Modern Applied Science
www.ccsenet.org/journal.html
Vol. 3, No. 7
July 2009

Effects of Temperature and Binder Type on the Dynamic Creep of Asphaltic Concrete Incorporating Geometrically Cubical Aggregates Subjected to Ageing

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Abstract

This paper presents an evaluation of the effects of temperature and binder type on the dynamic creep properties of asphaltic concrete mixtures incorporating granite aggregates produced via compression and impact modes of crushing. The creep test was carried out using the Asphalt Universal Testing Machine in accordance with procedures outlined in ASTM D4123. A conventional 80/100 bitumen and Styrene-Butadiene-Styrene (SBS) modified bitumen were used in sample preparation to evaluate the effects of binder types while the dynamic creep test was carried out at 40^{o}C and 60^{o}C. The results show that mixes prepared using geometrically cubical aggregate shape and SBS modified mixes exhibit higher creep stiffness than the unmodified mixtures. Temperature has a significant effect on creep stiffness, a mere 20^{o}C increase from 40^{o}C can cause the stiffness of unaged mixes to increase by as much as 51.8%. Linear regression analysis showed that mixes incorporating geometrically cubical aggregates and modified mixes are the least susceptible to creep stiffness.

Keywords: Creep stiffness, Short-Term ageing, Long-Term ageing, Modified binder, Geometrically cubical

1. Introduction

Permanent deformation in paving materials develops gradually with increasing number of load applications, and it appears as longitudinal depression in the wheel paths accompanied by small upheavals at the sides. The creep test provides sufficient information to determine the instantaneous elastic (recoverable) and plastic (irrecoverable) components and the time independent and time dependent of the materials response. Zhao (2002) defined the cumulative permanent strain curve into three zones: primary, secondary, and tertiary as shown in Figure 1. In the primary zone, the permanent deformation or strain accumulates rapidly. The incremental permanent deformation tends to decrease, reaching a constant value in the secondary zone. Finally, the incremental permanent deformation again increases and accumulates rapidly in the tertiary zone. In the field, Parker and Brown (1992) suggested that the top 7 to 10 cm of the pavement system is the portion which is most vulnerable to rutting. The rut rate depended on factors such as axle load, number of axle repetitions, tyre inflation pressure and pavement temperature. Kamal et. al. (2005) carried out creep tests on the cores extracted from the field. Mixes prepared using polymer modified bitumen were found to exhibit less accumulated strain at higher temperatures when compared to the conventional mixes.

The effects of coarse aggregate morphologies such as shape, angularity, and texture on the rutting resistance of hot mix asphalt (HMA) have been analyzed from field observations and laboratory standard tests. Significant increases in stability have been reported by Wedding and Gaynor (1961) when crushed gravel was used in place of uncrushed natural gravel in an HMA mixture. About 45 percent increase in stability has been reported with the substitution of all crushed aggregate (crushed gravel coarse and fine aggregate) for natural sand and gravel. Campen and Smith (1948) reported an increase in HMA stability of 30% to 190% by using crushed aggregate as compared to HMA incorporating natural rounded aggregate.

In service, HMA mixes undergo an ageing process resulting in bitumen embitterment. Typically, the effects of ageing on the mixture performance were investigated by ageing the bitumen and subsequently measuring the change in physical properties. In many instances, the process was extended into ageing of the mixes. Bell et al. (1994) found that the ageing rates for all bitumen tested have diminished significantly with temperature reduction suggesting that below 55^{o}C to 60^{o}C oxidative ageing may be relatively insignificant. Daniel at el. (2002) used two methods of simulating the hot-mix process. The first step involved a short term Rolled Thin Film Oven Test (RTFOT) with air-blowing procedure. For long term ageing comparisons, Pressure Ageing Vessel (PAV) ageing was compared with ageing in an environmental room maintained at 60^{o}C. Before that, all samples were RTFOT short term aged to simulate the hot-mix production process. It was found that 38 days of ageing in 1-mm thick films at 60^{o}C and 1 atm of air was approximately equivalent to 20 hours in the PAV in 3.2mm thick films at 100^{o}C, after RTFOT aged.

2. Material Characteristics

2.1 Aggregate

Crushed granite aggregates used for preparing asphalt concrete mixture were supplied by Yen Bumi Sdn. Bhd. The aggregates were re-crushed using a vertical shaft impact crusher shown in Figure 2, available in the laboratory of the School of Materials and Mineral Resources Engineering of the Universiti Sains Malaysia. The basic engineering properties of the geometrically cubical re-crushed aggregates is shown in Table 1.

2.2 Materials for Asphalt Mixes

The gradation of the HMA mixes met the requirements for the Malaysian Public Works Department ACW14 for wearing courses (JKR 1988) as depicted in Figure 3. The median gradation was regarded as the target gradation. Binder types used were a conventional binder (penetration grade 80/100) and an SBS polymer modified binder. The method of optimum binder content (OBC) determination based on the Marshall method of mix design is available in another literature (Hamzah et al., 2006). A total of 24 samples were prepared to determine the OBC and the result for mixes incorporating irregularly and geometrically shaped aggregates are shown in Table 2. Table 3 provides a guide on mix designation.

2.3 Dynamic Creep Test

The dynamic creep test was developed to estimate the rutting potential of asphalt mixes. This test was conducted using the Asphalt Universal Testing Machine, MATTA in accordance with the procedures outlined in ASTM D4123 (ASTM, 2005). The test parameters adopted are summarized in Table 4. Actual dynamic creep test was conducted at 40^{0}C, 1 hour loading time and 0.1 MPa applied stress.

2.4 Aging of Bituminous Mixtures

Short-term ageing was carried out on loose mix according to AASHTO R30-02 (AASHTO, 2002) procedures. The method consisted of curing mix samples in a forced-draft oven at 135°C for 4 hours. After curing, the samples were brought to the compaction temperature and compacted via impact mode. The long term ageing was carried out on compacted specimens after subjected to short term ageing. Specimens were placed in a forced-draft oven at 85°C for five days. To accelerate ageing, ultra-violet light was incorporated. After the aging period, the oven was turned off and allowed to cool to room temperature. The specimens were then extruded and tested for dynamic creep.

3. Result and Discussion

3.1 Dynamic Creep Behaviour of Unaged Mixes

The effect of temperature on dynamic creep of all unaged asphaltic concrete mixtures tested is shown in Table 5. In general, the dynamic creep at 40^0C is much higher compared to the corresponding value at 60^0C. The increase ranges from as low as 11.9% to as high as 107.7%. The positive effects of using geometrically cubical shaped aggregates can be seen from the overall results summarized in Table 5. Generally, mixes incorporating geometrically cubical shaped aggregates perform better than mixes with aggregates crushed using the conventional compression crusher. The percentage increase in creep stiffness is more pronounced with conventional mixes tested at lower temperatures. For instance, when tested at 40^oC, at binder content 5.5%, the creep stiffness of IK mix is 14.5 MPa but the stiffness modulus of HMA mixtures with CK mix is 21.4 MPa which represents a 47.6% increase. Table 5 also shows that the SBS mixes exhibit the highest creep stiffness compared to the conventional mix type. On average, the creep stiffness of the SBS mixes is 29% more compared to conventional mixes when tested at 40^oC. Within the limited range of binder content investigated, the appear to be no relationship between percentage increase in stiffness versus binder content though there is a general tendency for the stiffness to increase as binder content increases but reduces beyond the maximum value.

3.2 Effect of Short Term Ageing on Creep Stiffness

Table 6 shows the creep stiffness results of mixes at their respective OBC after exposure to short term ageing. The unaged results are shown for comparative purposes. On average, subjecting mixes to short term ageing causes an increase in stiffness by approximately 10.5% when tested at both temperatures. However, the general trend remains as in unaged mixes, namely mixes become less resistant to permanent deformation at higher temperature. An increase in 20^oC test temperature can reduce the creep stiffness of STA mixes by 15.8%. Resistance to permanent deformation of STA mixes can be increased by up to 26% by incorporating geometrically cubical aggregates. Compared to conventional mixes with irregularly shaped aggregates, the creep stiffness of SBS modified mixes with shaped aggregates subjected to STA can be significantly increased by up to nearly 50%.

3.3 Relationship between Cumulative Strain and Time of Loading for STA Mixes

Figures 4 and 5 show the relationship between logarithm of cumulative creep strain and logarithm of loading time of specimens tested at 40^oC and 60^oC respectively. There is an initial absence of data due to pre-conditioning which was necessary to obtain a proper seating of the test platens on the specimen prior to the actual creep test. A log-log graph was plotted to linearise the original accumulated strain versus loading time curve. Nevertheless, the resulting graph is not entirely linear but consisting of two straight lines of different slopes. The first straight (primary line) has a steeper slope ‘m’ compared to the gradient of the second curve (secondary line). The y-intercept ‘c’ represents the extrapolated permanent strain at loading time equals 1, while the slope of the line represents the rate of change in permanent strain as a function of the change in loading time. The slope therefore indicates the sensitivity of mix to rutting. The resistance to permanent deformation of a mix is expected to increase when the relative intercept becomes less and the slope of the line decreases. Table 7 presents the coefficients of the linear regression for both primary and secondary lines. An attempt was also made to regress all test results into a single linear equation and the coefficients of the linear regression are also shown in Table 7. A comparison of the regression constants for all mixes after STA indicates that:

- The ‘m’ for unaged mixes is higher compared to STA mixes. Hence, ageing of mix causes a reduction in creep susceptibility.
- SBS mixes exhibit the lowest slope compared to conventional 80/100 mixes.
- Mixes with geometrically cubical aggregates show lower ‘m’ value compared to irregularly aggregates mixes.
- The modified mixtures indicate good permanent deformation characteristics compared to the conventional unmodified mixes.
- For all mixes tested, the ‘m’ value increases when the temperature increases.

It can be concluded that mixes subjected to STA, modified mixes and mixes incorporating geometrically cubical aggregates are the least susceptible to creep. However, mixes also become more sensitive to creep stiffness as temperature increases.

3.4 Effect of Long Term Ageing and Ultraviolet on Dynamic Creep

A similar analysis is carried out for specimens subjected to LTA in addition to ultra-violet. The corresponding results are shown in Table 8. Compared to unaged mixes, a percentage increase of the creep stiffness by two-fold is observed on LTA samples, indicating the extent of binder hardening that has taken place during the LTA process. The conventional mix is found to be more adversely affected when its average creep stiffness increased by about 22.8% while the corresponding increase of the SBS modified bitumen is approximately 16%. As in previous findings, creep stiffness reduces at higher test temperature. The average percentage reduction is slightly less compared to those of STA specimens but much less compared to unaged mixes. This phenomenon can be explained in terms of the binder of aged mixes that has hardened hence making them less susceptible to temperature changes. The effect of temperature change on creep stiffness is lesser with the degree of ageing.

3.5 Relationship between Cumulative Strain and Time of Loading for LTA Mixes

Figures 6 and 7 illustrate the linear relationships between cumulative strain versus loading cycles plotted on a logarithmic scale. As in Section 3.3, the regression coefficients of the primary, secondary and single lines are summarized in Table 9. Similar trends with STA results are evident. The conventional and irregularly shaped mixes are more susceptible to ageing compared to mixes incorporating modified and geometrically cubical aggregate. The average 'm' for unaged, STA and LTA mixes are respectively $6.56x10^{-6}$, $3.61x10^{-6}$ and $1.86x10^{-6}$ respectively. It can be infer that each ageing process reduce mix sensitivity to creep by a half. Mixtures become less sensitive to creep at lower temperature as the bitumen becomes stiffer.

4. Conclusions

An increase in creep stiffness can be achieved when geometrically cubical re-crushed aggregates are used in asphaltic concrete mix compared to uncrushed irregularly shaped aggregates mix. An improvement in creep stiffness values is observed when SBS modified binder is used. Within the small range of binder content tested, there appear to be an optimum stiffness value for all mixes. Generally, mix creep stiffness reduces when the test temperature increases from 40^0C to 60^0C. The reduction is more pronounced with unaged mixes. The effect of ageing is to increase the creep stiffness but reduces the mix susceptibility to creep over time. The combined effect of geometrically cubical aggregates and modified binder can improve the creep stiffness to nearly 50%.

Acknowledgements

The financial support provided by Universiti Sains Malaysia in the form of a short term research grant for this study is very much appreciated. The authors wish to acknowledge the technicians of Highway Engineering Laboratory, School of Civil Engineering and technicians of Material Engineering, School of Materials and Mineral Resources Engineering for their help in carrying out the laboratory works. We also acknowledge Metso Minerals for loaning the Barmac Rock on Rock Vertical Shaft Impact (RoR VSI) crusher that enable preparation of the re-crushed aggregates to be made.

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Table 1. Aggregate Properties Used in the Mix

Property	**Test Value of Aggregate Shape**	
	Irregularly Shape	**Geometrically Cubical**
Flakiness Index (%)	17.57	7.94
Elongation Index (%)	33.24	11.89
Aggregate Crushing Value (%)	21.77	18.11
Aggregate Impact Value (%)	25.98	22.22
Water Absorption (%)	0.74	0.59

Table 2. Optimum Binder Content of the Mixes Investigated

Mix Type	**Optimum Binder Content (%)**	
	Irregularly Shaped	**Geometrically Cubical**
Conventional Mixes	5.0	4.8
SBS Modified Mixes	5.0	4.7

Table 3. The Mix Designation of Ageing Test

Binder Types	**Aggregate Shape**	**Mix Conditioning**	**Mix Designation**
80/100	Geometrically	Unaged	CK
	Irregularly	Unaged	IK
	Geometrically	Short Term	CKS
	Irregularly	Short Term	IKS
SBS	Geometrically	Unaged	CS
	Irregularly	Unaged	IS
	Geometrically	Short Term	CSS
	Irregularly	Short Term	ISS
80/100	Geometrically	Long Term	CKL
	Irregularly	Long Term	IKL
SBS	Geometrically	Long Term	CSL
	Irregularly	Long Term	ISL

Table 4. The Dynamic Creep Test Parameters Adopted in this Study

Parameter	**Duration**
Pulse period (ms)	1000
Pulse width (ms)	200
Test Loading Stress (kPa)	100
Terminal Pulse Count	3600

Table 5. Dynamic Creep Stiffness of Unaged Asphalt Mixes Incorporating Cubical and Irregularly Shaped Aggregates

Binder Type	Mix Designation	Binder Content (%)	Creep Stiffness at Test Temperature	
			40°C	60°C
Conventional 80/100	IK	4.5	14.5	12.7
		5.0	20.5	17.7
		5.5	18.6	12.4
	CK	4.3	21.4	13.7
		4.8	24.4	21.8
		5.3	20.0	12.8
SBS Modified	IS	4.5	19.6	15.2
		5.0	24.4	19.1
		5.5	23.1	12.7
	CS	4.2	26.3	15.9
		4.7	30.6	25.6
		5.2	29.5	14.2

Table 6. Dynamic Creep Stiffness (MPa) of Short-Term Aged Asphalt Mixes Incorporating Cubical and Irregularly Shaped Aggregates

Binder Type	Mix Designation	Un-Aged		STA	
		Temperatures (°C)		Temperatures (°C)	
		40°C	60°C	40°C	60°C
80/100	IK	20.5	17.7	22.8	18.7
	CK	24.4	21.8	27.6	24.3
SBS	IS	24.4	19.1	26.5	22.3
	CS	30.6	25.6	33.4	27.6

Table 7. Coefficients of the Linear Relationship between Log Cumulative Strain and Log Time of Loading for Primary, Secondary and Single Lines of STA Compared with Unaged Mixes

Type of Ageing			**Un-aged**			**Short Term Ageing**		
Primary Line								
Binder Type	**Mix Desig-nation**	**Tempe-rature (°C)**	**m ($1x10^{-6}$)**	**c ($1x10^{-3}$)**	**R^2**	**m $1x10^{-6}$)**	**c ($1x10^{-3}$)**	**R^2**
80/100	IK	40	71.5	44.2	0.78	32.2	29.4	0.78
	CK		51.6	40.2	0.80	29.2	29.4	0.77
SBS	IS		44.1	35.2	0.76	27.5	29.0	0.78
	CS		44.1	33.3	0.78	27.5	25.0	0.78
80/100	IK	60	38.2	33.3	0.76	23.0	23.5	0.78
	CK		37.7	33.1	0.80	22.5	23.1	0.78
SBS	IS		35.1	32.3	0.77	20.5	21.8	0.79
	CS		34.8	30.3	0.76	19.5	19.3	0.79
Secondary Line								
80/100	IK	40	6.9	62.6	0.94	3.7	41.6	0.96
	CK		6.5	58.6	0.94	3.5	41.6	0.96
SBS	IS		6.2	54.6	0.94	3.5	35.9	0.96
	CS		5.0	51.2	0.95	2.6	35.0	0.97
80/100	IK	60	4.8	49.9	0.95	2.5	34.5	0.97
	CK		4.5	47.2	0.96	2.3	32.3	0.97
SBS	IS		4.3	47.0	0.96	2.3	30.8	0.97
	CS		4.0	46.2	0.96	2.3	27.8	0.97
Single Line								
80/100	IK	40	8.8	56.9	0.85	4.9	38.5	0.80
	CK		8.2	55.1	0.72	4.6	38.5	0.80
SBS	IS		6.8	49.5	0.75	3.5	33.6	0.81
	CS		6.3	46.6	0.72	3.5	32.7	0.82
80/100	IK	60	6.1	45.8	0.79	3.4	32.2	0.83
	CK		5.8	43.7	0.76	3.3	30.1	0.83
SBS	IS		5.3	43.3	0.76	3.0	28.6	0.82
	CS		5.2	42.3	0.80	2.7	25.7	0.82

Table 8. Dynamic Creep Stiffness (MPa) of Long Term-Aged Asphalt Mixes Incorporating Cubical and Irregularly Shaped Aggregates

Binder Type	Mix Designation	Un-Aged Test		LTA Test Temperature	
		40°C	60°C	40°C	60°C
80/100	IK	20.5	17.7	24.9	21.7
	CK	24.4	21.8	30.3	27.3
SBS	IS	24.4	19.1	28.7	23.8
	CS	30.6	25.6	35.1	29.9

Table 9. Coefficients of the Linear Relationship between Log-Cumulative Strain and Log-Time of Loading for Primary, Secondary and Single Line soft LTA Compared with Unaged Mixes

Type of Ageing			Un-aged			Long Term Ageing		
Primary Line								
Binder	**Mix**	**Tempe-rature**	**m**	**c**	**R^2**	**m**	**c**	**R^2**
80/100	IK	40	71.5	44.2	0.78	17.8	18.2	0.85
	CK		51.6	40.2	0.80	17.5	16.2	0.84
SBS	IS		44.1	35.2	0.76	14.8	12.3	0.80
	CS		44.1	33.3	0.78	13.0	9.0	0.82
80/100	IK	60	38.2	33.3	0.76	11.3	7.8	0.80
	CK		37.7	33.1	0.80	11.0	7.3	0.80
SBS	IS		35.1	32.3	0.77	10.4	6.2	0.80
	CS		34.8	30.3	0.76	9.2	4.2	0.80
Secondary Line								
80/100	IK	40	6.9	62.6	0.94	1.8	25.5	0.99
	CK		6.5	58.6	0.94	1.8	23.6	0.98
SBS	IS		6.2	54.6	0.94	1.5	17.8	0.97
	CS		5.0	51.2	0.95	1.4	12.9	0.98
80/100	IK	60	4.8	49.9	0.95	1.4	12.7	0.98
	CK		4.5	47.2	0.96	1.4	10.6	0.98
SBS	IS		4.3	47.0	0.96	1.2	10.4	0.98
	CS		4.0	46.2	0.96	1.2	9.2	0.98
Single Line								
80/100	IK	40	8.8	56.9	0.85	2.4	23.7	0.84
	CK		8.2	55.1	0.72	2.3	21.8	0.83
SBS	IS		6.8	49.5	0.75	2.0	16.5	0.89
	CS		6.3	46.6	0.72	1.9	11.9	0.86
80/100	IK	60	6.1	45.8	0.79	1.9	11.4	0.85
	CK		5.8	43.7	0.76	1.8	9.6	0.85
SBS	IS		5.3	43.3	0.76	1.6	9.5	0.85
	CS		5.2	42.3	0.80	1.0	7.8	0.85

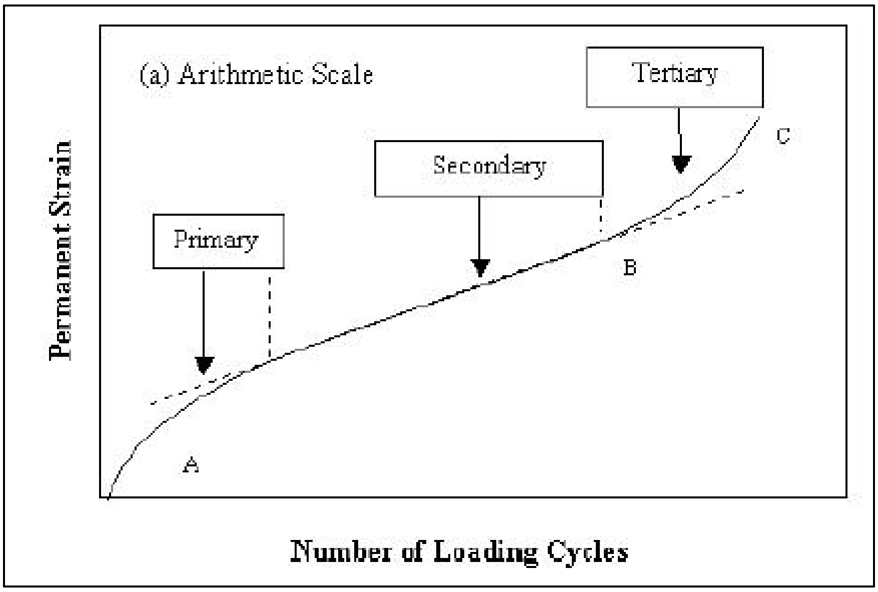

Figure 1. Typical Relationships between Permanent Strain and Number of Loading Cycles in Normal Scale (Zhao, 2002)

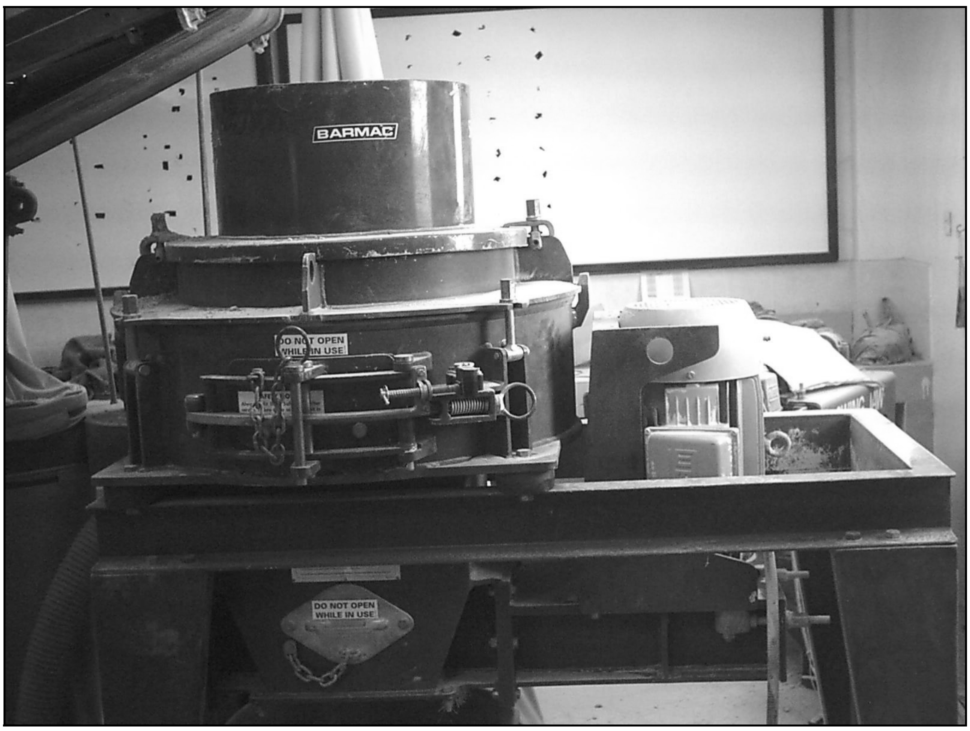

Figure 2. Vertical Shaft Impact Crusher Used to Crush the Aggregates

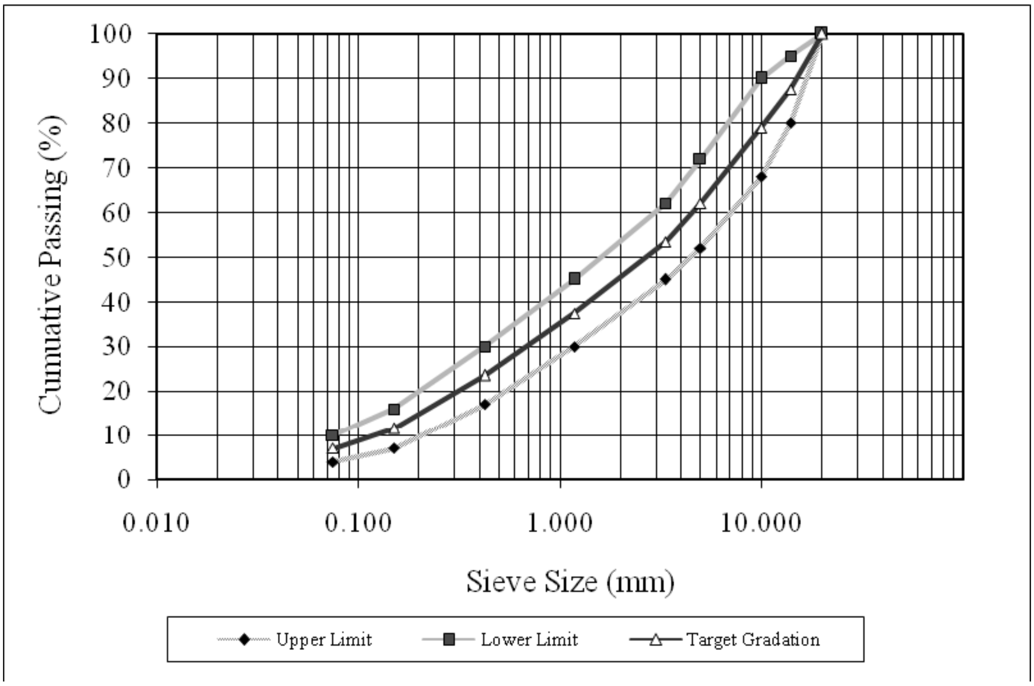

Figure 3. JKR Gradation Limits for ACW14 Used in this Investigation (JKR, 1988)

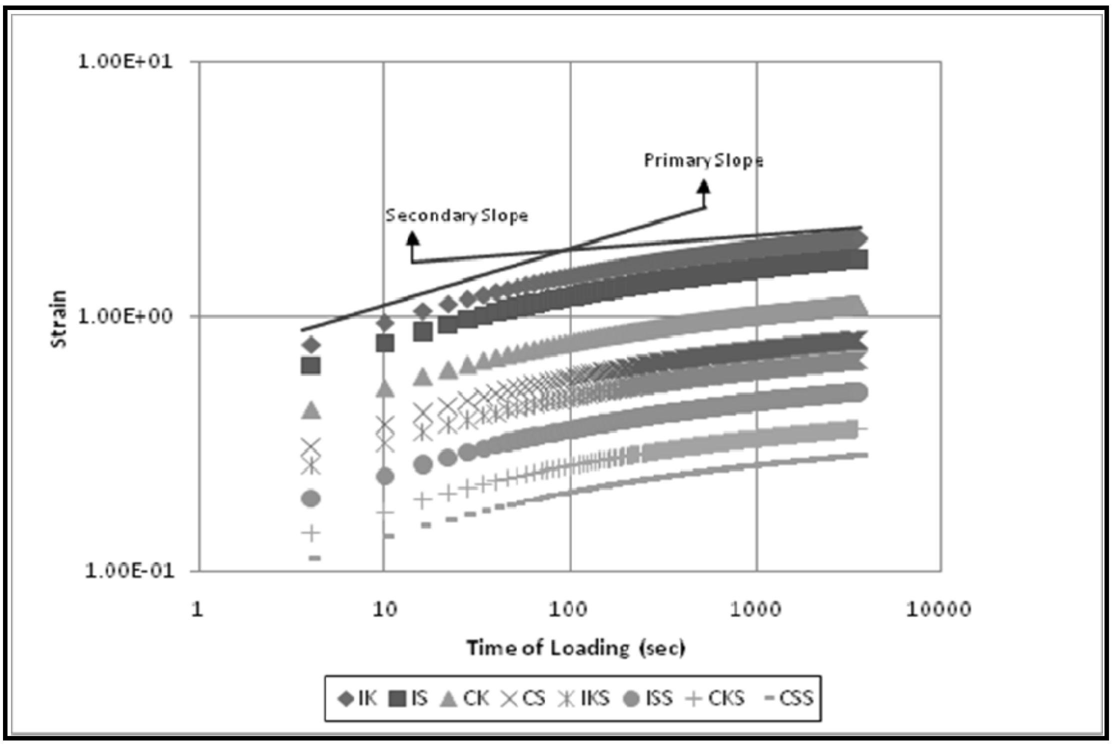

Figure 4. Relationship Between Log Cumulative Strain Versus Log Time of Loading

(Test Temperature 40°C)

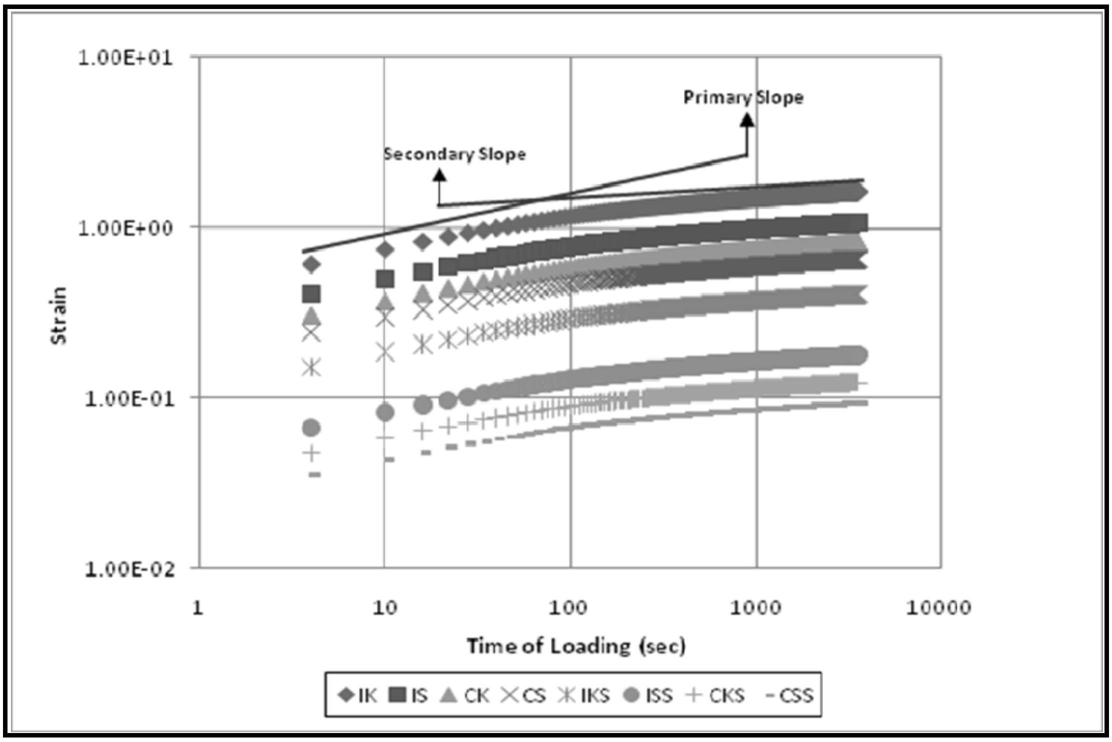

Figure 5. Relationship Between Log Cumulative Strain versus Log Time of Loading (Test Temperature 60°C)

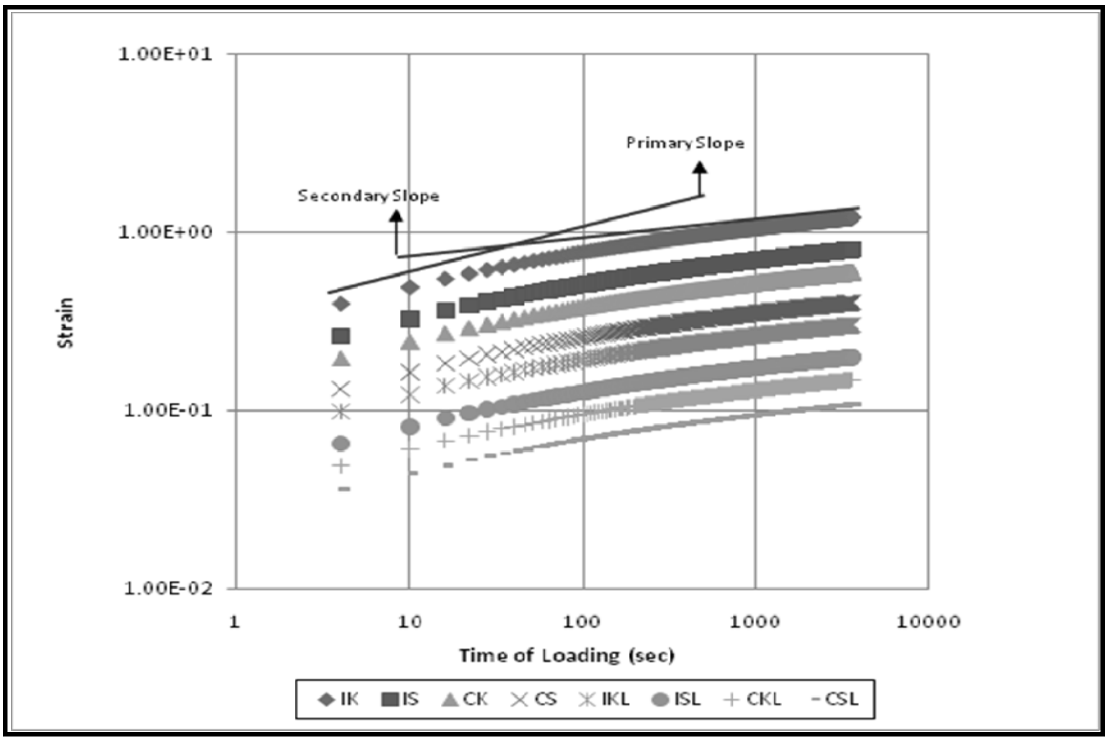

Figure 6. Graphical Determination of Primary and Secondary Slopes Log-Cumulative Strain versus Log-Time of Loading at 40°C

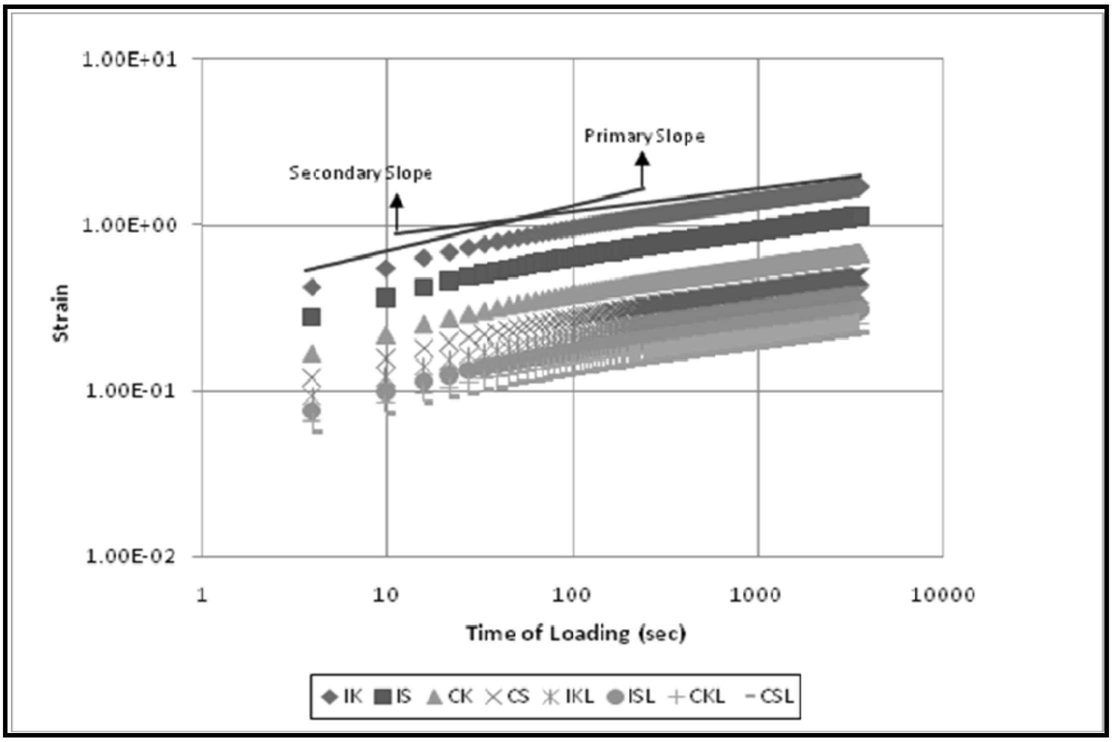

Figure 7. Graphical Determination of Primary and Secondary Slopes Log-Cumulative Strain versus Log-Time of Loading at 60°C