Evaluation of permanent deformation of asphalt pavement layers using quasi-static loading test

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During the last decade an important trend has been established towards the use of heavy wheel loading. Asphalt pavements experience service conditions in the field which include simultaneous different load levels, loading rates and different loading frequencies. These service conditions make the asphalt pavement mixtures undergo cyclic change in the deformation. That may remain permanent. A major concern today in many countries is the excessive permanent deformation in case of heavy axle loads. Viscoelastic behavior of asphalt concrete mixes can be investigated in the laboratory through determining the stiffness and deformation properties of compacted specimens at various conditions of load levels, loading rates, ...etc. This paper reports an experimental study that was carried out on different samples of asphalt pavement to study the effects of different degrees of compaction and stress levels on the permanent deformation of asphalt mixtures. The quasi-static loading test with long duration period was used throughout the program. Stress levels were 0.3 MPa, 0.4 MPa, and 0.5 MPa. Three degrees of compaction were followed; 35 blows, 50 blows and 75 blows. Test results show that the increase in stress level causes a significant increase in the values of maximum permanent strain at different degrees of compaction. At the same stress levels, the increase in the degree of compaction of asphalt mixtures has a great influence on the rate of permanent strain. On the basis of obtained data, formula predicting permanent strain of pavement at the beginning of steady state is proposed. The effects of number of load applications, degree of compaction and stress level are reflected in the proposed formula.

يشهد العالم خلال الفترة الزمنية الحالية زيادة ملحوظة فى نوعية وأحمال وحدات السير. وهذه الزيادة من المستجدات التي تساهم فى تولد الكثير من المشاكل والعيوب لسطح وطبقات الرصف الأمر • وتراعى الطرق الحديثة للتصميم مقدار التشكل اللدن ومعدل حدوثه تحت تأثير أحمال وحدات السير. ونظرا لأن معدل التشكل يتوقف على تكرار الأحمال وقيمها لذا فقد اتجهت الأبحاث الحديثة الى دراسة التشكل اللدن للخلطات الإسفلتية باستخدام التحميل الديناميكى •ويهدف البحث الى دراسة تأثير زيادة درجة الدمك وقيم الاجهادات على التشكل اللدن للخلطة الإسفلتية باستخدام اختبار الشبه أستاتيكى بمعدل تحمل مقداره ٣٦ ثانيه لدورة التحمل الواحدة وبتحليل نتائج الاختبارات المعملية التى أمكن الحصول عليها وجد أن زيادة درجة الدمك للخلطات الإسفلتية له تأثير ملحوظ فى خفض قيمة التشكل اللدن كذلك زيادة الاجهادات على الطبقات الإسفلتية يؤدى الى زيادة قيم ومعدل التشكل اللدن . لذا يوصى البحث بزيادة دمك الطبقات الإسفلتية المعرضة لأحمال مرور عالية• وبتحليل نتائج التجارب المعملية تم استنباط علاقة رياضية تربط بين معدل التشكل اللدن وعدد مرات تكراري الأحمال عند درجه دمك وإجهاد معين وهذه المعادلة تساهم فى دراسة سلوك الطبقات الإسفلتية والتنبؤ بمقدار التشكل لها عند أي عدد من تكرار الأحمال •

Keywords: Marshall tests, Quasi-static test, Permanent deformation, Degree of compaction, Rate of loading

1. Introduction

The rutting (permanent) mode of pavement distress has been recently viewed as a major problem on heavily traveled flexible pavement truck routes. Several researchers have developed procedures using layer theory and the permanent deformation characteristics of the layer materials to evaluate rutting behavior. Such analytical approaches were developed by Mclean et al.[1] and other researchers [2- 7].It is generally agreed that, one of the most important properties of an asphalt paving mix is its stability to resist permanent deformation under moving or stationary wheels of vehicles. The high axle load leads to excessive permanent deformation in asphalt pavements. Today a major concern in many countries is the excessive permanent deformation in heavy-duty asphalt-concrete pavements resulting from frequent repetitions of such heavy axle loads.

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2. Testing program

2.1. Materials

Asphalt cement from one local source (Alexandria Petroleum Company) in Alexandria City was used in this investigation. Tests indicated that the average penetration, flash point and specific gravity of used asphalt were 65, 317 C° and 1.03, respectively.

One type of coarse aggregate which consists of calcareous aggregate with size (2/12.5 mm), natural sand (as fine aggregate), and limestone dust (as mineral filler) were used in this study. Preliminary tests were carried out according to ASTM specification [8] to determine the material properties. The specific gravity, abrasion, water absorption and geometric characteristic tests were performed to specify aggregate properties used in this research. Main engineering properties of aggregates are given in table 1. Test results show that the coarse aggregate has good particle shape (angular), low water absorption and good resistance against abrasion.

2.2. Mix proportions

Specimens 4 C grade (0/11 mm) were prepared according to the Egyptian code [9]. Marshall tests were conducted according to ASTM [8]. The grading of the three aggregate blends and the specification limits are given in fig. 1. The specimens used in Marshall test were prepared at five levels of asphalt content; 4.5%, 5%, 5.5%, 6% and 6.5% by weight of mix. These specimens were prepared at three different compactive efforts, 35, 50 and 75 blows. Marshall test results for mixes have been complied at optimum asphalt content (5.5 %) as shown in table 2.

The table indicates that the stability value increases with the increase in the degree of compaction. At the same trend, the other characteristics of mixtures were improved by increasing the compactive effort from 35 blow to 75 blow.

Table 1
Engineering properties of aggregates

Properties	Calcareous aggregate	Natural sand	Limestone dust
Abrasion test (Los Angeles test)	12% after 100 rev. 26% after 500 rev.	_	_
Water absorption	1.5%	-	-
Specific gravity	2.56	2.61	2.75

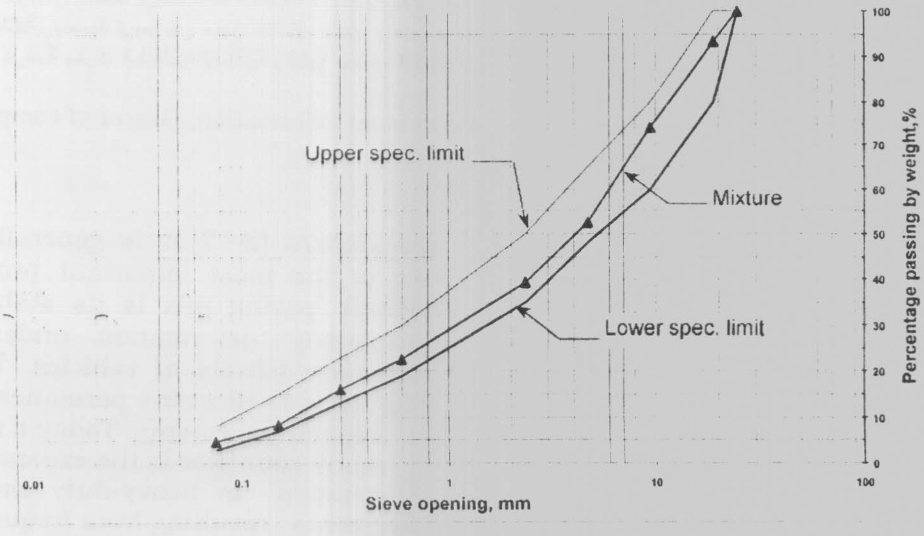

Fig. 1. Selected grain size distribution curve for 4c grade.

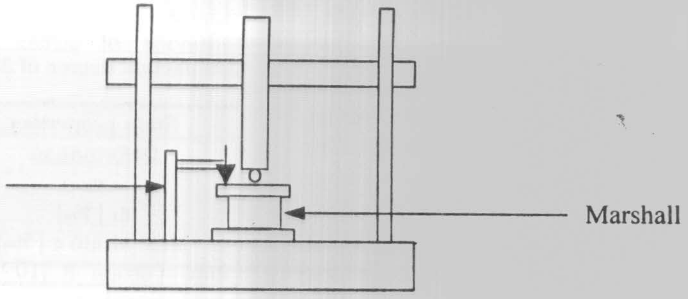

Fig. 2. Schematic diagram of compression machine.

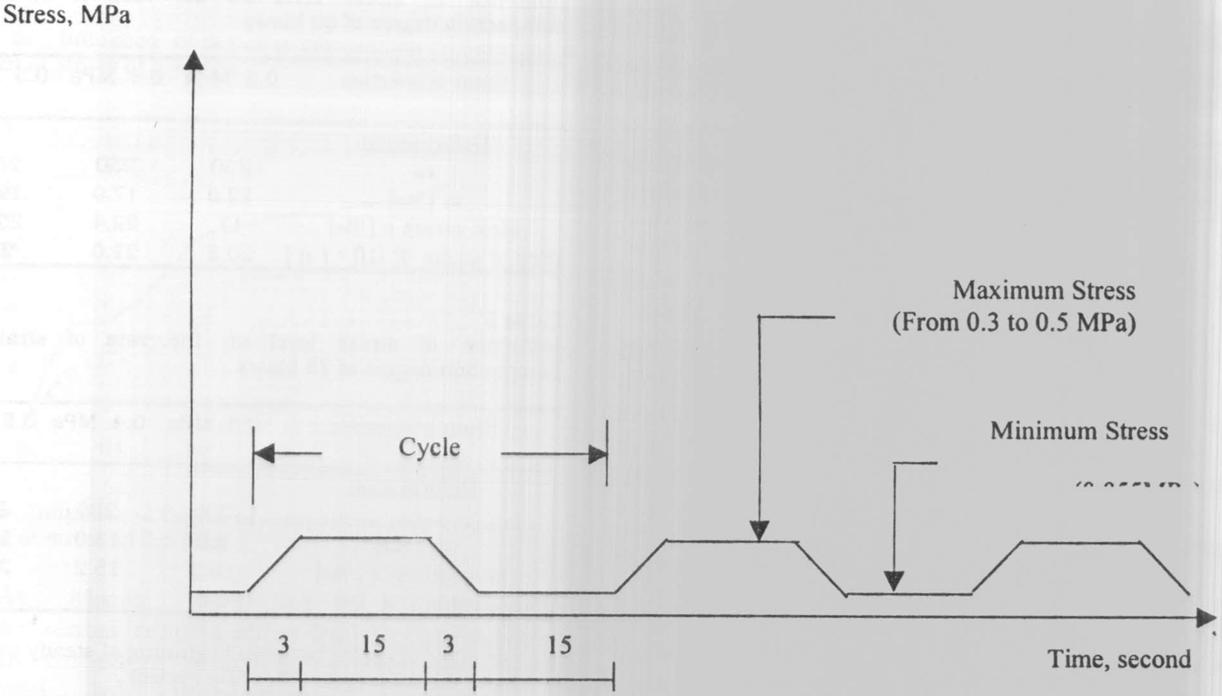

Fig. 3. Specified loading history.

Table 2
Marshall properties at optimum asphalt content

Marshall properties	35 Blows	50 Blows	75 Blows
Stability, kN	2.4	3.6	4.2
low, mm	3.4	3.2	2.6
Density, g/cm³	2.1	2.2	2.28
Air voids, %	5.8	4.2	3.6

2.3 Experimental procedure

Quasi-static loads were applied on Marshall specimens (h=6.25 cm, d= 10cm) in unconfined condition subjected to compressive uniaxial loading. Fig. 2 shows the schematic diagram of the compression machine. The loading history given in fig. 3 was followed throughout the tests. The cycle time was 36 second. The axial load was increased from a minimum stress (0.055 MPa) to a maximum stress within a period of 3 seconds. This was followed by a rest period of 15 second at the maximum stress, then, another period of 3 seconds through which the load was released from the maximum value to 0.55 MPa. Finally 15 seconds between two consecutive cycles of loading was selected. Each sample was exposed to 500 cycles load application in 5 hours. The permanent deformation was measured at every 50 cycles. Prior to load application, each sample was conditioned by applying a repeated load equal to 0.055 MPa for 10 cycles in order to insure full contact between loading head and the sample and to avoid a "hammering" effect during the testing stress. During performing the tests the recorded temperature was about 25±1C^o

2.4. Variables studied

Three degrees of compaction were selected to investigate their influence on the properties of asphalt concrete mixtures. These degrees were 35 blows, 50 blows and 75 blows. Three stress levels were used, 0.3, 0.4 and 0.5 MPa. These values are practically simulating the effects of heavy trucks [10].

3. Test results and discussions

3.1. Influence of changing the degrees of compaction on the permanent strain

Figs. 4,5 and 6 demonstrate correlation between permanent strain and number of load applications at different degrees of compaction and stress levels. Also, tables 3, 4 and 5 give the maximum permanent strain and the rate of strain. From these figures and tables it can be seen that at stress level of 0.3 MPa, the permanent strain values decrease from 22.4‰ to 17‰ by increasing the degree of compaction from 35 blows to 50 blows. This reduction is about 24%. On the other hand, the permanent strain is significantly affected by increasing the degree of compaction above 50 blows. Increasing the degree of compaction from 50 blows to 75 blows, leads to 39.4 % decrease in the maximum permanent strain values.

Table 3
Influence of stress level on the rate of strain at compaction degree of 35 blows

Stain properties	0.3 Mpa	0.4 MPa	0.5 MPa
Deformation			
e_n	300	300	300
e_l [‰]	12.4	16.0	18.3
Max. strain e [‰]	22.4	26.2	31.2
Rate of strain R [10^{-3} / n]	26.6	34	43

Table 4
Influence of stress level on the rate of strain at compaction degree of 50 blows

Stain properties	0.3 MPa	0.4 MPa	0.5 MPa
Deformation			
e_n	250	250	250
e_l [‰]	12.0	17.0	19.2
Max. strain e [‰]	17	22.4	25.0
Rate of strain R [10^{-3} / n]	20.8	21.0	23

Table 5
Influence of stress level on the rate of strain at compaction degree of 75 blows

Stain properties	0.3 MPa	0.4 MPa	0.5 MPa
Deformation			
e_n	200	200	200
e_l [‰]	9.0	13.0	18.0
Max. strain e [‰]	10.3	15.2	21.4
Rate of strain R [10^{-3} / n]	6.5	11	17

e_n = number of cycles between beginning of steady state and the final cycle (after 500 cycles) ,
e_l = permanent strain at beginning of steady state,
e = maximum permanent strain,
R = rate of permanent strain.

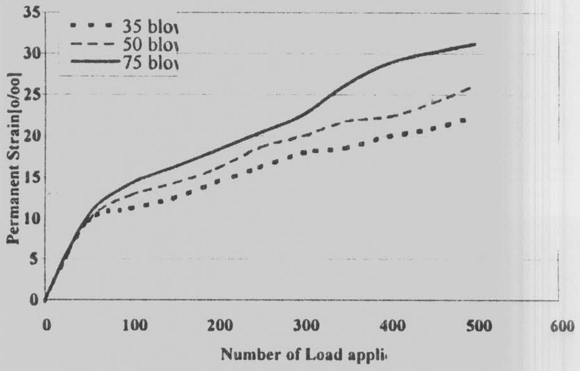

Fig. 4. Influence of degree of compaction on permanent strain at stress of 0.3 MPa.

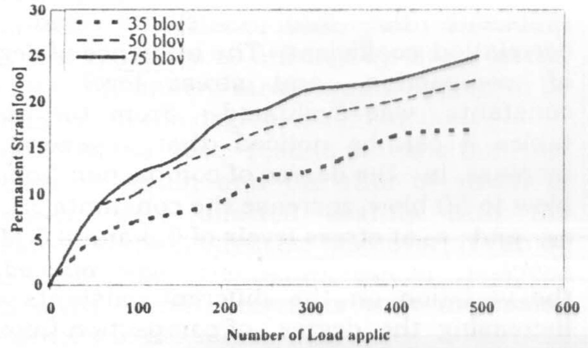

Fig. 5. Influence of degree of compaction on permanent strain at stress of 0.4 MPa.

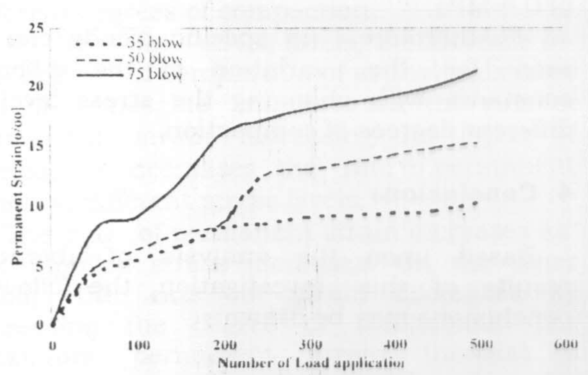

Fig. 6. Influence of degree of compaction on permanent strain at stress of 0.5 MPa.

At stress level of 0.4 MPa, the experimental results show that the permanent strain values of mixtures are not sensitively affected by increasing the degree of compaction from 35 blows to 50 blows. The maximum permanent strain value decreases from 26.2‰ to 22.4‰ by changing the degree of compaction from 35 blows to 50 blows while an increase in the degree of compaction from 50 blows to 75 blows reduces the permanent strain values from 22.4‰ to 15.2‰.

At stress level of 0.5 MPa, it can be noted that the increase in the degree of compaction from 35 blows to 50 blows affect the permanent strain values with increasing the number of load applications. In addition no significant difference in the permanent strain values was observed with increasing the number of load applications due to the change of the degree of compaction from 50 blows to 75 blows. The maximum permanent strains after 500 cycling of loading are 25.0‰ and 21.4‰, respectively. These results may be attributed to the fact that the asphalt samples in these two degrees of compaction reached the maximum density.

3.2. Effect of axial stress levels on permanent strain

The influence of applied axial stress on the permanent strain is evaluated. The variation between the maximum permanent strain after 500 cycles at the three stresses 0.3 MPa, 0.4 MPa and 0.5 MPa are presented in Table 5. This table indicates that an increase in the stress level from 0.3 MPa to 0.5 MPa causes a significant increase in the maximum permanent strain values at different degrees of compaction. This increase was about 40%, 47% and 107%, respectively, by increasing the axial stress from 0.3 MPa to 0.5 MPa at 35 blows, 50 and 75 blows. From the argument mentioned above, it can be concluded that the increase in the maximum permanent strain is dependent not only on the stress level but also on the degree of compaction (density of mixtures).

3.3. Rate of deformation related to degrees of compaction and stress levels

The stress levels and degrees of compaction have an effect on the rate of permanent strain of the asphalt mixtures. These results are detailed in tables 3,4 and 5. From these tables, it can be noted that the rate of permanent strain increases as the applied stress increases. On the other hand, this rate decreases by increasing the degree of compaction. Increasing the axial stress from 0.3 to 0.5 MPa, leads to an increase in the rate of strain increases from 26.6 to 43[10^{-3} / n] at 35 blow and from 20.8 to 23 [10^{-3} / n] at 50 blows. Similarly, the rate of permanent strain increases from 6.5 to 17 [10^{-3} / n] by increases the stress levels from 0.3 to 0.5 MPa. Furthermore, the results indicate that at comparable stress levels, the increase of degree of compaction in the asphalt mixtures has a noticeable influence on the rate of permanent strain. Increasing the degree of compaction from 35 blows to 75 blows decreases the rate of permanent strain at different stress levels. Therefore, it may be concluded that larger wheel loads and larger tire inflation pressure increase the rate of deformation of asphalt concrete mixes.

3.4. Proposed approach to predict permanent strain of asphalt pavement

The relationship between the permanent strain at beginning of steady state (after 200, 250 and 300 cycles of loading at 35, 50 and 75 blows, respectively.) and number of load applications was assumed to be cubic regression polynomial that may be written as follows:

$$e\,[\,‰] = a_0 + a_1 n + a_2 n^2 + a_3 n^3, \qquad (1)$$

where, e is the permanent strain [‰], and n is the number of load applications.

The coefficient a_0, a_1, a_2 and a_3 are constants depending on degree of compaction and stress levels. In addition, the correlation coefficient {r} of the regression polynomial was determined as rate of accuracy of the obtained statistic correlation. Table 6, 7 and 8 represent the four constants and the correlation coefficient. The influence of degree of compaction and stress level on the constants was evaluated. From the above tables it can be noticed that, in general, an increase in the degree of compaction from 35 blow to 50 blow, increase the constants, a_0, a_1, a_2, and a_3 at stress levels of 0.3 and 0.5 MPa. However no specific trends were noticed for the variation on the different constants with increasing the degree of compaction from 50 blows to 75 blows. Similarly, no trends were noticed with increasing the degree of compaction from 35 to 75 blows at stress level of 0.4 MPa.

Furthermore, no specific trends can be seen for the variation of the different constants with changing the stress level at different degrees of compaction.

4. Conclusions

Based upon the analysis of laboratory results of this investigation, the following conclusions may be drawn:

Table 6
Regression coefficients of eq. (1) at stress of 0.3 MPa

Comp. degree	Correlation factors				
	a_0	a_1	a_2	a_3	r.
35 blows	+2.4989E+03	- 4.1810E+02	+2.3847E+01	-4.0902E-01	0.997
50 blows	+3.3297E+03	-4.9418E+02	+2.4815E+01	-3.8454E-01	0.997
75 blows	-3.2062E+03	+41405E+02	-1.6713E+01	+2.3225E-01	0.999

Table 7
Regression coefficients of eq. (1) at stress of 0.4 MPa

Comp. degree	Correlation factors				
	a_0	a_1	a_2	a_3	r.
35 blows	-3.8205E+03	+8.1406E+02	-5.9448E+01	+1.2120E00	0.998
50 blows	+5.5276E03	-8.9479E+02	+4.8373E+01	-8.2354E-01	1.0
75 blows	+2.8130E+04	-3.8959E+03	+1.7889E+02	-2.6903E+00	0.994

Table 8
Regression coefficients of eq. (1) at stress of 0.5 MPa

Comp. degree	Correlation factors				
	a_0	a_1	a_2	a_3	r.
35 blows	+1.0318E+05	-3.3727E+04	+3.6590E+03	-1.3131E+02	1.0
50 blows	+1.1409E+05	-3.7136E+04	+4.0138E+03	-1.4360E+02	1.0
75 blows	+6.0710E+03	-1.2097E+03	+7.6019E+01	-1.4793E0+00	1.0

1. Test results show that, the permanent strain after 50 cycles of loading and unloading does not appear to be affected by stress levels, but the permanent strain would appear to be dependent on the degree of compaction.
2. Quasi-static test results indicate that the permanent strain and the rate of strain of mixtures were affected slightly with the repeated vertical stresses. Moreover, it can be concluded that at constant stress level, the permanent strain decreases with increasing the density of mixtures.
3. An increase in the stress level from 0.3 MPa to 0.5 MPa causes a significant increase in the maximum permanent strain values at different degrees of compaction.
4. At the same stress levels, the increase in the degree of compaction of asphalt mixtures has a noticeable influence on the rate of permanent strain. Increasing the degree of compaction decreases the rate of permanent strain at different stress levels.
5. The rate of permanent strain increases as the applied stress increases. On the other hand, the rate of strain decreases by increasing the degree of compaction. The maximum permanent strain increase is dependent not only on the stress level but also on the degree of compaction (density of mixtures).
6. The relationship between the permanent strain at beginning of steady state and number of load applications was assumed to be cubic regression polynomial.
7. It is recommend in case of roads subjected to heavy traffic loads to increase the compactive effort for the asphalt layers. This helps overcoming the problems of rutting distress. Moreover, selecting high quality materials and suitable mix design are important factors to reduce the rutting distress.

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