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DOMAINS OF PERMANENT DEFORMATION COEFFICIENT ALPHA AND MU FOR HARD GRADE ASPHALT CONCRETE MIXTURES

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Abstract: Permanent Deformation Coefficients, such as alpha (α) and mu (μ) show influence of mixture's properties on flexible pavement probable rut development. Assessment of these coefficients requires a data bank of mixture parameters (aggregate type, gradation, binder type, contents and **mixtures volumetric)**, temperature and loading conditions. A comprehensive laboratory study was carried out on six mixtures ranging from fine to coarse with three hard grade asphalt cements, which are used in typical hot weather areas of Pakistan. The specimens were subjected to cyclic loading on UTM-5P in order to study resistance against permanent deformation of the mixtures at 25, 40 and 55°C and permanent deformation coefficients alpha and mu. It was revealed from the current study that alpha and mu has opposite trends in all the six mixtures under the specified load and temperature domains. At low temperature (25°C) and stress levels (100 kPa), the mixtures showed same resistance to permanent deformation, while at high temperature (55°C) and stress level (500 kPa), mixtures with polymer modified asphalt showed better performance.

***Keywords**:* Pavement, Hot Mix Asphalt, Repeated Loading, Permanent Deformation, UTM-5P

Introduction

Wide domain of axle load, its frequency and magnitude together with dynamic effects of suspension, being applied on the roads has been increasing dramatically during the last two decades. The National Highway Authority (NHA), Pakistan, has been facing serious problems of premature pavement failures specifically in hot climatic areas, resulting in frequent reconstruction and high financial losses. One of the probable factors of increasing the amount of load is the decreasing trend of the railway share to accommodate transportation of goods in the recent decades. In order to cater for the growing axle load demand and to increase the performance of asphalt concrete mixtures, selection of appropriate binders, true prediction and accurate estimation of mixture's performance has become vital. Permanent deformation coefficients (alpha and mu) provide a means to evaluate the mix probable behavior in terms of its rate of change of the plastic response (alpha) and ratio of plastic to elastic response (mu). Barksdale [1] studied the effects of asphalt contents, air voids, number of blows in Marshall mixtures, aggregate gradation, and suggested the following permanent strain model.

$$\varepsilon_p = aN^b \tag{1}$$

where ε_p = permanent strain , N = number of load application, a = intercept coefficient; and b = slope coefficient.

Rauhut and Jordhal [2] studied the effects of temperature, deviator stress and asphalt content on permanent deformation, and proposed a permanent strain model which shows that both alpha and mu decrease with an increase in deviator stress but at different rate. They also mentioned that deviator stress has great influence on both the parameters. Rita and Matthew [3] determined permanent deformation coefficients, alpha and mu, using $\log_{10}\varepsilon_p$-$\log_{10}N$ as base relationship and proposed that these parameters could be used to assess plastic strain to elastic strain ratio. The permanent deformation parameters alpha and mu were calculated using the relationships as given in Equation 02 and 03.

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They further pointed out parameters that could not be accurately predicted as a function of test conditions and mixture's properties.

$$\mu = \frac{ab}{\varepsilon_r} \quad (2)$$

$$\alpha = 1 - b \quad (3)$$

Garba [4] reported the effects of material properties on permanent deformation of asphalt mixtures, mechanisms of the permanent deformation, and methods of its prediction. Fujie *et al* [5] studied the relationship between the number of load repetitions and permanent deformation, and found to include three distinct stages, namely the primary, secondary and tertiary stages. According to Mwangi [6] the stiffness and resistance to permanent deformation of asphalt mixtures strongly depends on the mixture composition, degree of compaction, rate of loading and temperature. Ziari and Mahid [7] studied the effects of temperature and different percentage of asphalt cement on the resistance to permanent deformation of HMA mixture, and concluded that significant degree of confidence that the asphalt mixture will not fail on the roadway due to permanent deformation can be achieved by simulating the laboratory test findings with field performance of asphalt mixture.

Tigdemir [8], studied different specimens of Hot Mix Asphalt (HMA), constructed in the laboratory and tested under repeated loading; first permanent deformation and later fatigue tests using Suleyman Demirel University Asphalt Tester equipment (SDU-Asphalt Tester). Li *et al* [9] proposed a prediction model of asphalt pavement permanent deformation based on improved grey prediction model.

Based on previous research, it may be concluded that basic relationship between plastic strain and load cycles is linear and change in stress level changes the value of permanent deformation coefficient and hence the permanent strain. The scope of the current study was limited to evaluate the influence of stress levels and temperatures on permanent deformation coefficient (α) and mu (μ) of asphalt mixtures.

Uniaxial load strain test was performed on six different asphalt mixtures using three asphalt types and two aggregate gradations. Pulse counts, width and pulse period were kept constant during the test and percentage accumulated strain were measured under each specified condition.

The present study attempted to determine the influence of stress levels and temperature on permanent deformation coefficients (α) and mu (μ) and their domains on asphalt mixture and to compare the permanent deformation behavior (percentage of accumulated strain) of Polymer Modified Asphalt (PMA) with its base asphalt, '60/70' and "40/50" penetration grade by varying temperatures and stress levels.

Materials and Methods

Coarse and fine aggregates used for asphalt mixture were obtained from a local lime stone quarry (Margalla). Mechanical and physical properties of aggregates were determined as per AASHTO, BS and ASTM standard and reported in Table 1. NHA in its general specifications [10] has specified two aggregate gradations, namely class 'A' and 'B', the coarser and finer respectively. Two gradations "01" and "02", within the envelope of single gradation (NHA class 'A' gradation), which has commonly been used in the field were chosen for this study as reported in Table 2, and graphically shown in Figure 1. Aggregate gradation "01" has relatively higher percentage material retained on sieve number 19, 9.5 and 4.75 mm, while gradation "02" has relatively greater percentage material retained on sieve number 2.36, 0.30 and 0.075 mm. Overall percentage of the mineral filler in both the gradations was almost the same

Table 1: Physical Properties of Aggregates.

Sr. No.	Test Description	Specification Reference	Results	Recommended Values (NHA General Specification) [10]
1	Flakiness Index (FI)	BS 812, Part 1	4.75%	15(Max)
2	Elongation Index (EI)	BS 812, Part 1	4.4 %	15(Max)
3	Aggregate Absorption	AASHTO T 166	0.88%	
4	Sand Equivalent	AASHTO T 176	72	45(Min)
5	Loss Angles Abrasion value (LAA)	AASHTO T96, ASTM C131	23%	30 (Max)
6	Sodium Sulphate Soundness value	AASHTO T104, ASTM C88	3.32%	12 (Max)
7	Deleterious materials	Asphalt Institute, SP-2,	1	0.2-10

Table 2: Adopted Gradations & Specifications.

Sieve Size		Combined grading (Asphaltic Wearing Course Class-A)			
Inch	mm	Gradation “1” (Coarse graded)	Gradation “2” (Fine Graded)	NHA Specifications ‘Class-A’	Asphalt Institute Gradation (1994)
1	25.00	100	100	100	100
¾	19.00	94	100	90-100	90-100
½	12.50	-	-	-	-
3/8	9.50	62	64.1	56-70	56-80
#4	4.75	42	43.2	35-50	35-65
#8	2.36	29	27.3	23-35	23-49
#50	0.300	9	7.5	5-12	5-19
#200	0.075	4.4	4.3	2-8	2-8

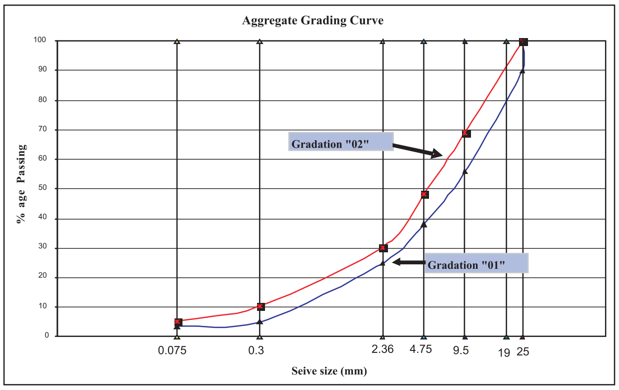

Figure 1. Aggregate gradation ‘01’ and ‘02’ under HA Class ‘A’.

Asphalt Cement (A.C.)

Two neat asphalt cements i.e. “60/70”, “40/50” penetration grade and one modified AC (“60/70” penetration grade modified with 1.6% Elvaloy Terpolymer 4170 in the presence of 0.7% superphsophoric acid) were used. The main aim for modifications was to enhance the tensile strength of the binder to increase its resistance to rut against high temperatures and heavy loadings [11]. The results of consistency tests on PMA matched with penetration grade “40/50”. The properties of all the three types of A.C (two neat and one modified) are shown in Table 3.

Table 3: Properties of different types of A.C.

Sr. No.	Description	PMA (1.6% Elvaloy 4170)	A.C penetration grade “60/70”	A.C penetration grade “40/50”
1	Type	Modified	neat	Neat
2	Ring & Ball Softening Point	58	49	56
3	Penetration	46	65	44
4	Ductility @ 25^{0}C	45	100	67
5	Specific gravity	1.023	1.03	1.032

Hot Mix Asphalt (HMA)

Asphalt Institute Marshall Method of Mix Design was adopted for the preparation of the six asphalt mixtures and test specimens [12]. The designations of Mixes are shown in Table 4. Design properties i.e. optimum asphalt contents, specific gravities, volumetric analysis, stability, flow, loss of stability and stiffness index, determined from each mix type are given in Tables 5 and 6. The stiffness index showed a prediction of probable mix performance against resistance to rutting.

Table 4: Mixture's Types.

Mix Description	Gradation Type	Binder
1a	coarser	PMA
1b	coarser	60/70 Pen. grade
1c	coarser	40/50 Pen. grade
2a	finer	PMA
2b	finer	60/70 Pen. grade
2c	finer	40/50 Pen. grade

Testing Methodology

The specimens (10.2cm x 6.3cm size) were prepared using traditional Marshall Compactor. Uniaxial repeated load strain test was then performed on 162 specimens [temperature (03) * stress (03) * specimens (03) * mixes (03) = 162]. Three temperatures i.e. 25^{o}C, 40^{o}C and 55^{o}C and three stress levels i.e. 100, 300 and 500 kPa were adopted to simulate laboratory test conditions with the field.

Repeated Load Uniaxial Strain Test

In UTM-5P (shown in Figure 2), strain test applied a repeated load of defined magnitude and cyclic duration to the specimens, where permanent strain correlates mix permanent deformation behavior with rutting potential in the field [13]. For the current study, a static conditioning stress and conditioning

Table 5: Hot Mix Asphalt Design Properties.

Mix Types	Optimum AC Contents (%)	Stability (Kg)	Loss of Stability (%)	Flow (0.25mm)	Stiffness index (Stability/flow)
1a (PMA)	3.83	1378	11.00	10.80	128
1b (60/70)	3.87	1305	14.30	11.00	119
1c (40/50)	3.95	1356	12.70	10.50	129
2a (PMA)	4.29	1335	8.90	9.80	136
2b (60/70)	4.31	1298	11.00	11.30	115
2c (40/50)	4.33	1314	10.50	10.50	125

Table 6: Hot Mix Asphalt Design Volumetric Properties.

Mix Types	Optimum AC Contents (%)	Gsb	Gmm	Gmb	VA (%)	VMA (%)	VFA (%)
1a (PMA)	3.83	2.650	2.522	2.373	5.90	13.90	58.00
1b (60/70)	3.87	2.65	2.515	2.371	5.70	13.99	59.00
1c (40/50)	3.95	2.65	2.514	2.370	5.70	14.10	60.00
2a (PMA)	4.29	2.662	2.520	2.395	4.96	13.90	64.00
2b (60/70)	4.31	2.662	2.516	2.386	5.17	14.23	63.70
2c (40/50)	4.33	2.662	2.515	2.384	5.20	14.32	63.70

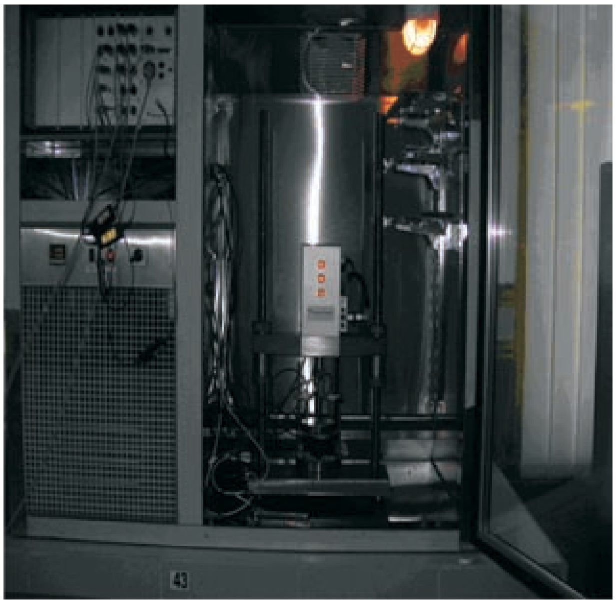

Figure 2. Universal Testing Machine (UTM-5P).

time was applied prior to commencement of the actual test. Conditioning time and conditioning stress were kept 100 sec and 10 kPa, respectively. Following the conditioning period and stress, a fixed 20 sec delay was programmed when no stress was applied. Subsequently, the specimens were subjected to repeated pulse loading of 1800 cycles at stress levels of 100, 300 and 500 kPa. The applied load varied in short pulse followed by a rest period. Pulse width and pulse period were kept 500 msec and 2000 msec, respectively. The magnitude of the loading stress and the width of the pulse applied to the specimen during a test were directly controlled by the "test loading stress" and "pulse width" parameters in the test set up and control edit screen. The minimum force (20 Newton) ensured that the loading actuator would not be lifted off the specimen between pulse applications. As pulse loading continued, the permanent deformation in terms of accumulated strain was measured using two Linear Variable Displacement Transducers and reported in Table 7.

Percentage accumulated strain was then plotted against pulse count on a log-log scale to obtain the straight line trends. The regression coefficients of straight line i.e intercept coefficient "a" and slope coefficient "b" were then measured using the following relationship.

$$y = ax + b \tag{4}$$

A typical plot (Figure 3) depicts how regression coefficients (a & b) have been computed [14]. Once regression coefficients had been calculated, the permanent deformation coefficients "alph" and "mu" were computed using the relationship given in equations 2 and 3. Alpha and mu were then plotted under each set of conditions.

Table 7: Permanent Strain of Mixtures.

Sr. No.	Temperature (°C)	Stress (kPa)	Permanent Strain of Mixtures					
			PMA-Coarser Mix (1a)	60/70-Coarser Mix (1b)	40/50-Coarser Mix (1c)	PMA-Finer Mix (2a)	60/70-Finer Mix (2b)	40/50-Finer Mix (2c)
1	25	100	0.193	0.281	0.183	0.286	0.403	0.315
2	25	300	0.399	0.564	0.375	0.516	0.572	0.493
3	25	500	0.616	0.686	0.592	0.907	0.958	0.926
4	40	100	0.332	0.424	0.389	0.540	0.590	0.536
5	40	300	0.547	0.742	0.666	0.609	0.774	0.676
6	40	500	0.881	0.990	0.946	0.989	1.057	0.995
7	55	100	0.438	0.577	0.526	0.8336	0.647	0.747
8	55	300	1.114	1.164	1.126	1.052	1.172	1.058
9	55	500	1.242	1.266	1.247	1.320	1.441	1.375

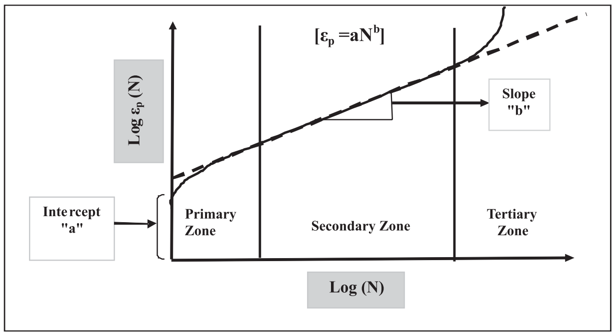

Figure 3. Log-log relationships between load repetition and permanent strain.

Results and Discussion

It was observed that A.C. type had relatively minor effects on the permanent deformation behavior of coarser and finer mixtures at low temperature (25°C) and stress level (100 kPa). At 40°C temperature and 300 kPa stress level, the coarser and finer mixtures showed minor difference in permanent deformation. At 500 kPa, the stress level and at 55°C temperature, percentage accumulated strain of coarse graded mixtures with PMA was less than that of the finer one.

The intercept coefficient increased with an increase in stress level for all mix types and test temperatures. Domain of 'a' for entire temperature ranges was observed to be from 4.06 to 5.52. The slope coefficient showed a reverse trend compared to the intercept coefficient. It decreased with an increase in stress levels, irrespective of mix types and test temperatures. For all asphalt mixtures, the domain of 'b' was observed to be from 0.07 to 0.20.

Permanent deformation Coefficient (α) graphically shown in Figure 4 has similar trends as intercept coefficient i.e. with an increase in stress level, alpha increased. Overall values of alpha for coarse as well as fine graded mixes had a range from 0.80 to 0.92. Mu, graphically shown in Figure 5, showed similar trends as the slope coefficient. It decreased with an increase in stress levels, irrespective of mix types and test temperatures. Overall domain of 'µ' for all the mixes was observed to be is 21.57 to 3.31. Standard deviation measured for 'µ' had a range from 0.304 to 1.64.

Alpha and mu reported by Rita *et al.* [3] range from 0.254 to 0.81 and 0.006 to 3.10 and the average values for the same from all the results were 0.56 and 0.58, respectively. In their study, a constant load frequency of 60 cycles/minutes (0.1 sec load duration and 0.9 sec. rest period) was used for all test specimens, prepared at 3.5%, 6.5% and 9.5% air voids. The specimens were subjected upto 30,000 load repetitions with a deviator stress range from 68 kPa to 200 kPa and three temperatures i.e. 65, 80, and 95°F [3]. The results of alpha and mu, derived by Monismith [15] and Rauhut [2] were 0.56, and 0.28 to 0.35, 0.45 to 0.9 and 0.1 to 0.48, respectively. Alpha and mu reported by this research ranged from 0.8 to 0.92 and 3.31 to 21.57, respectively. Average values of alpha and mu from all the results were 0.881 and 10.812, respectively. Comparison of values is shown in Table 8. The specimens, prepared at 5 to 7 % air voids, were subjected to 1800 load repetitions at constant load frequency 60 cycles/minutes, under unconfined conditions, at different stress levels (100, 300, 500 kPa) and temperatures (25, 40, 55°C). Domains of alpha and mu with respect to temperature and stress level have been shown in Figs. 6 and 7.

Table 8: Comparison of Results with Other Researchers.

Research Study	Domains of Alpha	Average Values	Domains of Mu	Average Values
Monismith et al, 1976 [15]	0.56	-	0.28 ---0.35	-
Rauhut et al, 1978 [2]	0.45---0.9	-	0.1---0.48	-
Rita et al, 1991 [3]	0.254---0.81	0.56	0.006---3.10	0.58
Current Study	0.8---0.92	0.86	3.31---21.57	10.81

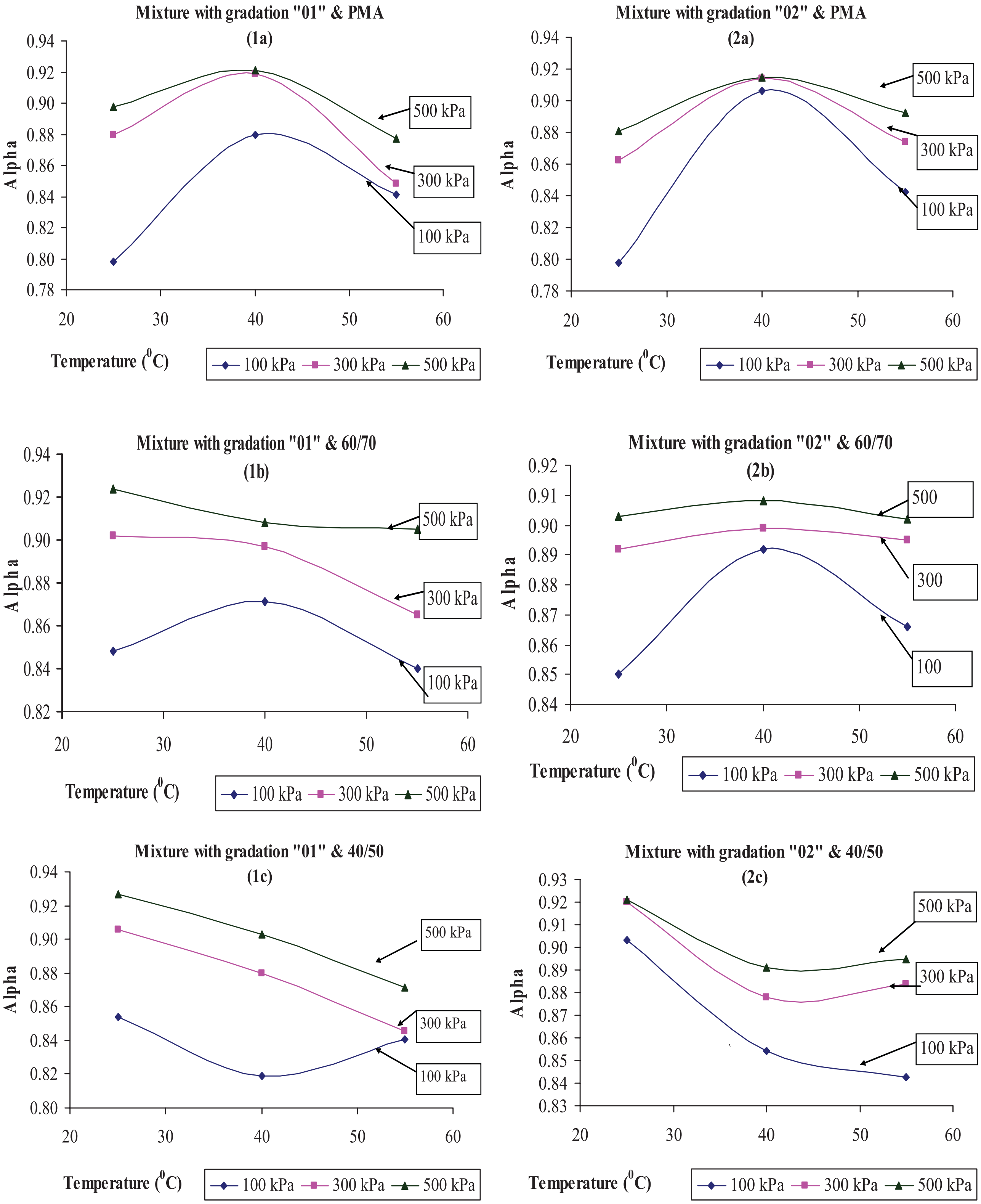

Figure 4. Influence of temperature on alpha.

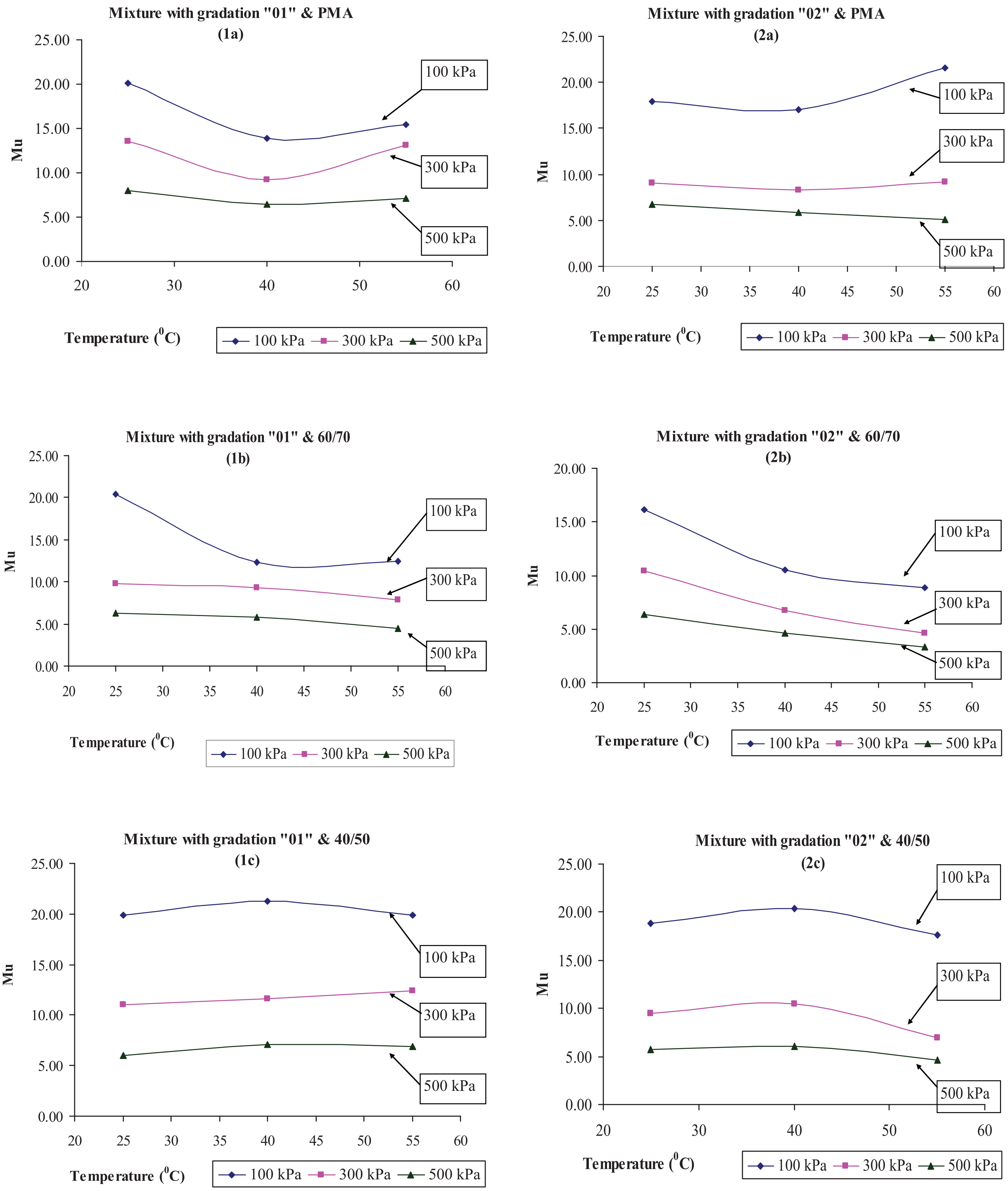

Figure 5. Variation of Mu with stress level.

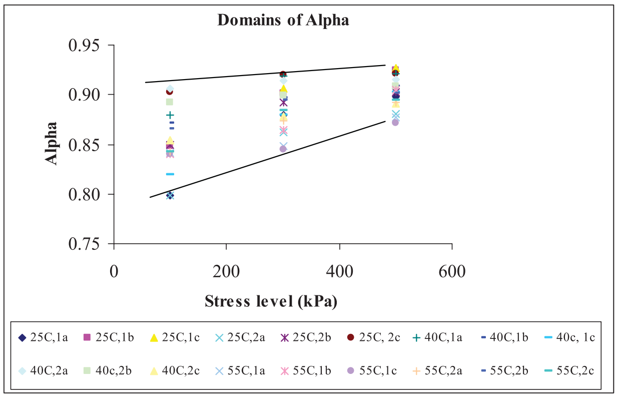

Figure 6. Domains of alpha for mixes at 25, 40, & 55^{o}c.

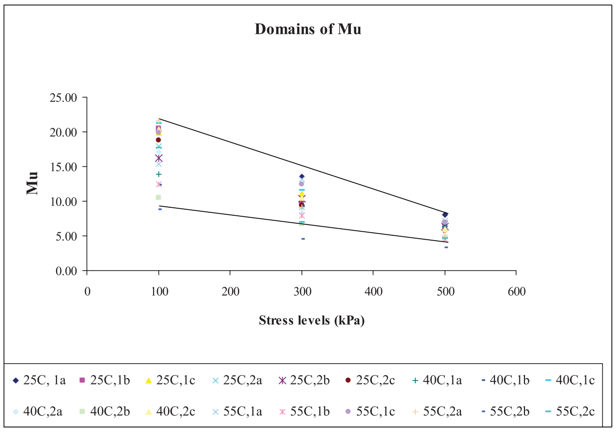

Figure 7. Domains of Mu for mixes at 25, 40, & 55^{o}c.

Conclusions

Based on permanent strain results, overall performance of mixtures with "60/70" penetration grade is lower as compared to "40/50" penetration grade and PMA. Coarse mixture with PMA has minimum percentage accumulative strain at higher temperature (55^{o}C) and stress level (500 kPa). Alpha (α) increases with the increase in stress levels, but mu (μ) decreases under the same conditions. Effect of temperature observed on the domains of alpha is minor, while mu varies significantly. At low temperature (25^{o}C) and stress level (100 kPa), coarser asphalt mixtures have narrower range for mu (19.85 to 20.45) than the finer mixtures (16.17 to 18.81). Alpha varies from 0.8 to 0.92 for all type of asphalt mixtures. Influence of higher stress level is greater than that of higher temperature on alpha and mu. Aggregate gradation has dominant effect on permanent deformation parameters than AC types. Values of alpha for coarser mixtures are higher than those for finer mixtures. Conversely, values of mu for coarser mixtures are relatively lower than those for finer mixtures. Mixtures with PMA & 40/50 pen grade show closer values of alpha and mu than the mixtures with 60/70 pen grade. Domains of alpha and mu observed for asphalt mixture used in current study are 0.80 to 0.92 and 3.32 to 21.57, respectively.

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