies normal forces that are supplemented with a rocking or gyratory motion to work the mix into a denser configuration while it is totally confined. The gyratory compaction method has three variable parameters: vertical ram pressure, number of gyrations, and gyratory inclination angle. The gyratory compactor used in this study was modified to incorporate both the 1.25° and the 6° angles of gyration. Sample thicknesses were measured at different numbers of gyrations for specimens prepared at the 1.25° and the 6° angles angle of gyration. Compaction was stopped when the target value for the total air voids (5% based on the job mix formula) was obtained.

6. TEST METHODS AND RESULTS

Laboratory compacted specimens and field cores extracted were subjected to the following laboratory characterization tests:

- Marshall Stability and Volumetric Analysis
- Resilient Modulus Test
- Static Creep Test (Shell Method)
- Particle Orientation Analysis

Further, the cores extracted after 4 years of traffic densification were subjected to above characterization tests in addition to Lottman test to determine the additional moisture susceptibility of the mixes over four years of traffic densification.

6.1 Marshall Stability and Volumetric Tests

The bulk specific gravity was evaluated after samples had cooled to room temperature, according to ASTM D2726. Further, the maximum specific gravity test was assessed using the Rice Method on the sampled material from the four roads. Air voids were calculated using bulk specific gravity and maximum theoretical specific gravity data. Three of the eight specimens for each type of compaction and each location were tested for Marshall Stability as per ASTM D1559. Specimens were placed in a water bath at 60^{O}C for a period of 30 minutes and were tested for Marshall Stability and flow. A summary of air voids, bulk density, Marshall stability, and flow for all laboratory compacted specimens and field cores (just after paving and after 4 years of traffic) is provided in Table 4.

Table 4. Summary of mix characteristics for the laboratory compacted specimens and field cores.

Road No.	Compaction	Stability (kN)	Flow (mm)	Air Void (%)	Bulk Density (gm/cm^2)
1	Marshall (Auto)	20.1	4.61	4.31	2.352
	Marshall (Manual)	34.9	2.88	4.32	2.371
	Kneading	17.3	4.26	5.85	2.315
	Gyratory 1.25^o	31.0	3.27	5.10	2.321
	Gyratory 6^o	33.3	3.31	3.25	2.379
	Field cores after paving	30.1	2.91	5.04	2.335
	Field cores after 4 years	25.5	2.41	3.04	2.384
2	Marshall (Auto)	22.1	4.20	3.83	2.360
	Marshall (Manual)	35.3	3.12	3.05	2.379
	Kneading	18.4	4.89	5.50	2.319
	Gyratory 1.25^o	33.1	2.32	5.00	2.332
	Gyratory 6^o	36.2	2.69	2.97	2.381
	Field cores after paving	29.6	3.10	5.01	2.331
	Field cores after 4 years	23.4	2.83	2.83	2.384
3	Marshall (Auto)	19.5	3.98	4.51	2.331
	Marshall (Manual)	30.1	2.09	3.53	2.355
	Kneading	14.5	5.01	5.65	2.303
	Gyratory 1.25^o	29.1	3.12	4.90	2.320
	Gyratory 6^o	30.8	3.56	3.08	2.366
	Field cores after paving	24.3	2.65	4.75	2.325
	Field cores after 4 years	20.3	2.43	2.92	2.369
4	Marshall (Auto)	24.0	3.48	3.94	2.379
	Marshall (Manual)	37.2	2.85	3.34	2.394
	Kneading	19.5	4.77	6.28	2.321
	Gyratory 1.25^o	34.3	2.16	5.12	2.350
	Gyratory 6^o	37.1	2.58	2.81	2.407
	Field cores after paving	28.2	2.37	5.30	2.345
	Field cores after 4 years	22.6	2.0	2.71	2.409

Top

6.2 Resilient Modulus Test

Several types of moduli have been used to represent the stiffness of asphalt concrete mixtures. Three of these are dynamic, resilient, and complex. The Modulus of Resilience is most commonly used for the asphalt concrete mixture evaluation. Three of the remaining five samples compacted by the five different methods plus the field cores were tested for dry and soaked resilient modulus. The samples were first soaked at 60^{o}C for 24 hours in a water bath. This was followed by soaking them at 25 ^{o}C for two hours before testing them at 25^{o}C. This test was performed in accordance with ASTM D-4123. The retained modulus is used as a measure of compacted mix resistant to stripping. The resilient modulus is determined by using a repetitive load of one cycle per second (0.1 second load duration and 0.9 second rest period) after which measurement of the applied load and recoverable deformation is conducted. Table 5 summarizes the Modulus of Resilience and its quotient values both before and after moisture conditioning.

6.3 Creep Test

The creep test can be used in an integrated mixture evaluation to provide data for the following two purposes: to evaluate susceptibility to deformation and to determine stiffness at longer durations of loading [Van de Loo, 1978]. Some researchers have indicated that static and dynamic test measurements have provided similar stiffness trends. In this study, the creep test was performed according to the Shell procedure [Shell, 1978]. The creep test was performed at a temperature of 60^{o}C on two of the laboratory compacted specimens and on the field specimens. Although the creep test is normally conducted at 40^{o}C, a recent study [Abdul Wahab and Ramadhan, 1995] showed that the pavement temperature in the Saudi Arabia reaches 70 ^{o}C, so the test temperature was increased to compensate for the extreme temperatures of the Eastern Province of Saudi Arabia. The creep test as described in the Shell Pavement Design Manual was performed on specimens at a stress level of 0.1 MN/m^2 (14.5 psi) and was applied smoothly and quickly without impacting the specimens. The stress level was maintained for one hour then released, and the data recording continued for another hour. The measured vertical deformation at different loading times was accurately recorded on a computer through a data logger. The data logger was set to take readings of the vertical deformation at one minute intervals.

The creep test results are presented in the form of elastic strain, viscoelastic strain, and permanent strain in Table 6. Since the creep test is used primarily to determine the viscoelastic behavior of asphalt mixes, the vertical deformation was recorded during each test and was plotted with respect to time. A typical creep curve is shown in Figure 1 for a specimen compacted with the gyratory shear compactor (1.25° angle) from location 4. In Figure 1, the total strain of the sample was 13.09E-03, out of which 6.51E-03 is the elastic strain, 2.58E-03 constitutes the viscoelastic portion, and the permanent strain is 4.00E-03. Figure 2 represents permanent strain for laboratory and field compacted specimens graphically.

Top

6.4 Particle Orientation

The particle orientation of bituminous mixtures is not considered a fundamental engineering property. It is also a difficult parameter to define, especially if the mix has only a few flat, elongated particles. However, random orientation of the crushed rock particles has been discussed in the literature and can be very important. Thus, particle orientation was included in

Table 5. Summary of the modulus of resilience for the laboratory and field compacted specimens.

Road No.	Compaction	M_r Dry (ksi)	M_r Soaked (ksi)	Quotient M_r
1	Marshall (Auto)	661	500	0.756
	Marshall (Manual)	1376	1159	0.842
	Kneading	1277	933	0.731
	Gyratory 1.25^o	2092	1953	0.934
	Gyratory 6^o	1876	1660	0.885
	Field cores after paving	1920	1650	0.960
	Field cores after 4 years	1789	1306	0.730
2	Marshall (Auto)	812	701	0.863
	Marshall (Manual)	1180	995	0.843
	Kneading	1365	1180	0.864
	Gyratory 1.25^o	1680	1569	0.934
	Gyratory 6^o	1465	1292	0.882
	Field cores after paving	1710	1505	0.880
	Field cores after 4 years	1520	1186	0.780
3	Marshall (Auto)	592	504	0.851
	Marshall (Manual)	1052	895	0.851
	Kneading	1178	950	0.866
	Gyratory 1.25^o	1704	1565	0.918
	Gyratory 6^o	1339	1210	0.904
	Field cores after paving	1680	1522	0.906
	Field cores after 4 years	1435	1005	0.705
4	Marshall (Auto)	1027	880	0.857
	Marshall (Manual)	1302	1151	0.884
	Kneading	1694	1450	0.856
	Gyratory 1.25^o	1902	1775	0.933
	Gyratory 6^o	1494	1300	0.870
	Field cores after paving	1856	1702	0.917
	Field cores after 4 years	1508	1237	0.819

this study. First, the field cores were used to determine if there was preferred orientation or just random orientation in the field compacted mixtures. The next step was to compare the field samples to the laboratory compacted specimens. Three of the field and three of the laboratory compacted specimens for each type of compaction method were cut into two equal portions in the trial to define the orientation angle of each sample. After that, pictures were taken showing how the particles were oriented. Results indicated no general trend (i.e. random distribution). It was therefore concluded that this criterion could not be used to distinguish between the different compaction methods.

6.5 Lottman Test

Lottman Test designated as AASHTO T-283 "Resistance of Compacted bituminous mixture to moisture induced damage" requires the measurement of the change of diametral tensile strength resulting from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures. The cores taken after 4-years of traffic densification from each road section under study were cleaned and divided into two subsets consisting of three cores in each subset. One subset was tested dry at room temperature of 25^{o} C. The other subset was conditioned in water by applying 18 inch of Hg partial pressure for a period of ten minutes. The vacuum saturated specimens were placed in a 60^{o}C water bath for 24 hours. After 24 hours the specimens (field cores) were removed and placed in a water bath at 25^{o} C for a period of 2 hours. Then the indirect tensile strength of the dry and conditioned specimens at 25^{o} C was determined. Finally the numerical index of resistance of asphalt mix to the detrimental effect of water as the ratio of the original strength was calculated as shown in Table 7.

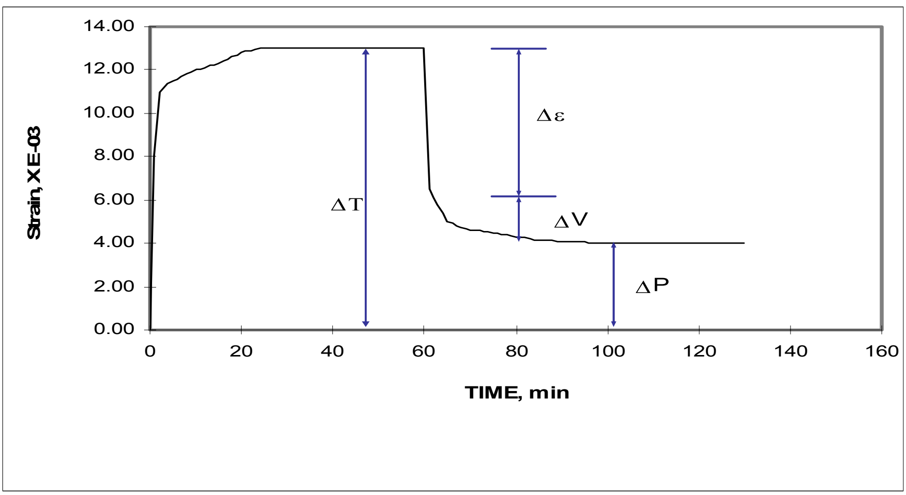

Figure1.Creep curve for specimens compacted with the gyratory shear compactor (1.25° angle) from location 4

Top

Table 6. Summary of the creep test results for the laboratory and field compacted specimens.

Road No	Compaction	Elastic Strain μm	Viscoelastic Strain μm	Permanent Strain μm	Total Strain μm
1	Marshall (Auto)	6.72E-03	2.98E-03	8.51E-03	1.82E-02
	Marshall (Manual)	8.68E-03	3.66E-03	8.17E-03	2.05E-02
	Kneading	9.36E-03	4.26E-03	6.72E-03	2.03E-02
	Gyratory 1.25°	1.03E-02	3.64E-03	4.91E-03	1.89E-02
	Gyratory 6°	4.67E-03	4.08E-03	3.03E-03	1.18E-02
	Field cores after paving	9.33E-03	2.42E-03	7.02E-02	1.87E-02
	Field cores after 4 years	3.81E-03	3.25E-03	2.53E-03	9.59E-03
2	Marshall (Auto)	1.13E-02	4.54E-03	1.01E-02	2.59E-02
	Marshall (Manual)	1.03E-02	3.15E-03	1.14E-02	2.48E-02
	Kneading	8.59E-03	3.15E-03	6.97E-03	1.87E-02
	Gyratory 1.25°	8.85E-03	3.37E-03	4.35E-03	1.65E-02
	Gyratory 6°	1.03E-02	3.35E-03	7.17E-03	2.08E-02
	Field cores after paving	8.41E-03	3.23E-03	5.43E-03	1.71E-02
	Field cores after 4 years	6.70E-03	3.78E-03	6.31E-03	1.68E-02
3	Marshall (Auto)	7.51E-03	4.36E-03	1.31E-02	2.50E-02
	Marshall (Manual)	9.45E-03	4.12E-03	9.93E-03	2.35E-02
	Kneading	5.97E-03	2.9E-03	7.87E-03	1.67E-02
	Gyratory 1.25°	8.06E-03	4.03E-03	4.29E-03	1.64E-02
	Gyratory 6°	8.60E-03	3.27E-03	8.57E-03	1.84E-02
	Field cores after paving	7.97E-03	5.91E-04	5.97E-03	1.78E-02
	Field cores after 4 years	7.52E-03	3.05E-03	8.23E-03	1.88E-02
4	Marshall (Auto)	9.60E-03	5.40E-03	6.13E-03	2.11E-02
	Marshall (Manual)	9.57E-03	6.27E-03	5.72E-03	2.16E-02
	Kneading	8.34E-03	3.66E-03	6.90E-03	1.89E-02
	Gyratory 1.25°	6.51E-03	2.58E-03	4.00E-03	1.31E-02
	Gyratory 6°	1.30E-02	2.73E-03	3.94E-03	1.97E-02
	Field cores after paving	1.32E-02	3.00E-03	4.76E-03	2.09E-02
	Field cores after 4 years	8.56E-03	3.25E-03	3.47E-03	1.53E-02

Top

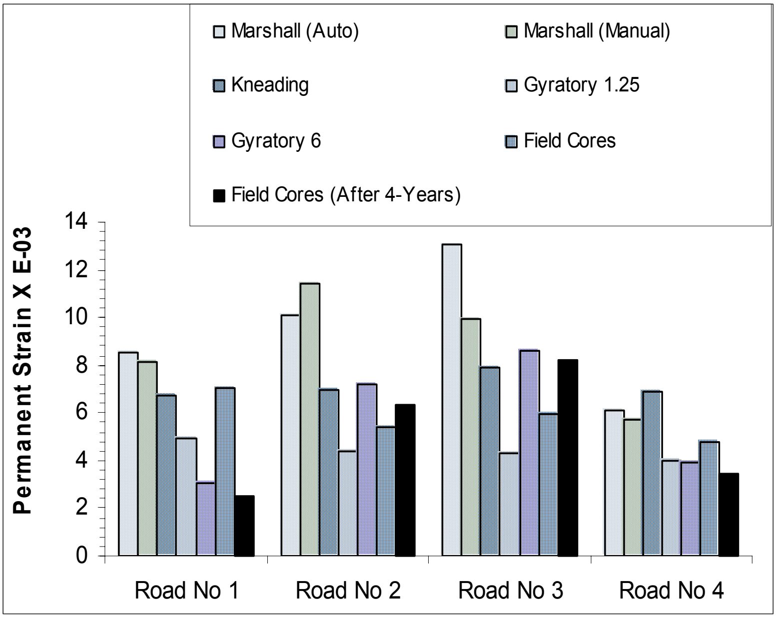

Figure 2 Permanent strain for laboratory and field compacted specimens.

Table 7. Lottman test results on field cores taken after 4 years of traffic compaction.

Road No.	**Average Initial ITS (kN)**	**Average Initial ITS (kN)**	**Loss (%)**
Road No. 1	11.7	9.1	22.16
Road No. 2	10.9	7.8	28.22
Road No. 3	9.4	6.1	34.75
Road No. 4	11.4	9.4	20.23

7. DATA ANALYSIS

The Marshall Stability of the samples compacted with the gyratory shear compactor at a 1.25° angle of compaction was found to be very close to those of the field cores as shown in Table 4. This suggests that to some extent the samples compacted with the gyratory compactor at an angle of 1.25° simulate field compaction. Moreover, Marshall Manual Impact Compaction consistently gave a denser specimen with higher stability values than those prepared with the automatic Marshall compactor. The stability values for the specimens compacted with the kneading compactor were low compared to specimens compacted by other compaction techniques. However, the samples compacted with either the Marshall manual compactor or the gyratory shear compactor at an angle of 6° gave higher stability values. This did not, however, reflect any trend.

Top

It is evident from Table 4 that samples compacted with the gyratory shear compactor at an angle of 1.25° yielded a bulk specific density that was very close to those of the field cores taken just after paving for all road projects. However, samples compacted with the gyratory shear compactor at an angle of 6° yielded a bulk specific density that was very close to those of the field cores taken after four year of traffic densification for all road projects. The bulk density of the samples compacted with the Marshall compactor showed an erratic trend. It was also noticed that the manually operated Marshall hammer yielded higher specimen densities than those compacted with the automatic Marshall hammer. It is believed that some sort of kneading action takes place when the hand hammer strikes the specimen at an angle that is slightly different than true vertical. The samples compacted with the kneading compactor gave the least bulk densities, but these were less than the bulk densities of the field cores. Though the air voids for samples compacted with the Kneading compactor were found to be the highest, the samples compacted with the gyratory shear compactors at an angle of 1.25° and 6° gave air voids that were very similar to those of the field cores taken after paving and after four year of traffic densification respectively. Marshall Stability did not show any trend as compared to the air voids or the bulk density. Thus, keeping in view the results and trends of Marshall Stability, bulk density, and air voids, it can be concluded that the samples compacted with the 1.25° gyratory shear compactor and 6° gyratory shear compactor produced samples that were more realistic to the field situation just after paving and after four year of traffic densification.

From the analysis of data in Table 5, it can be concluded that the Modulus of Resilience for specimens compacted with the different compaction techniques gave varied values and that the specimens prepared using the gyratory shear compactor at an angle of inclination of 1.25° gave values which were closest to those of the field cores taken just after paving. Further, the Retained Modulus Ratio for the samples compacted with the gyratory shear compactor at an angle of 1.25° were found to be the highest. The samples prepared using the gyratory shear compactor at an angle of inclination of 6° gave values which were closest to those of the field cores taken after 4 years of traffic densification, while the Retained Modulus Ratio of these core were very similar to that of samples prepared by kneading compactor. The samples compacted with the Marshall compactor did not give any trend for Resilient Modulus values. The Modulus of Resilience for the samples compacted with the Automatic Marshall compactor had the least Modulus of Resilience values. Hence, based on the higher Modulus of Resilience values and the low durability index of the samples compacted with the Gyratory Shear Compactor at an angle of 1.25°, it can be concluded that this compaction technique best replicates the field cores taken just after paving.

The creep test results, as shown in Table 6, indicate that the samples compacted with the gyratory shear compactor at an angle of 1.25° had the highest elastic strain and the lowest permanent strain. The specimens compacted with the gyratory compactor at an angle of 1.25° gave the highest elastic strain and the lowest permanent strain values indicates that these samples are less prone to permanent deformation. With the samples compacted with the automatic Marshall compactor, the permanent strains were found to be the highest, but they did not exhibit any trend as in the case of the samples compacted with the gyratory shear compactor. Also, the elastic

Top

strain values of the samples compacted with the gyratory compactor at an angle of 1.25° and 6° were not significantly different from the elastic strain values of the field cores extracted just after paving and after four years of traffic densification. The Lottman test results, as shown Table 7, indicate that the loss in indirect tensile strength followed the trend similar to that quotient modulus of ratio (Table 5). Further, these mixes are not susceptible to stripping.

The results of this study corroborate the findings of Consuergra, et al., [1992] where the Texas gyratory compactor, irrespective of the angle of gyration, was ranked first in terms of its ability to produce compacted mixtures with engineering properties similar to those produced in the field. Although there is no single laboratory method that always provided the best match based on field compaction, overall, the gyratory shear compactors (1.25° angle and 6° angle) was found to be better than the other compaction methods. The gyratory shear compactor (1.25° angle of compaction) gave a higher Resilient Modulus, higher elastic strain, lower permanent strain, and reasonable air voids as compared to samples compacted by other compaction methods. Also, the bulk density of these samples was very similar to those of the field cores taken just after paving. However, the gyratory shear compactor (6° angle of compaction) did have better engineering properties as that of samples compacted by the gyratory shear compactor (1.25° angle of compaction), but were found to be very close to the properties of field cores extracted after four years of traffic compaction. The manual Marshall compactor performed somewhat better than expected as the tamping action possibly imparted in each operation will not always fall on the same portion of the specimen; it will thus provide for rearrangement of the aggregate particles after each blow.

8. CONCLUSIONS

Based on the literature search and the analysis of data from this study, the following conclusions are drawn:

1. The method of compacting asphalt aggregate mixtures significantly affects the asphalt's fundamental engineering properties, such as air voids, bulk density, and modulus of resilience.
2. Overall, the gyratory shear compactor (1.25° angle of gyration) appeared to be more closely representing the engineering properties of the field cores taken just after paving simulating the actual compaction during construction.
3. The gyratory shear compactor (6° angle of gyration) tied for second place on the basis of its elastic and viscoelastic behavior as compared to that of the field cores extracted after four year of traffic densification.
4. The gyratory shear compactor excelled in the speed with which compaction was achieved as compared to the other compaction techniques. Because of its operational simplicity, the gyratory compactor seems to be the most prudent choice, irrespective of the angle of gyration, as the compaction device to be used for future preparations of specimens for mixture design.

Top

5. The Marshall automatic impact compactor did the poorest job of simulating field compaction. The absence of a kneading effect during compaction, which is due to the uniform impact type load applied by the mechanical version of the Marshall hammer, is probably the major reason behind the poor comparison to the field cores.
6. Manual compaction is expected to perform better than automatic compaction as the tamping action imparted by the operator will not always fall on the same portion of the sample; therefore, it will provide rearrangement of the aggregate particles after each blow.
7. Lottman test results indicate that all the field cores extracted after four years of traffic densification had average loss in indirect tensile strength except field cores from Road No. 3. Cores from this road also showed least durability index in terms of modulus of resilience, this may be due to finer gradation of mix (binder course).

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Top

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Top