THE RESISTANCE OF PERMANENT DEFORMATION BEHAVIOUR OF THE ASPHALTIC CONCRETE (AC) MIXTURE CONTAINING RECYCLED POLYETHYLENE PLASTICS PACKAGING WASTE AGGREGATE REPLACEMENT (AC-PLASTIPHALTS)

Latif Budi Suparma[1]

ABSTRACT

This paper discusses the resistance to permanent deformation behaviour of the dense graded AC-Plastiphalt mixture, asphaltic concrete mixture containing granulated recycled polyethylene waste plastic as aggregate replacement. The permanent deformation observed in this investigation is presented in the rutting value calculated from the data resulted from the dynamic creep test conducted in the laboratory.

The dynamic creep tests were conducted using the MATTA at two level test temperature, i.e. 40 and 60 °C. Dynamic creep test results indicated that the AC-Plastiphalt mixtures at higher test temperatures have better deformation resistance than the control mixtures and the LDPE incorporation increased the elastic recovery response of the AC-Plastiphalt. At both test temperature of 40 and 60 °C, the AC-Plastiphalt mixtures had lower estimated rut depth values compared to the control mixtures. For instance, the estimated rut depth for AC-Control increases from 2.3mm at 40°C to 4.5mm at 60°C (increase 1.9 times) after ten million standard axles wheel passes on the pavement. According to these results, it can be concluded that the AC-Plastiphalt has better resistance to permanent deformation compared to the conventional AC mixture.

INTRODUCTION

Rutting or permanent deformation is one of the predominant types of distresses observed in bituminous surfacing. Rutting occurs due to the viscoelastic nature of bituminous mixtures and is caused by two mechanisms – consolidation under traffic and plastic flow (Mallick *et al.*, 1995). In flexible pavements, shear deformations resulting from high shear stresses in the upper portion of the bituminous layer appear to be the primary cause of rutting with the repeated application of these stresses under conditions of comparatively low mixture stiffness leading to the accumulation of permanent deformations at the pavement surface.

The creep test is carried out either in the static or dynamic mode of loading. Each test typically lasts two hours, and gives results which allow the characterisation of the mixtures in terms of their long term deformation behaviour (BS 598, 1995). Better correspondence in terms of mixture ranking, with respect to creep deformations or strain rates, has been shown to exist between the repeated load axial and the wheel tracking tests than the ranking produced by the static creep test (Gibb *et al.*, 1994).

The use of granulated recycled waste plastics as aggregate replacement in bituminous mixtures shows that the mechanical properties, such as Marshall stability and the indirect tensile strength, are much higher compared to the conventional mixtures (Zoorob and Suparma, 2000)

MATERIALS USED AND SPECIMEN MANUFACTURE

Table 1 shows the aggregate gradation of the control and Plastiphalt dense graded Asphaltic Concrete (A.C.) mixtures. The A.C. gradation was developed at Leeds (Zoorob *et al*, 1999) using maximum aggregate packing principles and is specifically designed to withstand combinations of heavy traffic stresses at elevated temperatures.

Table 1. Aggregate gradations used in this investigation

Sieve size (mm)	% passing by mass	
	AC-Control	AC-Plastiphalt
14	100	100
10	95.7	94.6
6.3	89.2	86.5
5.0	75.6	69.6
2.36	45.9	57.1
0.6	45.2	56.2
0.4	40.2	50.0
0.15	16.7	20.8
0.075	10	12.4
Bitumen type	50-pen.	100-pen.

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A softer bitumen was selected for the AC-Plastiphalt because early trials indicated that the mix was very strong and did not require the use of a hard bitumen. This has the added advantage that the mixing and compaction temperatures of the bituminous mix which are controlled by the viscosity of the binder could thus be lowered.

The plastic pellets, used in the AC-Plastiphalt mix were predominantly composed of low density polyethylene (LDPE) of single size (5.0-2.36 mm). Table 2 shows the characteristics of the bitumens and waste LDPE plastic pellets used in this investigation.

It was decided in this investigation to replace by volume the mineral aggregate fraction having the same size as the plastic granules in the original A.C mixes with LDPE pellets. The aggregate gradation of the resultant Plastiphalt mixes was therefore very similar in terms of volumetric proportions to the original control mixes.

Table 2. Characteristics of the bitumens and waste LDPE plastics used in the investigation

Test description	Bitumen types		Waste LDPE plastic pellets
	50-pen	100-pen	
1. Penetration at 25°C (dmm)	54	98	---
2. Specific gravity	1.03	1.02	0.92
3. Softening point (°C)	48.5	45	120
4. Melting point (°C)	---	---	140

Based on the selected gradings and the size of the waste plastic granules; a maximum of 29.7% by volume of the total AC-control mix was replaced with waste LDPE plastics to create the AC-Plastiphalt mixes. The main variable between the Plastiphalt and the control mixes would therefore be the specific gravity of the combined aggregate fractions

The experimental mixtures were manufactured at five different bitumen contents. The Leeds Design Method (Cabrera, 1996) was then used to obtain the optimum bitumen content (o.b.c.) of the design mixture. At o.b.c, further investigations and tests were carried out to fully characterise the properties of the design mixture.

The mixing and compaction temperatures need to be carefully controlled to cater for the differing softening points of the two plastic types. At worse, with minimal temperature control, the plastics behave as inert aggregates contributing to the continuation of the mineral aggregate interlock. On the other hand, if the mixing and compaction temperatures are carefully selected, the plastics can be compacted near their softening point temperatures thus creating a much greater improvement in the resultant mix strength as the semi-molten plastic granules key into and strongly adhere to the surrounding mineral aggregate particles.

For the A.C control mixes, the combined aggregates and bitumen were mixed in a thermostatically controlled preheated twin paddle mixer at a mixing temperature of 150 °C which resembles the optimum bitumen viscosity of 0.2 Pa.s. On the other hand, a compromise between the optimum bitumen viscosity and the softening and melting points of the waste plastics had to be considered for the Plastiphalt mixes. This is because once the mixing temperature exceeds the melting point, the plastics transform into a low viscosity fluid which flows and reduces the workability of the mix. It is recognised that for optimal compaction the viscosity of the bitumen should lie between 2 and 20 Pa.s (Whiteoak, 1991). Mixing and compaction of all specimens was carried out using a gyratory compactor (Gyropac) at 125 °C for the AC-Plastiphalt. The energy of compaction applied with the Gyropac was set at 240 kPa vertical pressure. The number of compactive revolutions for the AC-Plastiphalt was 120 gyrations corresponding to heavy compactive efforts at a fixed angle of gyration of 2°.

Determination of the optimum binder content (o.b.c.)

The o.b.c for both mixtures was determined using the Leeds Design Method (LDM) (Cabrera, 1996). The LDM recommends that the o.b.c for dense graded mixtures should be obtained as the arithmetic mean of the o.b.c at maximum compacted mix density, minimum voids in the mineral aggregate (VMA), and maximum stability. The Marshall quotient (MQ) (kN/mm) values are defined as the ratio of Marshall stability (kN) to flow (mm).

The o.b.c for the AC-Control mix was calculated at 5.0% which agrees with previous investigations (Zoorob *et al*, 1999), whilst the o.b.c for AC-Plastiphalt mix was determined at 6.0% (Zoorob and Suparma, 2000).

VOLUMETRIC AND MECHANICAL PROPERTIES OF MIXES AT O.B.C.

Further characterisation tests were carried out at the o.b.c value for each mix type and the results of all tests conducted on the design mixes are shown in Tables 3. All the results are obtained from compacted specimen at the optimum bitumen content of each mix type and each result is from an average of three test specimens.

Table 3. Mix properties of control and Plastiphalt mixes

Properties	Dense graded mixtures	
	AC-Control	AC-Plastiphalt
1. Optimum bitumen content (%)	5.0	6.0
2. Mix Density (g/cm^3)	2.37	1.99
3. Porosity (%)	3.7	2.9
4. VMA (%)	15.5	13.6
5. Marshall Stability at failure (kN)	16.9	41.3
6. Flow (mm)	3.65	7.90
7. Marshall quotient/MQ (kN/mm)	4.63	5.23
8. % retained Marshall Stability (%)	85	106

As expected, the compacted density values of the Plastiphalt mixes were lower than those of the control mixes. In dense graded AC mixes, a 29.7% coarse aggregate replacement by volume with the lower specific gravity LDPE, results in a 16% reduction in bulk density of the compacted mix. The reduction in bulk compacted density is accompanied by a reduction in the VMA which indicates a tighter, more dense aggregate skeleton. This result would be advantageous in terms of haulage costs.

DYNAMIC CREEP TEST

It has been suggested that the static creep test does not reflect the performance of modifiers which improve the values of elastic recovery properties of a material, as well as repeated loading conditions (Valkering *et al.*, 1990). Due to the incorporation of plastics material in the bituminous mixtures investigated in this study, the unconfined dynamic creep test was selected for further characterisation of the rutting behaviour of Plastiphalt mixtures.

The unconfined repeated load creep test used in this study was carried out using the MATTA testing machine. All specimens used for the unconfined dynamic creep test were Marshall specimens prepared at optimum bitumen contents. The standard test temperature selected was 40 °C, but since creep is a high temperature phenomenon, the test was also conducted on an additional set of specimens at a higher test temperature of 60 °C.

Test conditions

Typical conditions under which the unconfined dynamic uniaxial creep test is carried out are:

a. Standard test temperature 40 °C, for simulating very hot climates 60 °C,
b. Pre-loading for 2 minutes at 0.01 MPa, as a conditioning stress,
c. Loading regime; this consists of 3600 pulses of magnitude 0.1 MPa. Each pulse is composed of pulse width of duration 1000msec and a pulse period duration of 2000msec. The accumulated loading and unloading testing times equals 2 hours.
d. At the conclusion of the 2 hours pulses loading, an additional 1 hour recovery period during which specimen rebound is monitored.

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The results of dynamic creep test are presented in Table 4.

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	b. 60 °C	8.32	7.12
2. Slope of creep curve at:	a. 40 °C	0.34	0.51
	b. 60 °C	1.49	0.49
3. % creep recovery after 1 hour unloading at	a. 40 °C	3.05	14.45
	b. 60 °C	0.57	12.11

Cumulative irrecoverable axial strain

Based on the results obtained and presented in Figure 1, at both test-temperatures of 40 °C and 60 °C, the AC-Plastiphalt mixtures were found to generate higher strains compared to the control mixture. The incorporation of granulated LDPE has resulted in higher cumulative axial strains. At the end of the creep test, after 3600 loading pulses which equates to 1 hour loading time, the axial strains of the AC-Control specimen were measured at 6737 and 12018 microstrains at 40 and 60 °C respectively. These values were found to be lower than the values obtained on AC-Plastiphalt specimens which were 12057 and 14059 microstrains at 40 and 60 °C respectively.

A softer bitumen was selected for the AC-Plastiphalt because early trials indicated that the mix was very strong and did not require the use of a hard bitumen. This has the added advantage that the mixing and compaction temperatures of the bituminous mix which are controlled by the viscosity of the binder could thus be lowered.

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Cumulative irrecoverable axial strain

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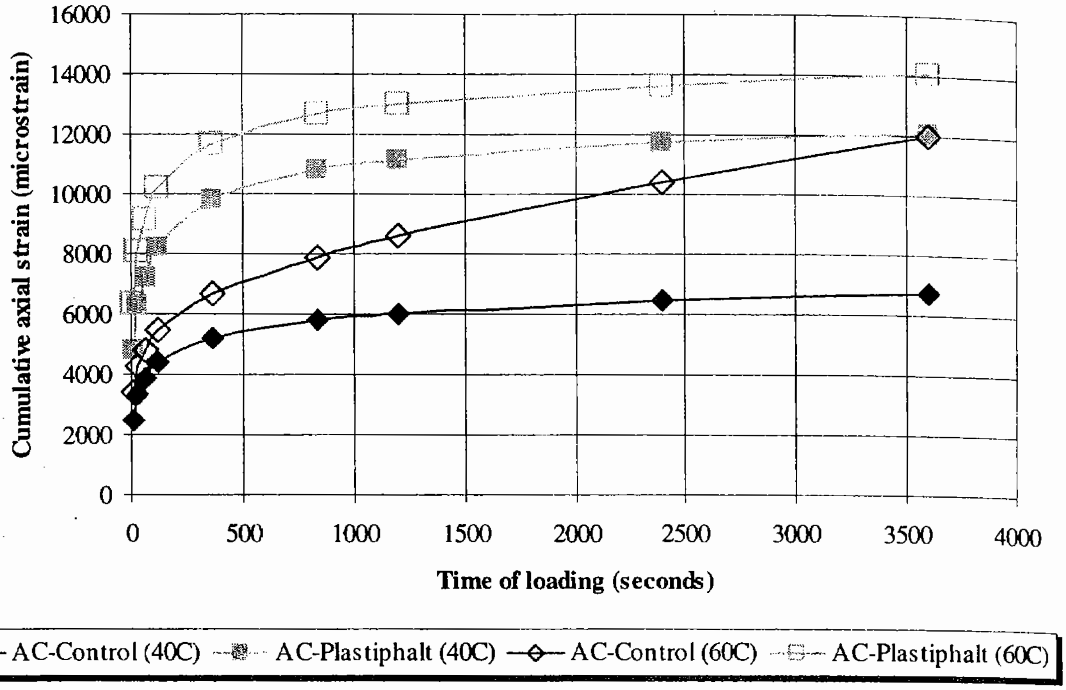

Figure 1. Relationship between cumulative irrecoverable axial strain and time of loading at various test temperature of dense graded A.C. mixtures

Such behaviour may have been anticipated from earlier Marshall flow and tensile test results which clearly showed that at failure the AC-Plastiphalt mixtures have higher strain values. The main reason of the higher strains may be due to the LDPE plastics incorporated in the mixture which was blended with 100pen bitumen. Additionally, the plastic material itself is quite elastic (modulus elasticity of polyethylene about 96.55 MPa (14000 psi) (Clauser, 1984)), hence this material has high elasticity.

Creep stiffness

The creep stiffness is indicative of the resistance to permanent axial deformation and for bituminous specimens is basically obtained from the ratio of applied stress to the cumulative compressive strain at a defined temperature and time of loading [BS DD-185: 1990]. During the test, axial deformation is continuously monitored as a function of time. Knowing the initial height of the specimen and the magnitude of axial strain ε, the creep stiffness modulus S_{mix} at any loading time can thus be determined:

$$S_{mix\,(t,T)} = \frac{\sigma}{\varepsilon_t} \qquad (1)$$

where

$S_{mix(t,T)}$ = creep stiffness modulus (MPa) at test temperature T and loading time t;

σ = applied stress (kPa) = 100 kPa;

$\varepsilon_{(t)}$ = cumulative irrecoverable axial strain at time t.

The creep stiffness value at the end of the test or after 1 hour cumulative loading is normally reported. This value is obtained using the above equation with the measured cumulative irrecoverable axial strain after 1 hour loading time.

The cumulative creep stiffness values can be calculated at any loading time during creep testing of dense graded A.C. mixtures at the two test temperatures. As predicted, the creep stiffness values of AC-Plastiphalt mixtures at 40 and 60 °C were found to be lower than the values obtained from the AC-Control mixture. The creep stiffness values at 1 hour loading time (after 3600 loading pulses) are presented in Table 4. It can be seen that at 40 °C, the creep stiffness of the AC-Plastiphalt mixture was 8.30 MPa which only is 54% of the stiffness of the control mixture (14.95 MPa). However, at the higher temperature of 60 °C, the AC-Plastiphalt stiffness value was 7.12 MPa which equates to 82% of the value calculated for the AC-Control mixture (8.32 MPa).

Slope of the creep curve

Under repeated loading, larger strains and hence lower creep stiffness values may occur due to the effect of the pulsed loading on the aggregate skeleton (Gibb *et al.*, 1994). Therefore, instead using the S_{mix} value at 1 hour loading time to rank the creep performance of bituminous mixtures, the rate of strain (slope of creep curve) with time is used as an alternative method.

Basically, the creep curve can be seen that the curve can be divided into three stages i.e. primary, secondary and tertiary creep stages. The primary stage is indicated by a rapid increase in permanent strain values at the beginning of the test accompanied by a decreasing strain rate. The secondary stage is characterised by a strain rate which is approximately constant, implying a linear relationship between loading pulses and permanent deformation. The final stage, i.e. the tertiary stage, is characterised by an increasing rate of permanent deformation and is related to failure of the test specimen.

The slope of the creep curve is obtained from the secondary stage of the creep test and is determined by plotting results of cumulative axial strain v.s loading time obtained from a dynamic creep test on a log-log scale. For any creep test, the loading time t at which the primary creep stage ends and the secondary stage begins is a point of contention. To maintain consistency, it was decided after careful examination of all the creep curves generated in this investigation, that the starting point for the secondary creep stage was at a loading time of 840 seconds.

Since the secondary creep stage is characterised by a constant rate of strain increase with time, the test data from the secondary stage were regressed into a straight line. The slope of the creep line is thus indicative of the mixture resistance to creep deformations. A steeper slope indicates a mixture more susceptible to rutting. The equations of the regression lines from the secondary creep stage can be represented using general equations:

$$\varepsilon = a + b.T \qquad (2)$$

where:

ε =cumulative irrecoverable axial strain (microstrain),

a = constant,

b = slope of creep line, and

T = time of loading (second).

Results of the slopes of the creep lines obtained from dense graded A.C. mixtures are also presented in Table 4. The AC-Plastiphalt mixtures were found to have higher creep slope values than the slopes of the control mixtures at 40 °C. However, the creep slope values of the Plastiphalt mixtures were found to be lower at 60 °C. This indicates that at higher temperatures the Plastiphalt mixtures have better deformation resistance than the control mixtures.

For mixtures having the same aggregate gradation, at 40°C one would expect the creep properties (indicated by slope of the creep line) of the binder to be the major contributor to the stiffness of the mixtures. Since the AC-Plastiphalt and AC-Control had almost identical gradations, the reduction in creep stiffness value at 40°C is clearly a reflection of the response of the mixture to the substitution of 50-penetration grade bitumen in the control with 100-penetration bitumen in the AC-Plastiphalt. As the test temperature increased it was interesting to notice that the effect of the bitumen type was no longer so critical. It was not clear at this stage whether there was any enhanced bond between the flexible plastic component and the mineral aggregates in the mixture compensating for the binder stiffness of the 100-penetration.

Other factor that can be argued may be due to the changing of rheological behaviour in the mixture as a result of incorporating LDPE. However, in this investigation the interaction of the LDPE with the bitumen itself (blend between LDPE and bitumen) was not studied. Further work needs to be carried out on the rheological characterisation of LDPE-bitumen blends.

Creep recovery

Creep recovery values are presented based on the recovery strain after 1 hour unloading time. The values are expressed as percentage of the recovery strain value divided by the cumulative strain at the end of creep test.

$$\mathrm{CRec.} = \frac{\varepsilon_R}{\varepsilon_L} \qquad (3)$$

where

CRec = creep recovery (%);

ε_R = recoverable axial strain after 1 hour unloading (microstrains),

ε_L = cumulative irrecoverable axial strain (microstrain) at the end of creep test (after 3600 loading pulses).

Creep recovery values reflect the elastic behaviour of the bituminous mixtures subjected to compressive loading. Table 4 also includes creep recovery values of dense graded A.C. mixtures tested in this investigation. The creep recovery values of the AC-Plastiphalt after 1 hour unloading were found to be 14.45% and 12.11% at 40 °C and 60 °C test temperatures respectively; whilst 3.05% and 0.57% recovery values were recorded for the control mixture at 40 °C and 60 °C respectively. These results reflect the increased elastic response of the AC-Plastiphalt mixture as a result of the incorporation of plastics component.

The LDPE form used in this investigation is in granular form which is in direct contact with aggregate particles in the mixture. When the stress applied, the LDPE may slightly flex under load and rebound after unloading.

PREDICTION OF PERMANENT DEFORMATION

Permanent deformation or rutting of bituminous pavement is one of the predominant types of distresses observed in bituminous mixtures resulting from the viscoelastic nature of bituminous mixtures. The results obtained from creep tests are routinely used to predict the permanent deformation of bituminous mixtures resulting from vehicular traffic.

Estimation of rut depth

Hill, *et al.* [1974] assumed that the rate of permanent deformation is dependent, amongst other factors, on the level stress imposed, the bitumen film thickness and the bitumen properties. The deformation is also dependent on the temperature and time of loading as is stiffness modulus of the mixture (S_{mix}). Values of S_{mix} can be derived from the creep test at a certain value of bitumen stiffness and at a certain test temperature.

The stiffness modulus of bitumen that corresponds to its viscous component can be estimated using the following equation.

$$S_{bit.visc} = \frac{3\eta}{N.T_w} \qquad (4)$$

where

$S_{bit,visc}$ = viscous component of bitumen stiffness (kPa)

η = viscosity of bitumen (Ns/m^2) as a function of penetration index (PI) value and softening point of bitumen and can be obtained by using Van de Loo nomograph

N = number of stress application

T_w = loading time of one load pulse, in this section it is assumed that a vehicle speed of 50 km/h results in a T_w value of 0.02 seconds.

Van de Loo [1978] proposed that the rut depth value can be estimated from the following relationship:

$$R_d = \frac{C_m \times h \times \sigma_{avg}}{S_{mix}} \qquad (5)$$

where

R_d = rut depth (mm)

C_m = correction factor for the-so-called dynamic effect which takes account of differences between static (creep) and dynamic (rutting) behaviour. This factor is dependent on the type of mixture and has been found empirically to be in the range 1.0-2.0. Table 5 describes the values of C_m factors of different mixture type.

h = pavement layer thickness (m)

σ_{avg} = average stress in the pavement under the moving wheel (MPa), dependent upon bituminous layer type and pavement temperature.

S_{mix} = stiffness of the mixture (MPa) derived from creep test at a certain value of bitumen stiffness $S_{bit} = S_{bit,\,visc}$.

Table 5. C_m values

Mixture type	C_m
Sand sheet and lean sand mixtures, lean open asphaltic concrete	1.6 – 2.0
Lean bitumen macadam	1.5 – 1.8
Asphaltic concrete, Gravel and asphalt dense bitumen macadam	1.2 – 1.6
Mastic asphalt, HRA	1.0 – 1.3

According to Table 5, the C_m values selected to be used in the computation of rut depth estimation in this investigation were 1.4 for the dense graded Asphaltic Concrete mixtures (AC-Control and AC-Plastiphalt). The values selected were based on the average value C_m values of each mixture. The following numerical assumptions were used to estimate the rut depth value of all mixtures investigated based on the above equations (Equations 4 and 5): T_w = 0.02 sec; C_m = 1.0; σ_{avg} = 0.25 MPa. The viscosity of bitumens obtained from the Van de Loo nomograph shown are presented in Table 6.

Table 6. Viscosity of bitumen

Bitumen type	PI	Viscosity of bitumen (Ns/m^2) at:	
		T = 40°C	T = 60°C
50-pen	-1.4	10000	220
100-pen	-0.9	5000	200

Rut depth estimation results

Results of rut depth estimation for various traffic loading from 1 million to 100 million standard axles at two temperatures investigated are presented in Figures 2 for dense graded A.C. mixtures. Based on this results, it can be seen that generally rut depth values increase with increasing number of standard axles and increasing temperature. The results also indicate that a highly significant correlation exists between estimated rut depth and number of standard axles (all correlation coefficient values obtained from the graph were above 0.98) with the form of:

$$R_d = a \times N^b \qquad (6)$$

where

R_d = rut depth;
N = number of wheel passes in million standard axles;
a = the interception of the line with the Y-axis;
b = the slope of the line

Table 7 shows regression parameters of the lines in Figures 2 for the relationships between estimated rut depths and number of standard axles. For comparison, Table 8 presents the estimated rut depth values at selected number of wheel passes (1, 10 and 100 million standard axles/mSAL) at two different pavement temperatures.

Table 7. Regression parameters for rut depth estimation ($r^2 > 0.98$)

Mixture type	40°C		60°C	
	'a'	'b'	'a'	'b'
AC-Control	1.54	0.18	3.00	0.18
AC-Plastiphalt	1.40	0.11	1.97	0.11

Table 8. Estimated rut depth values (mm)

Mixture type	40°C			60°C		
	1 mSAL	10 mSAL	100 mSAL	1 mSAL	10 mSAL	100 mSAL
AC-Control	1.5	2.3	3.5	3.0	4.5	6.8
AC-Plastiphalt	1.4	1.8	2.3	2.0	2.5	3.2

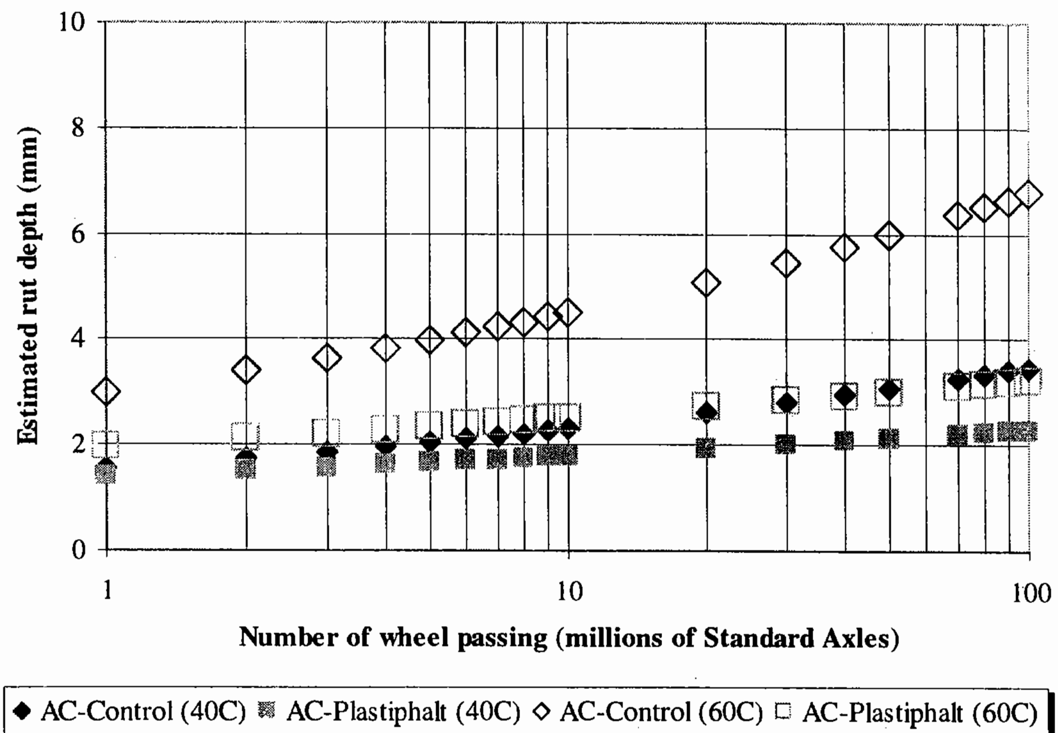

Figure 2. Rut depth estimation of dense graded Asphaltic Concrete mixtures at 40 and 60 °C

The following summaries by comparing the results obtained between different mixtures of dense graded A.C. mixtures and two different pavement temperatures:

1) At both test temperature of 40 and 60 °C, the AC-Plastiphalt mixtures had lower estimated rut depth values compared to the control mixtures. Both constants, 'a' and 'b', of the AC-Plastiphalt mixture were found to be lower than the values obtained on the conventional A.C mixtures.
2) Pavement temperature was found to be more significant on the estimated rut depth values of the conventional A.C. mixture as presented in Table 5, compared to the values calculated for the AC-Plastiphalt. For instance, the estimated rut depth for AC-Control increases from 2.3mm at 40°C to 4.5mm at 60°C (increase 1.9 times) after ten million standard axles wheel passes on the pavement.

   For the AC-Plastiphalt mixture the estimated rut depth values calculated at 40°C and 60°C were not much different. The rut depth increase was found to be only 1.3 times, i.e. the rut depth value increases from 1.8mm at 40°C to 2.3mm at 60°C.

CONCLUSIONS

The dynamic creep behaviour can be summarised as follows:

a. at both test-temperatures of 40 °C and 60 °C, the AC-Plastiphalt mixtures were found to generate higher irrecoverable strains compared to the control mixture,
b. the creep stiffness values of AC-Plastiphalt mixtures at 40 and 60 °C were thus found to be lower than the values obtained from the AC-Control mixture,
c. the AC-Plastiphalt mixtures were found to have higher creep slope values than the slopes of the control mixtures at 40°C, but lower at 60°C. This indicates that at higher temperatures the Plastiphalt mixtures have better deformation resistance than the control mixtures.
d. the creep recovery values of the AC-Plastiphalt after 1 hour unloading were found to be higher at all test temperatures investigated compared to the results found from the control mixture. These results reflect the increased elastic response of the AC-Plastiphalt mixture as a result of the incorporation of the plastics component.

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