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INFLUENCE OF DIFFERENT FACTORS ON PERMANENT DEFORMATION OF HOT ASPHALT CONCRETE MIXTURES

Amjad H. ALBAYATI[1,*], Hasan AL-MOSAWE[2]

[1] Civil Engineering Department, University of Baghdad, Baghdad, Iraq.
[2] Department of Civil Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
[*] corresponding author: a.khalil@uobaghdad.edu.iq

Abstract

The performance of flexible pavements is significantly impacted by the permanent deformation (rutting) of asphalt pavements. The research aims was to evaluate the permanent deformation of asphalt mixtures under different conditions. To achieve this aim, 108 cylindrical specimens have been prepared and tested under repeated loading in uniaxial compression mode. Five factors were considered in this research. They include testing temperature, loading conditions (stress level and duration), and mixture properties (bitumen type and content). The permanent deformation is evaluated in term of the following parameters, permanent micro strain ε_p, resilient micro strain ε_r, initial permanent strain (intercept, a), accumulation rate of permanent deformation (slope, b), rate of decrease in permanent deformation α and constant of proportionality between permanent and elastic strains Mu. The test results showed that the ε_p and a are increased as the testing temperature increased. In addition, the ε_p value for load duration of 0.4 s is 1.64 times the value for 0.1 s. Finally, the findings showed that the resilient response of the material is comparatively more sensitive to bitumen content than the plastic response. Furthermore, the rutting resistance is highly affected by the variables considered in this research.

Keywords:

Permanent deformation;
Asphalt mixture;
Resilient strain;
Intercept;
Slope.

1 Background

One of the major types of flexible pavement distresses that is related to load application is permanent deformation. Permanent deformation is generally characterized by the rutting that occurs under the wheel path of the vehicle under repeated load application. Pavement rutting is considered a primary factor affecting pavement serviceability [1].

Several factors contribute to reducing the original quality of the pavement with time. The main factors are; traffic loadings, quality control during pavement construction, and pavement materials characteristics. The reduction in pavement quality and serviceability will cause the pavement to fail or inconvenient ride quality [2]. Several researchers have investigated road safety issues related to the mixture properties. The effect of Photo luminescent coating for the pavement mixture on road safety was studied in [3].

The well-known form of permanent deformation and pavement failure is the rutting and fatigue cracking [4]. A 1.1-inch rut depth causes a decrease in the flexible pavement serviceability index from 4.2 to 2.5 [5].

Rutting is generated by the gradual increase in traffic load application, and if the asphalt mixture does not conform to the specification requirements a longitudinal depression will appear under the wheel path and small upheavals in the sides of the wheel path [6] as shown in Fig. 1.

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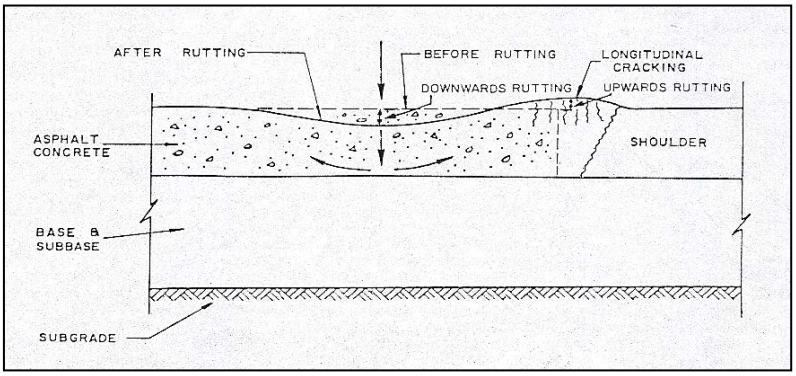

Fig.1: Rutting in flexible pavement.

Avoiding rutting failure is beneficial for road safety rather than the structural performance of the pavement. The rutting would cause difficulty in steering and hydroplaning issues. In Iraq, it is estimated that rutting distresses start to appear after a year of road construction due to the high axle load and high temperature during summer [7]. Severity levels of rutting, according to [8], are shown in Table 1.

Table 1: Rutting evaluation based on AASHTO 1993.

Average rut depth [mm]	Severity level
6-13	Low
13-25	Medium
> 25	High

Several researchers have studied the effect of some variables on the performance of asphalt mixtures. Al-Mosawe [9] studied the effect of different variables on the mechanical properties of asphalt mixtures. The study mainly focused on the aggregate gradation of the mixture, however other factors, such as testing temperature, binder content, and compaction effort were considered. It was found that at low testing temperatures, the difference in aggregate gradation is negligible, while as the testing temperature increases the aggregate gradation starts to take its role in the mixture in resisting the applied load.

Mota et al [9] conducted a study to evaluate the binder rheology and aggregate gradation on the permanent deformation of asphalt mixtures. They performed a testing program by using seven different asphalt binders with different Superpave performance grades (PG) and both dense-graded and gap-graded mixtures. It was found the mixtures manufactured with the modified binder performed much better than those unmodified when evaluating the wheel tracking test results.

Abd Al Kareem and Albayati [11] investigated different mixture types to minimize rutting in asphalt concrete wearing course, namely, Dense Hot Mix Asphalt (DHMA), Open Graded (OG) mixture, Stone Mastic Asphalt (SMA) mixture, and high modulus asphalt concrete mixtures originally known as Beton Bitumineux a Module Eleve (BBME). Natural Sisal Fibers (SFs), Carbon Fibers (CFs), and mixtures modified with hydrated lime (HL). It was found that the BBME mix type, as well as HMA modified with HL, give the best resistance to rutting in comparison with other types of mixes. Also, Albayati et. al [11] investigated the effect of HL size on the performance of asphalt concrete mixtures. Three different sizes of HL (regular, nano, and sub-nano scales) were evaluated to understand their effect on the asphalt mixtures performance. Five replacement percentages of HL were used to manufacture wearing asphalt mixtures instead of the limestone filler. The highest rutting reduction was observed by using 2 % nano HL replacement.

Alrajhi et al [12] used four different types of binders to characterize how the rest duration affected the permanent deformation properties of two asphalt concrete (AC) mixtures. Repeated load permanent deformation studies coupled with rest periods under varied stress and temperature settings were part of the experimental program. Consequently, to bridge the gap in the literature that is related to the contributory factors related to permanent deformation, the need has been arising for this research which considers the influence of mixture variables (bitumen grade, bitumen content) and testing conditions (temperature, stress level, load duration) on the permanent deformation as well as the resilient response of mixtures.

2 Material characterization and methodology

Bitumen, aggregate, and fillers were used in this research and were evaluated using the common tests. Results were compared with the Iraqi State Corporation for Roads and Bridges specifications [13]. Fig. 2 shows the method used in this research to satisfy the aim of this research.

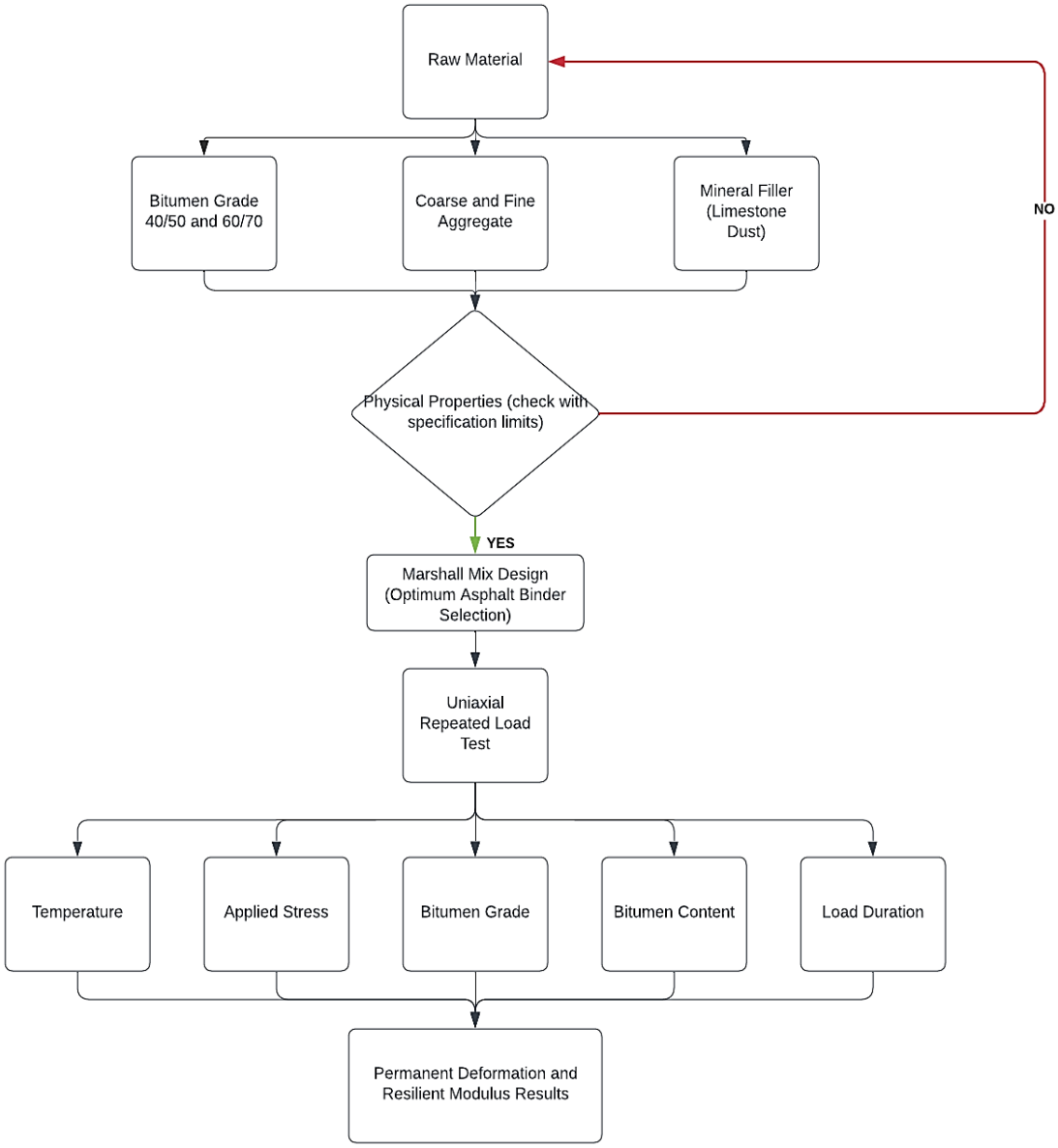

Fig. 2: Methodology flow chart.

2.1 Asphalt binder

To determine the effect of asphalt binder type, two bitumen grades were considered: an AC 40-50 and 60-70. Both types are supplied from the Dora refinery, which is located southwest of Baghdad. Table 2 below displays the characteristics of bitumen.

2.2 Aggregate

Al-Nibaie quarry provided the aggregate for this study, and a mix facility in Baghdad also uses it. Plants typically utilize this kind of aggregate to make asphalt mixtures. According to SCRB standard SCRB, R/9 [13], the aggregate was sieved and weighted to match the wearing course gradation. Fig. 3 illustrates the final gradation curve. Table 3 provides the results of the usual tests used to evaluate the physical characteristics of aggregate. The coarse aggregate is defined as particles retained on sieve No. 4, whether the fine aggregate particles are those passed sieve No. 4.

Table 2. Properties of asphalt binder.

Property	ASTM designation	Penetration grade 40-50		Penetration grade 60-70	
		Test results	SCRB specification	Test results	SCRB specification
Penetration at 25 °C,100 g, 5 [s·dmm]	D 5	43	40/50	66	60/70
Softening point, [°C]	D 36	52	……	47	…..
Ductility at 25 °C, 5 cm/min, [cm]	D 113	100+	100+	….	100+
Flash point, [°C]	D 92	279	Min.232	272	Min.232
Specific gravity	D 70	1.038	……	1.027	……
The residue from thin film oven test - Retained penetration, % of original - Ductility at 25 °C, 5 cm/min, [cm]	D 1754 D 5 D 113	57.6 81	55+ 25+	63.4 105	52+ 50+

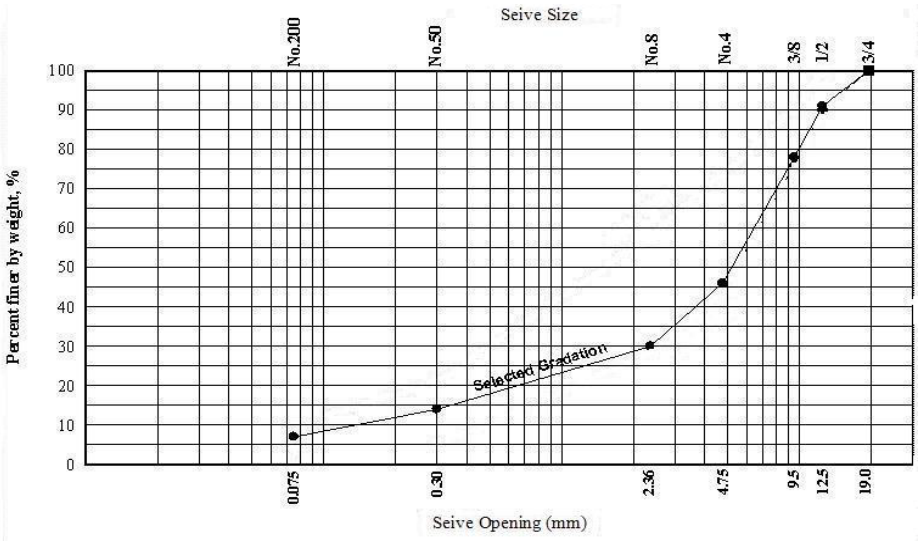

Fig. 3: Aggregate gradation chart.

2.3 Mineral filler

Filler is considered as a non-plastic material that pass sieve No. 200 (0.075 mm). Limestone dust obtained from Karbala was used as the filler in this research. The filler was tested and the results are shown in Table 4.

Table 3: Physical properties of aggregates.

Property	ASTM designation	Test results	SCRB specification
Coarse Fraction of Aggregate			
- Specific gravity, bulk	C 127	2.621	……
- Specific gravity, apparent		2.678	……
- The absorption of water [%]		0.453	……
- Abrasion Los Angeles [%]	C 131	22.1	<30
- Soundness (Na_2So_4) [%]	C 88	4.14	<10
- Degree of crushing [%]		96.1	>90
Fine Fraction of Aggregate			
- specific gravity, bulk	C 127	2.653	……
- specific gravity, apparent		2.682	……
- The absorption of water [%]		0.678	……
- Sand equivalent [%]	D 2419	57	>45.

Table 4: Physical properties of mineral filler.

Property	Test results
Specific gravity	2.784
Passing sieve No.200 (0.075 mm), [%]	95

3 Preliminary test: Marshall mix design

To fulfil the requirements of the factorial experiment design, the tests were conducted at optimum binder content and at binder contents 0.6 percent above, and 0.6 percent below the optimum. In order to obtain the optimum asphalt content, a complete mix design was performed using the Marshall design method as described in Asphalt Institute manual series No. 2 [14]. Table 5 presents the results for the final mix design with the optimum binder content of 4.6 %. The results for both mixtures (i.e., AC 40/50 and AC 60/70) meet the Iraqi specification requirements SCRB, R/9 [13].

Table 5: Marshall properties at optimum content of asphalt binder.

Property	Mix type		The requirements of (SCRB) specification
	AC 40/50	AC 60/70	
Stability [kN]	9.25	9.02	min. 8
Flow [mm]	3.50	3.75	2-4
Air voids [%]	4.20	4.35	3-5
VMA [%]	15.46	16.00	min.14

4 Axial repeated load test

Using the pneumatic repeated load apparatus (Fig. 4), cylindrical specimens with the diameter of 101.6 mm (4 inches) and the height of 203.2 mm (8 inches) were subjected to uniaxial repeated loading tests. In these tests, axial permanent deformation was determined under repetitive compressive loading with the stress level of 69, 137.9, and 206.9 kPa (10, 20, and 30 psi). The load was applied as a rectangular wave with a constant loading frequency of 1 Hz. Two load duration intervals (0.1 s and 0.4 s) were used with the corresponding rest period of 0.9 s and 0.6 s respectively). The axial repeated load tests were carried out at 20 °C, 40 °C, and 60 °C (68, 104, and 140 °F). The test specimen preparation procedure can be found elsewhere [1]. The test output is the permanent axial deformation of specimen at each applied cycle. The following equation is used to compute the permanent strain ε_p:

$$\varepsilon_p = \frac{p_d x 10^6}{h} \tag{1}$$

where:
ε_p - permanent axial strain,
p_d - permanent axial deformation,
h - the height of specimen.

Additionally, during this test, the axial resilient deflection r_d is measured and used to determine the resilient strain ε_r as well as the resilient modulus M_r using the following formulas:

$$\varepsilon_r = \frac{r_d x 10^6}{h} \tag{2}$$

$$M_r = \frac{\sigma}{\varepsilon_r} \tag{3}$$

where:
σ - repetitive axial stress.



Fig. 4: Pneumatic repeated load apparatus.

The results of permanent deformation in this study are represented by the linear log-log fitting between the number of load repetitions and permanent macrostrain as presented in the equation 4, which is suggested originally by Barksdale [15] and Monismith et al. [16]:

$$\varepsilon_p = aN^b \tag{4}$$

where:
N = number of repetitive stress applications,
a and *b* = intercept and slope coefficient.

The permanent deformation parameters α and M_u were derived using the relationship provided in equations (5) and (6) after regression coefficients *a* and *b* had been calculated [17]:

$$\alpha = 1 - b \tag{5}$$

$$M_u = \frac{ab}{\varepsilon_r} \tag{6}$$

where *α* is a permanent deformation parameter indicating the rate at which incremental permanent deformation decreases as the number of load applications increases, and M_u is the permanent deformation parameter representing the constant of proportionally between permanent strain and resilient strain (i.e., plastic strain at *N* = 1).

5 Analysis of tests results

5.1 Graphical analysis

One of the initial phases in the univariate analysis is "typically a graphic study of the properties of the data sample" [18]. Although there are obviously many factors involved in this research, which necessitates a multivariate analysis, the graphical analysis provides a solid place to start when identifying broad patterns in data. The analysis of the results began by identifying “sort” variables: i.e., temperature, loading, and material parameters by which the data files could be sorted. These variables were selected based on the findings in the background paragraph and comprised temperature, stress magnitude, load duration, bitumen type, and bitumen content. In order to evaluate the specific effects on both the plastic and elastic characteristics as defined by the parameters shown below, the full data file was sorted by each of the aforementioned "sort" variables, i.e., *a*, *b*, *α, M_u, ε_r, and ε_p.*

For instance, the test temperature was used to first sort the full data file. To more effectively illustrate how temperature affects a given parameter, the mean values of each elastic and plastic parameter were determined at each temperature. Table 6 displays the means for each "sort" variable. Because the parameters *b* and *α* are related by the equation *α* = 1- *b*, the trends for *b* are the exact reverse of those for *α*. Therefore, just one of the two - the parameter *b* - along with the other referred to above - will be discussed in the discussion that follows.

Table 6: Mean elastic and plastic parameters for each sort variable.

Variable		ε_r	ε_p	Intercept	Slope	Alpha	Mu
Temperature [°C]	20	304	935	119	0.2076	0.7859	0.0748
	40	428	4474	227	0.4281	0.5555	0.2428
	60	539	22969	497	0.6547	0.3452	0.5736
Stress [kPa]	69	229	2362	113	0.3839	0.6160	0.2105
	137.9	422	5425	261	0.4308	0.5628	0.2799
	206.9	620	9561	469	0.4921	0.5078	0.4008
Bitumen grade [dmm]	40-50	402	8106	226	0.4268	0.5635	0.2463
	60-70	423	10941	336	0.4334	0.5609	0.3478
Bitumen content [%]	-0.6 Opt.	382	8164	324	0.4016	0.5919	0.3592
	Opt.	420	9878	267	0.4336	0.5662	0.2866
	+0.6 Opt.	468	10336	252	0.4715	0.5284	0.2453
Load duration [s]	0.1	395	7146	223	0.3956	0.6000	0.2376
	0.4	451	11772	339	0.4646	0.5244	0.3565

ε_r micro-mm/mm, strain, ε_p micro-mm/mm, strain, intercept = a, slope = b.

5.2 Effect of temperature

Fig. 5 shows that temperature has a significant impact on the permanent strain, intercept, slope, resilient strain, and M_u. For instance, ε_p and an increased by a factor of 4.8 and 1.9, respectively, when the temperature rose from 20 to 40 °C. The permanent strain increased by a factor of 5.13 with further temperature increase from 40 to 60 °C, whereas the intercept increased by a factor of 2.18. This implies that temperature effects on the permanent strain and intercept do not vary linearly, i.e., the rate of plastic deformation increases with increasing temperature.

It appears that the temperature affects the slope and the resilient strain in essentially the same ways, as seen by the numbers in Table 6 and Fig. 5. With constants of proportionality of +0.011 percent and +5.875 micro-mm/mm per 1 °C, respectively, both are roughly linearly proportional to the temperature. These results, along with those pertaining to permanent strain and intercept, demonstrate that hot summer temperatures increase the rutting mode of failure in asphalt concrete pavement. Regarding M_u, it is calculated as follows: $M_u = a \cdot b / \varepsilon_r$.

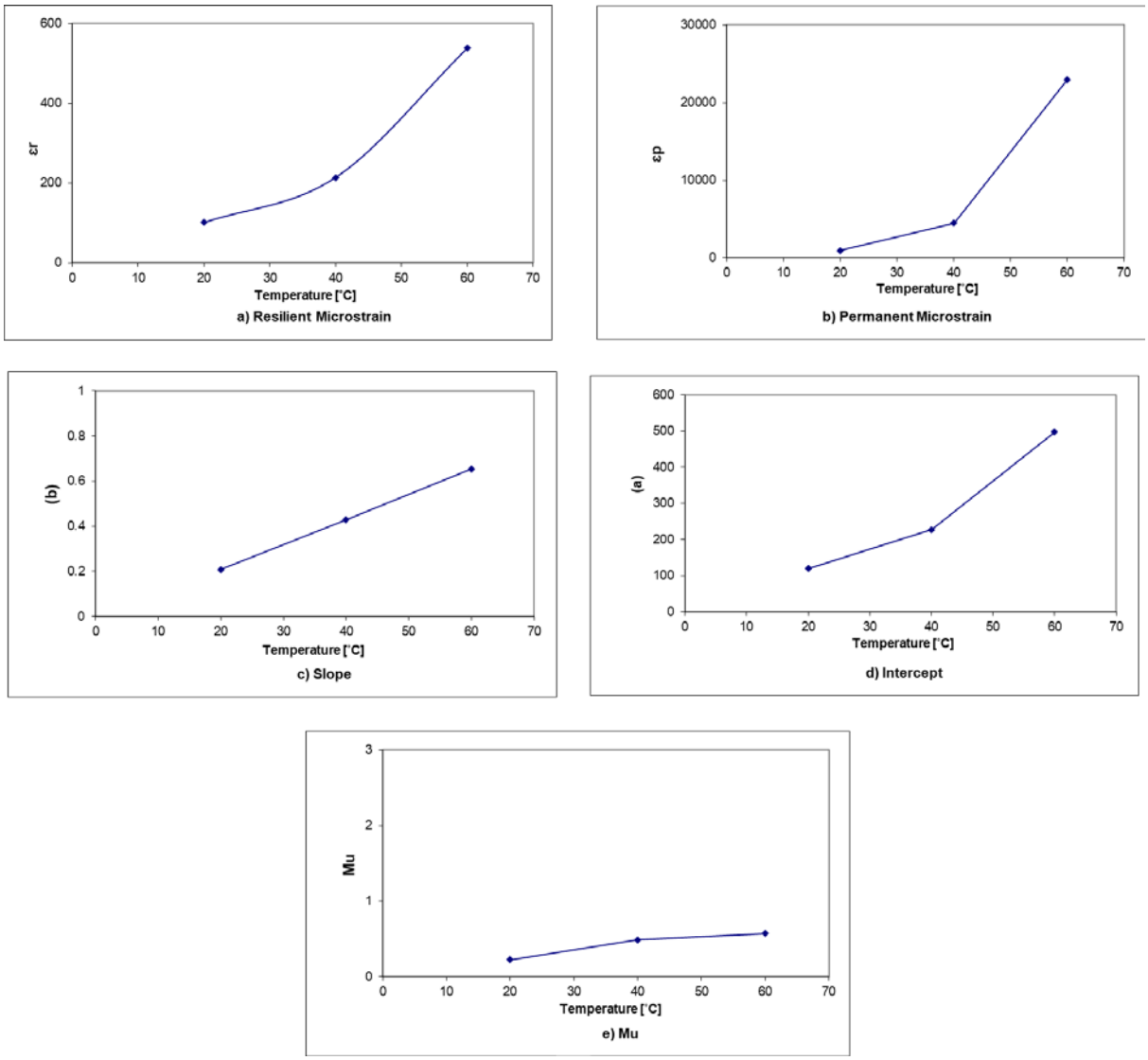

Fig. 5: Effect of testing temperature on strain and permanent deformation.

One may expect, if all the terms related to M_u increase with temperature, this would nullify the influence of temperature on M_u. Using the computed mean of each term to calculate M_u, the following values are obtained:

M_u 20 °C = 119·0.2076/304 = 0.074
M_u 40 °C = 227·0.4281/428 = 0.242
M_u 60 °C = 497·0.6547/539 = 0.573

Considering the component of the Mu equation separately, (i.e., the numerator represents the permanent deformation and the denominator represents the elastic response), it may be observed that the numerator increased by factors of 3.9 and 3.3 respectively for the increase in temperature from 20 to 40 °C. Whereas the corresponding increases in denominator are 1.4 and 1.25 respectively, so the rate of increase for the numerator and denominator are not similar. Therefore, it is possible to argue that the M_u value varies with the change in temperature.

5.3 Effect of stress

Fig. 6 shows the variation of elastic and plastic strain as well as plastic deformation parameters with the applied stresses. Examinations of the presented data suggest that the ascending rank of association of stress with the studied parameters can be arranged in the following manners: resilient strain, intercept, permanent strain, M_u and slope.

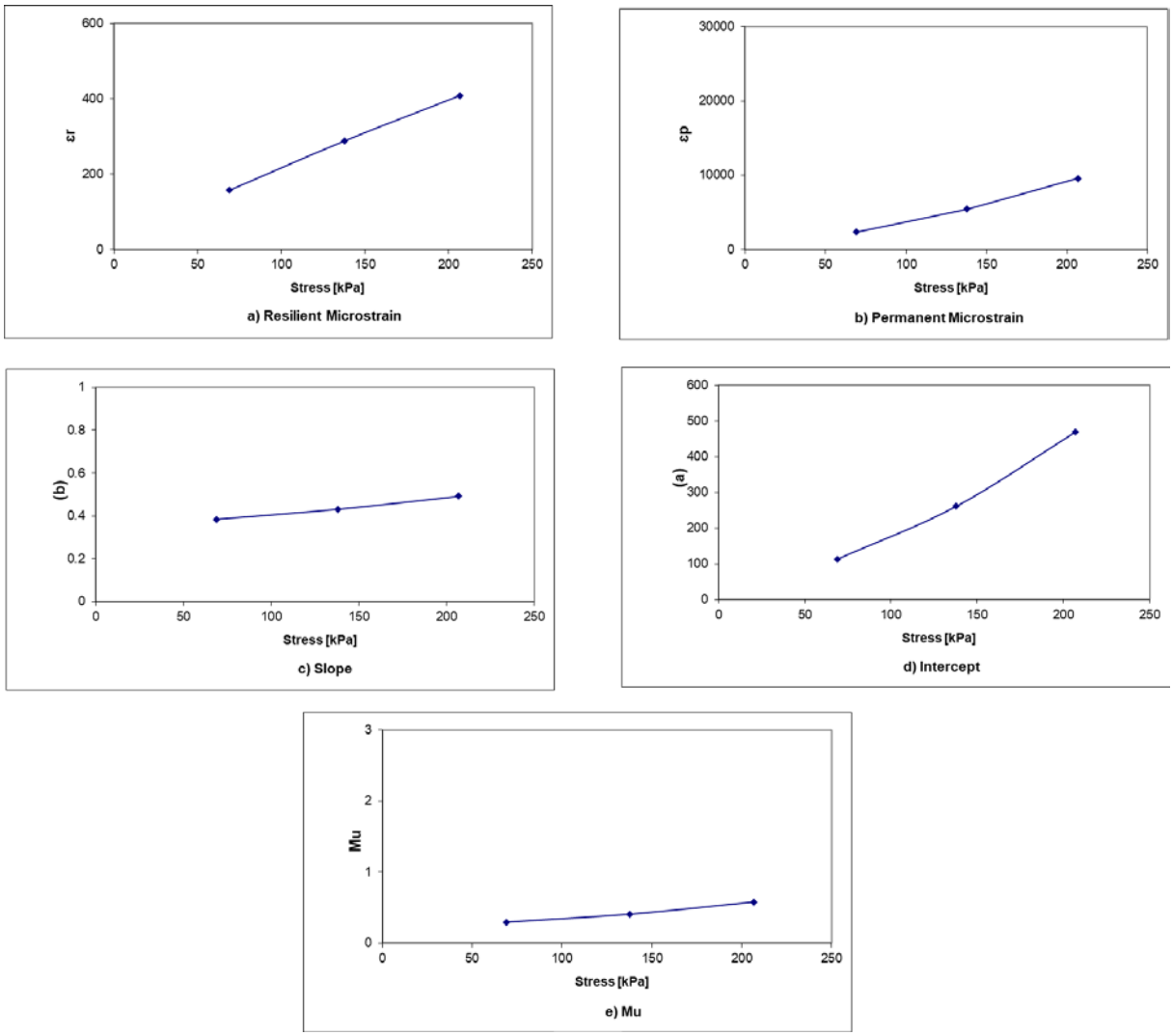

Fig. 6: Effect of applied stress on permanent deformation parameters and strain.

Based on the presented information, it is possible to argue that the elastic strain and permanent strain are linearly related to stress; the former increases by a factor of 2.7 while the latter by a factor of 4 when the stress increased from 69 to 206.9 kPa (10 to 30 psi). It is suggested that the intercept value for stress level 206.9 kPa is 4 times the value for a stress level of 69 kPa. It is also possible to conclude that the relationship between M_u and stress follows the same trend as that between slope and stress.

5.4 Effect of bitumen grade

Fig. 7 depicts how the kind of bitumen affects elastic and plastic strain as well as plastic deformation parameters. The bitumen grade has a greater impact on the plastic strain and the intercept coefficient than other parameters, as shown by the data presented. With this kind of bitumen, there are less variations in elastic strain, slope, and M_u values. For instance, the average resilient strain value for bitumen grades 60 to 70 is over 1.05 times that of bitumen grades 40 to 50. The permanent strain, which is 1.35 times the value for bitumen grade 40–50, is the same. The *a* for bitumen grades 40 to 50 is less than two-thirds of that for bitumen grades 60 to 70, indicating a discernible variation in the intercept. According to statistics, the slope's change with bitumen grade is not significant. However, it would be feasible to counter that the somewhat higher slope *b* value for bitumen grades 60 to 70 indicates that the rate of permanent deformation is marginally higher for the softer, less viscous bitumen.

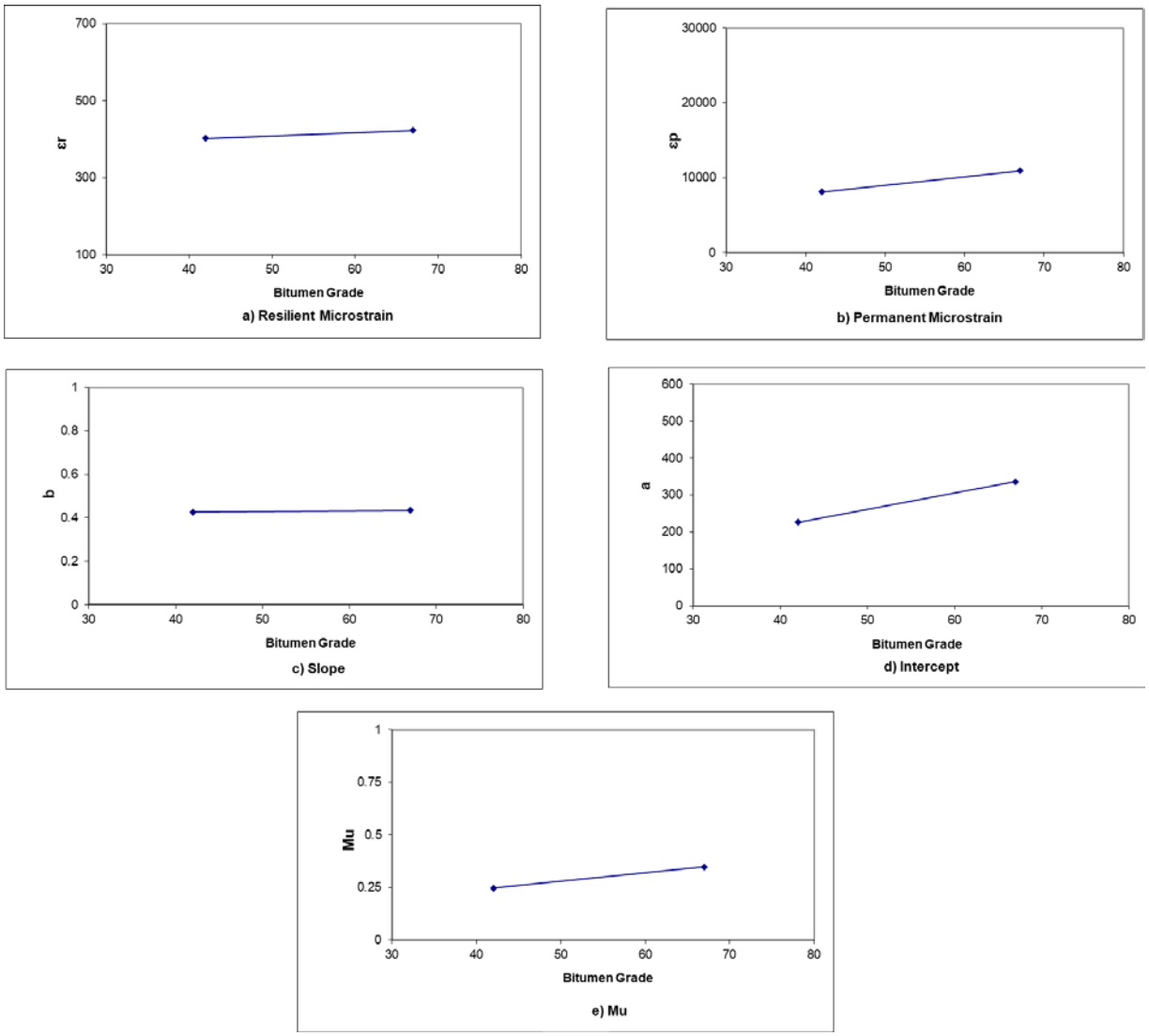

Fig. 7: Effect of bitumen grade on strain and permanent deformation parameters.

The Mu variation with bitumen type may also be attributed to this possible explanation. Using the mean value of ε_r, slope and intercept to calculate M_u, resulted in increase in M_u value with the increase in bitumen grade as shown below:

M_u 40-50 = 226·0.4268/402 = 0.239

M_u 60-70 = 236·0.4334/423 = 0.241

The examination of the presented data shows that the measured increase in values of ε_r and ε_p are higher with the softer bitumen than with high viscous bitumen 40-50. Furthermore, the permanent deformation, i.e., the numerator of the M_u term, increases by a factor of 1.5 (from 96.45 for bitumen grade 40-50 to 145.65 for bitumen grade 60-70), whereas, the resilient micro-strain increases by a factor 1.05 (from 402 micro-strain for bitumen grade 40-50 to 423 for bitumen grade 60-70) with the softer bitumen. This observed behavior may suggest that the plastic response of the material is more sensitive to the bitumen grade than the elastic response.

5.5 Effect of bitumen content

The data in Table 6 and Fig. 8 suggest that the analyzed bitumen contents had an impact on the material's plastic reaction. When the bitumen percentage is increased from 4 to 4.6 %, the plastic strain increases, but this increase tends to level out when the bitumen concentration is increased from 4.6 to 5.2 %.

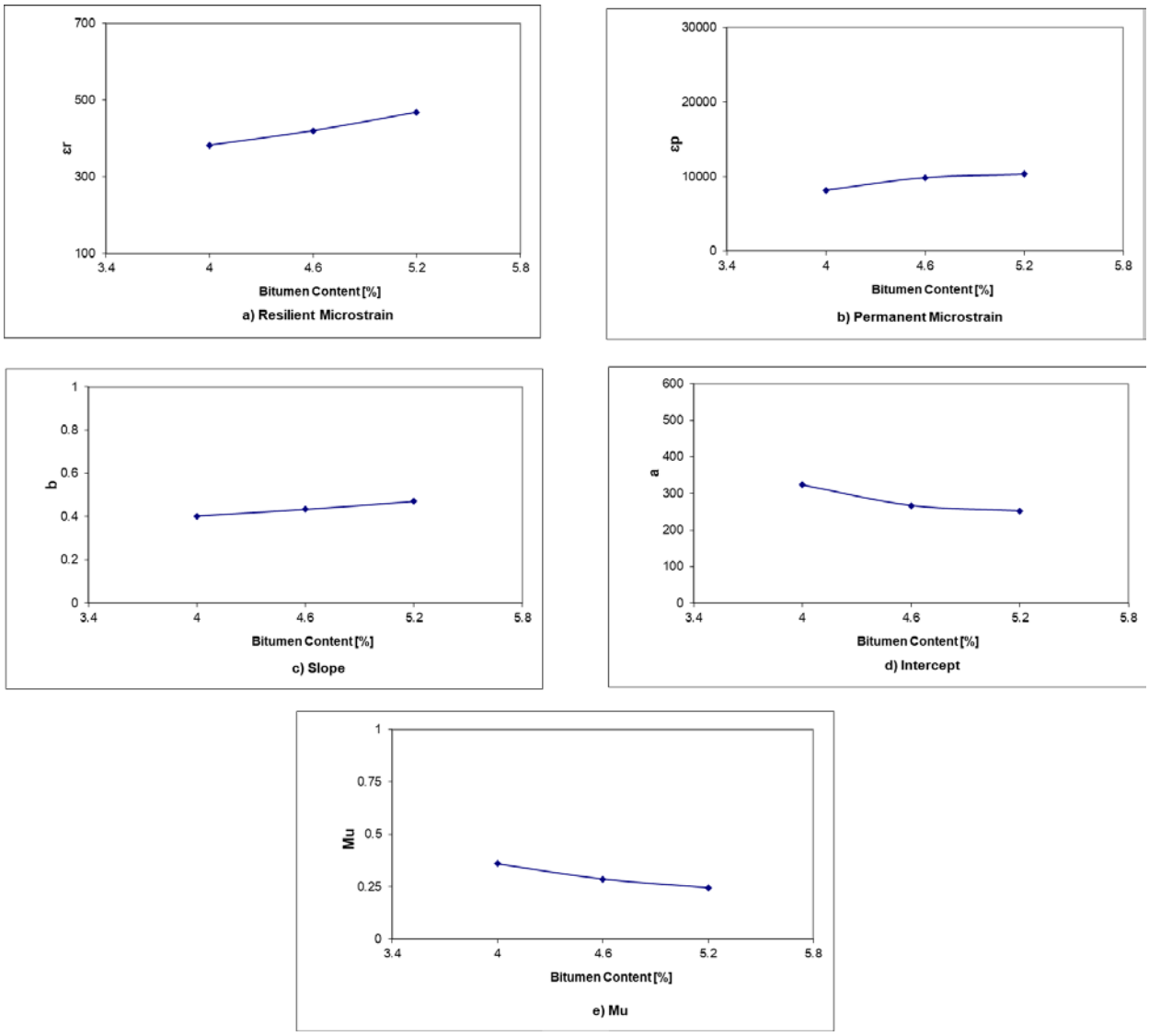

Fig. 8: Bitumen content's impact on parameters that determine strain and permanent deformation.

By contrast the resilient strains which range from 382 to 468 micro-mm/mm are proportional to the bitumen content, as example for the 1.2 percent range of bitumen contents, the constant of proportionality is +66.67 micro-mm/mm for each 1 percent change in bitumen content. This indicates that the resilient behavior of asphalt concrete is more sensitive to asphalt content than plastic behavior. In terms of permanent deformation parameters, the slope values indicate that the plastic deformation increases with increasing bitumen content. However, the intercept and M_u values decrease with increasing bitumen content.

5.6 Effect of load duration

The influence of load duration may be recognized more clearly when evaluating the trend of variation of the plastic strain, intercept, and M_u values with a change in load duration. The change in slope and resilient strain values varies with the load duration but to a lesser extent. The variations are shown by interpreting the data presented in Fig. 9. The permanent strain value for a load duration of 0.4 s is 1.64 times the value for 0.1 s, whereas the elastic strain value for this load duration is 1.14 times the value for 0.1 s. The plastic to elastic strain ratio increases by a factor of 1.43. This may explain the observation that rutting in the right lane of highways is higher than that of the left lane (fast lane). In other words, right lanes are usually used by slow-speed (high load duration) vehicles while left lanes are used by fast-moving traffic (low load duration). However, it should be noted that this is not the only reason for the difference in rutting between the right and left lanes of the highway.

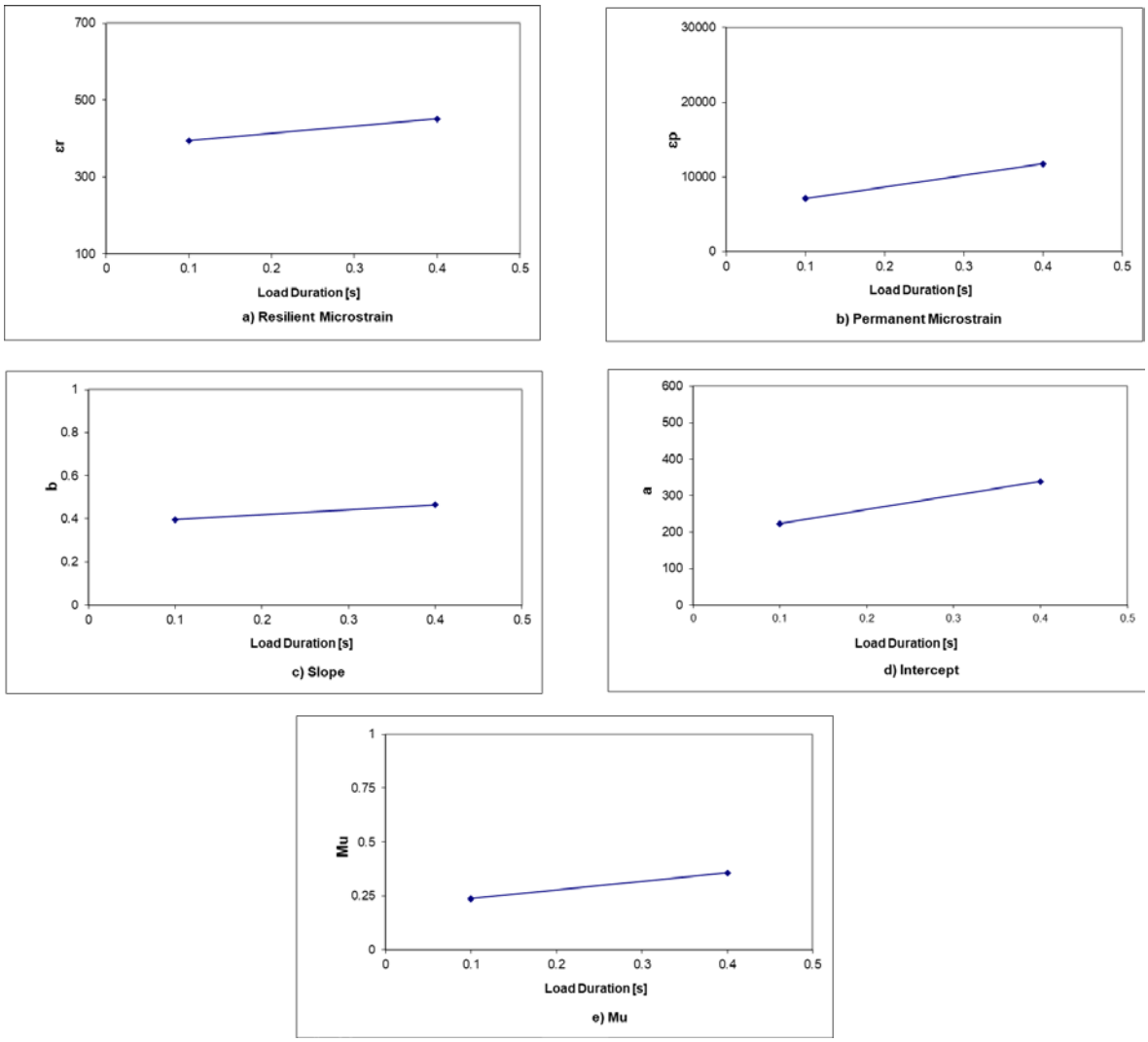

Fig. 9: Effect of load duration on strain and permanent deformation parameters.

Evaluation of the variation of the intercept, M_u and slope with load duration provides further evidence to the discussion described as above. The computation of M_u would be:

μ 0.1 = 223·0.3956/395 = 0.2233

μ 0.4 = 339·0.4646/451 = 0.3492

The obtained M_u values suggests that the permanent deformation (numerator of M_u) increases by a factor of 1.78 and resilient strain (denominator) increases by a factor of 1.14 (i.e., decrease in the resilient modulus of asphalt concrete). Finally, the M_u value for 0.4 sec. load duration is 1.5 times than of the 0.1 sec.

6 Conclusions

On the basis of this research findings, the following principal conclusion can be drawn:

1) the environmental factor of temperature has a significant effect on the plastic strain and intercept, when there is a rise in temperature from 20 to 40 °C, the plastic strain increases by a factor of 4.8 whereas the intercept by a factor of 1.9, when there is a further rises in temperature from 40 °C to 60 °C, the corresponding factors are 5.13 and 2.18.

2) The results show that the temperature influences the slope and the resilient strain essentially in the same manner. Both are approximately linearly proportional to the temperature with constants of proportionality of +0.011 percent and +5.875 micro-mm/mm per 1 degree centigrade, respectively.

3) The elastic strain and permanent strain are linearly related to stress; the former increases by a factor of 2.7 while the latter by a factor of 4 when the stress increased from 69 to 206.9 kPa. It is also possible to suggest that the intercept value for a stress level 206.9 kPa is 4 times the value for a stress level of 69 kPa.

4) The examined bitumen contents have a low influence on the plastic response of the material, by contrast, the resilient strains which range from 382 to 468 micro-mm/mm are proportional to the bitumen content, for the 1.2 percent range of examined bitumen contents, the constant of proportionality is +66.67 micro-mm/mm for each 1 percent change in asphalt content.

5) The permanent strain value for a load duration of 0.4 s is 1.64 times the value for 0.1 s, whereas the elastic strain value for this load duration is 1.14 times the value for 0.1 s.

Conflict of interest

The authors declare that they have no conflict of interest.

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