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Research Article

Evaluation of Permanent Deformation of Unmodified and Rubber-Reinforced SMA Asphalt Mixtures Using Dynamic Creep Test

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This paper presents the evaluation of permanent deformation of rubber-reinforced SMA asphalt mixtures by using dynamic creep test. The effect of trans-polyoctenamer as a cross-linking agent in permanent deformation of rubberized mixtures was also evaluated. Dynamic creep test was conducted at different stress levels (200 kPa, 400 kPa) and temperatures (40°C, 50°C). Permanent deformation parameters such as dynamic creep curve, ultimate strain, and creep strain slope (CSS) were used to analyse the results. Finally, the creep behaviour of the specimens was estimated by the Zhou three-stage creep model. The results show that crumb rubber and trans-polyoctenamer significantly affected the parameters especially at high stress and temperatures. Consistent findings were observed for all permanent deformation parameters. Moreover, based on Zhou model, it was concluded that resistance to permanent deformation was improved by application of crumb rubber and trans-polyoctenamer.

1. Introduction

Mechanical behaviour of asphalt highly depends on ambient temperature due to its viscoelastic properties. Asphalt becomes softer and less viscous as temperature increases. On account of that, asphalt binder becomes more susceptible to adopt permanent deformation and thus accelerates rutting in wheel tracks. Moreover, stress induced by loading is another main parameter that leads to permanent deformation in asphalt pavement.

Rutting is observed as the main distress mechanism typically occurring in countries with high pavement in-service temperature like Malaysia. Malaysia essentially experiences tropical weather with the mean annual air temperature of 28°C and maximum air temperature of 45°C and the maximum average air temperature during the hottest 7-day period (over the pavement design life) being 38°C [1]. Road pavement temperature in Malaysia on the other hand ranges from 20°C in the early hours of the day to as high as 60°C in midday during a hot day. In addition, overloaded vehicles are very common users of Malaysian roads. In 2008, 27% or 270,000 out of the one million registered commercial vehicles on the roads in the country were commonly overloaded. Overloading of such with high environmental temperature could cause great damage to pavements and therefore deteriorate pavement performance faster than planned.

Incorporating waste tyre in the pavement can be used to tackle some of the pavement problems as shown by many research studies [2–4]. Due to the benefits offered by crumb rubber, many research works have been implemented on the effects of chemical additives to further increase the performance of rubberized binder. Recent studies have shown that the properties of rubberized binder can be improved by adding substances such as chemical stabilizer, an activation agent, and polymers in which the main function is to activate the rubber asphalt interaction and improve cross-linking. For instance, incorporating trans-polyoctenamer to rubberized binder improves the elastic responses at high

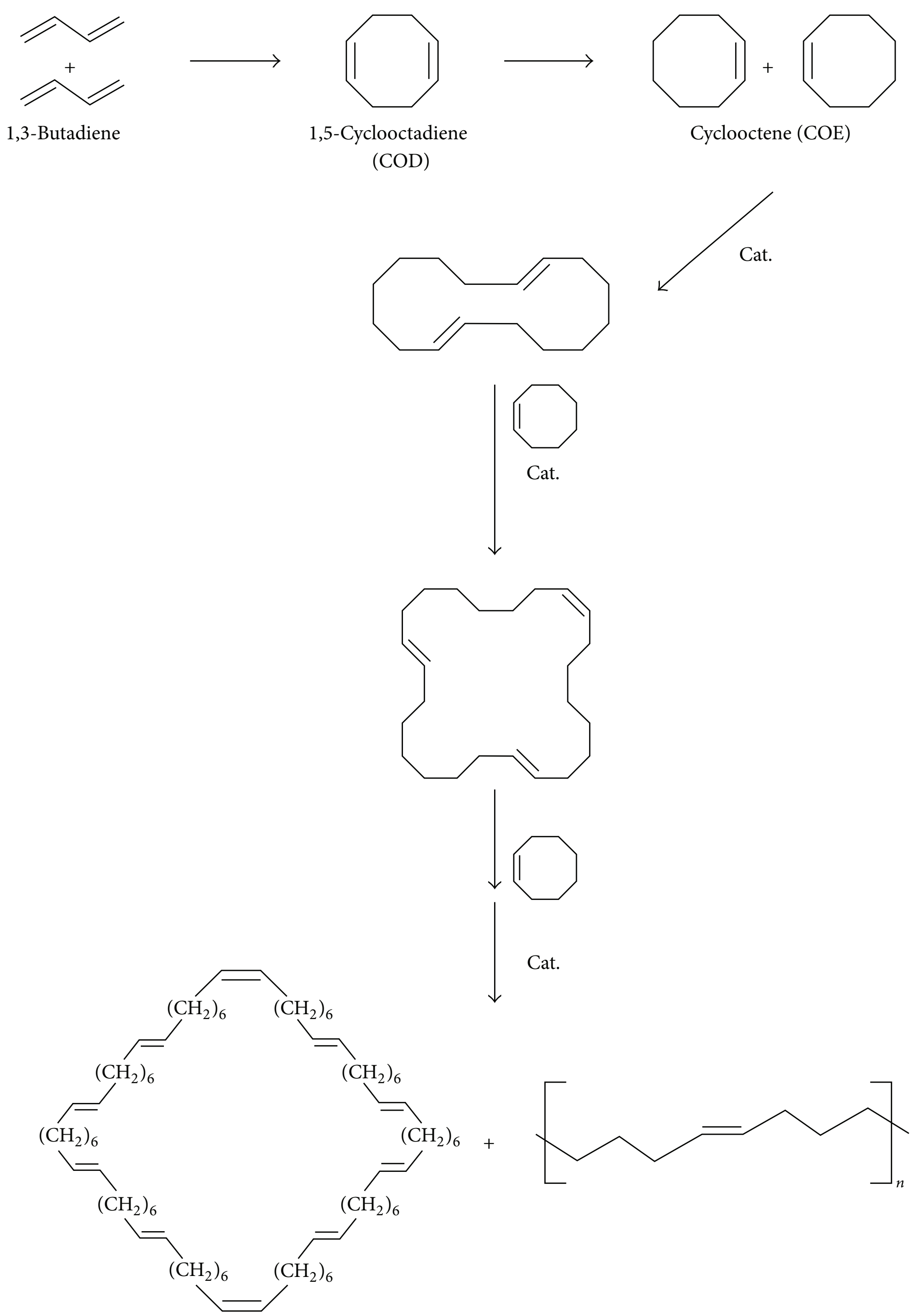

Figure 1: Synthesis of trans-polyoctenamer [22].

temperatures and reduced creep stiffness at low temperatures [5]. Therefore this modification reduces the risk of cracking at low temperatures and rutting at high temperatures.

Trans-polyoctenamer is a kind of polymer with a double bond structure, in which the main task is to cross-link the sulphur of the asphaltene and the sulphur on the surface of the crumb rubber to form a ring and mesh composed of chain polymers [6]; thus, it prevents the sinking of the rubber particles by increasing the viscosity. Evonik Degussa GmbH [7], explained that trans-polyoctenamer chemically bonds to the crumb rubber during its blending and converts the thermoplastic asphalt to a thermoset polymer that can help reduce cracking and rutting. Trans-polyoctenamer is structured of cyclooctene which is synthesized from 1,3-butadiene via 1,5-cyclooctadiene. Cyclooctene is polymerized to polyoctenamer that produces both linear and cyclic macromolecules. The molecular formula of polyoctenamer is –(C4H7=C4H7)– *n* and its synthesis is shown in Figure 1.

Dynamic creep test performed using such well recognized apparatus like the Universal Testing Machine (UTM),

Table 1: Properties of crushed granite aggregate used in this study.

Properties	Specification	Results	REAM requirement	Conform
Aggregate crushing value	BS812: part 3	20%	<25%	Yes
Polished stone value	BS812: part 3	51.7	>40%	Yes
Flakiness index value for coarse aggregate	BS182: part 3	4%	<25%	Yes
Flakiness index value for fine aggregate	BS182: part 3	13%	<25%	Yes
Water absorption for coarse aggregates	ASTM C 127-88	0.586%	<2%	Yes
Water absorption for fine aggregates	ASTM C 127-88	0.723%	<2%	Yes

which provides multiple output data with reasonable test time and less material consumption, seems to be the most popular option to evaluate permanent deformation of asphalt mixtures. To match the real environmental conditions, the influence of different temperature and loading conditions (e.g., frequency, duration, load cycles, and stress level) on permanent deformation can be evaluated and incorporated under UTM. Previous research reported that dynamic creep test had very good correlation with measured rut depth and a high capability to estimate rutting potential of asphalt layers. Research conducted by Kaloush and Witczak [8] mentioned that dynamic creep test is an appropriate laboratory method to investigate the permanent deformation of modified and unmodified asphalt mixtures. Moreover, it is reported by Fontes et al. [9] that results from the dynamic creep tests are so closely correlated with the results of wheel tracking test.

In addition to the laboratory tests, many researchers are interested in developing the performance models to characterize the permanent deformation and further estimate the future pavements' service. As reported by Zhou et al. [10], various mathematical models, among which are well known models such as power-law model, *VESYS* model, Ohio State model, Superpave, and AASHTO 2002, have been developed for fitting the creep curve and estimating the flow number (FN) parameter in asphalt mixtures. However, these models are limited to describing only the primary stage. West et al. [11] have also developed a three-stage model, but their model cannot estimate the boundary points of curve stages. Therefore, a new three-stage model comparable to the field performance termed as Zhou model [10] is proposed as follows:

$$\begin{aligned}
&\text{Primary stage: } \varepsilon_p = aN^b, \quad N < N_{PS} \\
&\text{Secondary stage: } \varepsilon_p = \varepsilon_{PS} + c\left(N - N_{PS}\right), \\
&\qquad \varepsilon_{PS} = aN_{PS}^b, \\
&\qquad N_{PS} \le N \le N_{ST} \\
&\text{Tertiary stage: } \varepsilon_p = \varepsilon_{ST} + d\left(e^{f(N-N_{ST})} - 1\right), \\
&\qquad \varepsilon_{ST} = \varepsilon_{PS} + c\left(N_{ST} - N_{PS}\right), \quad N \ge N_{ST}.
\end{aligned} \tag{1}$$

Many current research studies used Zhou model to evaluate permanent deformation of unmodified and modified asphalt mixtures [12–14]. It seems that Zhou model outweighs the other model as it can develop mathematical functions to characterize three-stage permanent deformation behaviour of asphalt mixes. Moreover, Zhou model also can be used to identify the transition point between stages especially the new indicator of asphalt mixes: flow number, FN [15].

2. Objectives and Experimental Procedure

Due to hot weather with an increase in traffic loading experienced in Malaysia, this study was conducted to investigate the permanent deformation of commonly used aggregate gradation, SMA 20. Effects of crumb rubber as asphalt modifier on permanent deformation characteristics of SMA 20 mixture were also evaluated. To achieve this objective, control and rubberized mixtures were tested for dynamic creep by means of UTM at different stress levels (200 and 400 kPa) and temperatures (40 and 50°C). To further improve performance of rubberized asphalt as well as to study the chemical reactions, trans-polyoctenamer was added. Consequently, test results were analysed to determine the permanent deformation parameters such as dynamic creep curve, ultimate strain, and creep strain slope (CSS). Finally, creep models were derived based on Zhou three-stage model.

3. Materials and Specimen Preparation

3.1. Aggregates, Asphalt, Crumb Rubber, and Cross-Linking Agent. Kajang Rock Quarry Sdn. Bhd. located in Kajang, Malaysia, is the supplier of the aggregates. Crushed granite aggregate used in sample preparation is a mixture of coarse aggregate, fine aggregate, and mineral filler sieved from 20-nominal-size aggregate, 10-nominal-size aggregate, and quarry dust. A 2% Portland cement by weight of the mixtures as proposed under REAM SP 4/2008 is used in all specimens' preparation [16]. Table 1 shows the physical properties of crushed granite aggregate tested in accordance with ASTM international standards (ASTM) and British Standard (BSI) with quality requirement specified by REAM SP 4/2008.

Bitumen grade 80/100 penetration obtained from the vacuum distillation residue derived from crude oil is widely used in Malaysian road construction. In this study, bitumen 80/100 was obtained from Asphalt Technology Sdn. Bhd. located at Port Klang, Malaysia. The basic properties of asphalt including penetration, softening point, and high temperature viscosity tested in accordance with ASTM D 5, ASTM D 36, and ASTM D 4402 are presented in Table 2 [17–19].

Table 2: Basic properties of asphalt and rubberized asphalt.

Properties	Control asphalt	Rubberized asphalt	
	80/100 pen	12R	12R 4.5V
Penetration (25°C, 100 g, 5 s) (0.01 mm) (ASTM D 5)	95.00	67.50	66.29
Softening point (ring and ball) (°C) (ASTM D 36)	44.25	51.00	53.00
Viscosity at 135°C (mPa s) (ASTM D 4402)	375.25	807.80	997.80

Table 3: Specification of crumb rubber used in this study.

Chemical and physical properties	Rubber size 30 mesh
Acetone extract (ISO 1407), %	10 ± 3
Ash content (ISO), %	8 ± 3
Carbon black (ISO 1408), %	30 ± 5
Rubber hydrocarbon (RHC), %	52 ± 5
Passing (ASTM D5644), %	>90
Heat loss (ASTM D1509), %	<1
Metal content (ASTM D5603), %	<1
Fiber content (ASTM D5603), %	<3

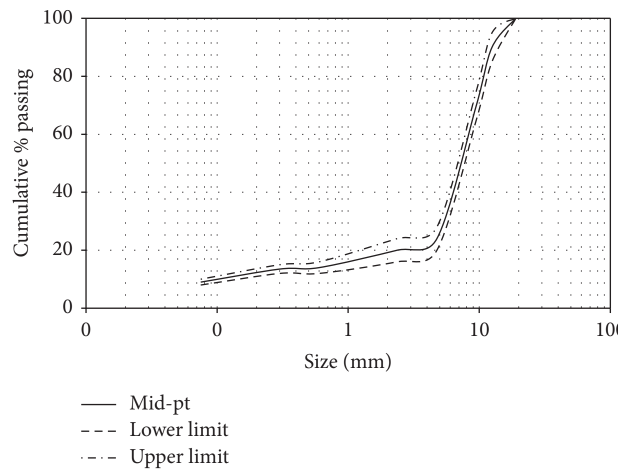

Figure 2: SMA 20 aggregate gradation.

In order to investigate the effect of the crumb rubber on rutting resistance of SMA 20 mixtures, crumb rubber sized 30 mesh (0.60 mm) supplied by Rubplast Sdn. Bhd. was used in this study. Twelve percent (12%) of crumb rubber by weight of bitumen 80/100 penetration was used in preparation of rubberized bitumen. Table 3 shows the chemical and physical properties of crumb rubber.

Trans-polyoctenamer bought from Evonik Degussa GmbH, Germany, with the trademark *Vestenamer* was chosen as a cross-link dispersant, which, along with crumb rubber, might improve the binder performance. The recommended dosage, 4.5% by weight of crumb rubber, was incorporated into rubberized bitumen [20–22]. Table 4 shows the chemical and physical properties of trans-polyoctenamer, respectively.

3.2. Mix Design

3.2.1. Preparation of Rubberized Asphalt. Rubberized asphalt was prepared by adding crumb rubber sized 30 mesh (0.60 mm) to 80/100 pen asphalt cement. In this study, rubberized asphalt was prepared with 12% crumb rubber (12R) and 12% crumb rubber with 4.5% trans-polyoctenamer (12R 4.5V). The mixing was done using propeller mixer at speed of 200 rpm for 45 minutes and mixing temperature was maintained at 180°C. Crumb rubber and trans-polyoctenamer were added simultaneously at the beginning of the mixing. For all types of rubberized asphalt, amount of crumb rubber is calculated by weight of the asphalt, while amount of trans-polyoctenamer is calculated by weight of the crumb rubber.

The laboratory produced rubberized asphalt was given identification names. Table 5 presents the binder ID with the matrix for three types of binders developed and evaluated in this study. Control sample designated as control was prepared with bitumen 80/100 penetration. 12R stands for rubberized asphalt prepared with 12% of crumb rubber (by weight of 80/100 penetration bitumen), whereas 12R 4.5V is rubberized asphalt prepared with 12% crumb rubber (by weight of bitumen 80/100 penetration) and 4.5% trans-polyoctenamer (by weight of crumb rubber).

3.2.2. Preparation of Specimen. In this study SMA 20 aggregate gradation as shown in Figure 2 was used in preparation of all specimens. Optimum asphalt content determined by Marshall method was used. It was determined that optimum asphalt content for control specimen is 5.0%, whereas 5.5% is the optimum asphalt content for specimens prepared with 12R and 12R 4.5V binder. Table 6 shows the mix design of specimens evaluated in this study. The same designations were also used in specimen prepared from the respective binders.

Each specimen comprised 1100 g of aggregates and 2% of Portland cement by weight of the mix. Aggregate and cement were heated in the oven for one hour at 150°C. Aggregate was then transferred to the pan and heated at higher temperature of 170°C. The rubberized asphalt (12R and 12R 4.5V) at optimum content was added to the aggregate and mixed at 170°C until all aggregates were fully coated with the binder. Mixture was then transferred to the Marshall mould and was spaded 15 times around the parameter and 10 times over the interior. Mixture was compacted by applying 50 blows for both sides with the Marshall compactor when temperature reached 140°C. After compaction, the mould was removed from the base-plate; the specimen was cured for 24 hours in the mould at room temperature before extruding it by means

Table 4: Specification of trans-polyoctenamer used in this study.

Property		Test method	Unit	Value
Molecular weight M_w	GPC	DIN 55672-1	—	90,000
Glass transition temperature	Tg	ISO 11357	°C	−65
Crystallinity	23°C	ISO 11357	%	30
Melting point	DSC 2nd heating	ISO 11357	°C	54
Apparent density	23°C	ISO 60	g/l	560
Density	23°C	ISO 1183	g/cm^3	0.91
Tensile test				
Stress at yield			MPa	7.5
Strain at yield		ISO 527-1/-2	%	25
Strain at break			%	400
	23°C		kJ/m^2	165
Tensile impact strength	0°C	ISO 8256	kJ/m^2	190
	−20°C		kJ/m^2	240

Table 5: Matrix of binders developed.

Base bitumen 80/100 penetration	Rubber content, %	Trans-polyoctenamer, %	
Binder ID		0	4.5
Control	0	√	
12R	12	√	
12R 4.5V	12		√

Table 6: Mix design of specimens.

Specimens ID	Optimum asphalt content, %	Binder used
Control	5.0	Bitumen 80/100 pen.
12R	5.5	12R
12R 4.5V	5.5	12R 4.5V

of an extrusion jack. Similar procedure was followed for preparation of control specimen except mixing temperature was done at 150°C and compacted at 135°C.

4. Creep Test

Maximum particle size of aggregate in the mixtures is 19 mm (≤20 mm); therefore specimens were trimmed at top and bottom side with a diamond saw to the final thickness of 50 mm. Both sides of each sample were coated with a thin layer of silicone grease containing graphite flakes in order to obtain smooth faces. This is to eliminate the influence of unevenness of specimen face which would affect the test results.

The repeated creep test was performed using Universal Testing Machine (UTM). It is the most commonly used device to measure the permanent deformation of asphalt mixture in laboratory. Specimen will be placed in the temperature controlled cabinet for 2 hours to ensure that equilibrium temperature is reached. Specimen was then placed between the platens. The assembled platens and specimen were aligned concentrically with the loading axis of the testing machine. The displacement measuring device is then attached to the platens. The vertical deformation is then measured by the linear variable differential transducers (LVDTs). In this study, the loading parameters consisted of a haversine wave shape with two stress levels of 200 kPa and 400 kPa and in addition two test temperatures of 40°C and 50°C were selected. The load was applied for 0.5 s followed by a rest period of 1.5 s. The specimen was terminated after 1800 load cycles or until accumulated strain reaches 100,000 μs. The accumulated strain was calculated by using the following equation:

$$\varepsilon = \frac{h}{H_0}, \quad (2)$$

where ε is the accumulated strain, h is the axial deformation, mm, and H_0 is the initial specimen height, mm.

5. Result and Analysis

5.1. Dynamic Creep Curve. After testing, dynamic creep curves of all specimens were obtained. These data are depicted in Figures 3(a)–3(d). It can be found that there are significant differences among these curves. Each dynamic creep curve consists of two parts, namely, primary stage and secondary stage. Primary stage presents recoverable elastic strain due to densification of the mixture while secondary stage shows viscoelastic strain resulted by cumulative axial strain [23]. In this test, tertiary stage of specimen did not occur due to a short loading period of 1800 cycles except for control mixture tested at 400 kPa stress level and 50°C.

Higher accumulated axial strains values indicate that mixes have lower rutting resistance potential. It is apparent that specimens prepared with rubberized asphalt show a lower cumulative permanent strain compared to control specimen as seen in Figures 3(a)–3(d). This is because crumb rubber which has partially digested into the asphalt absorbs

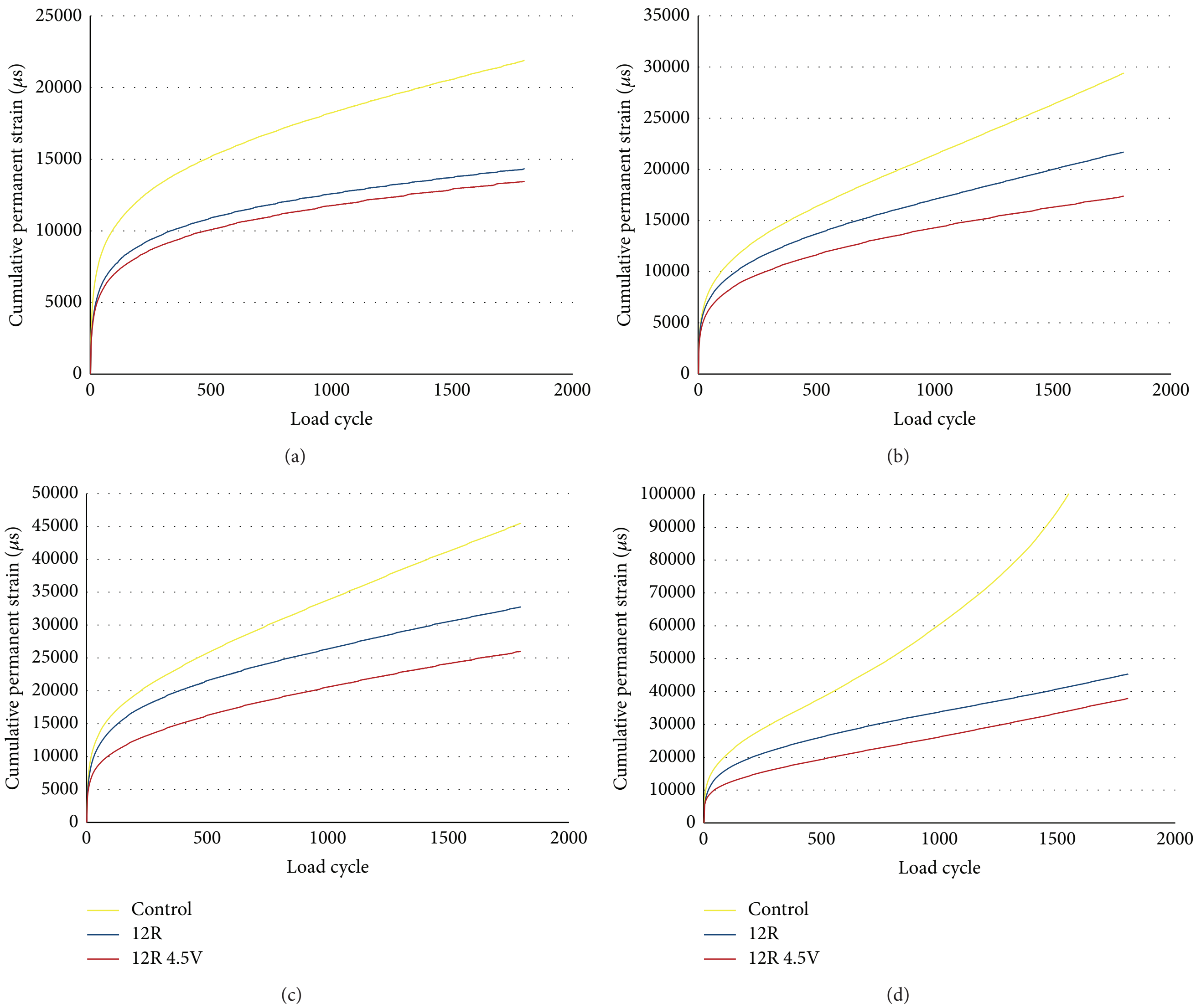

Figure 3: Cumulative permanent strain versus load cycle for control and rubberized mixtures tested at (a) 200 kPa at 40°C, (b) 200 kPa at 50°C, (c) 400 kPa at 40°C, and (d) 400 kPa at 50°C.

the aromatic oils from the asphalt into the rubber's polymer chains. It implies the formation of gel-like material that results in higher viscosity and elasticity of the asphalt. Such interactions improve the binder networking and allow greater film thickness surrounding the aggregate in the mixture. This will reinforce the aggregate bonding of the mixtures thus resulting in higher strength. Furthermore, the crumb rubber which is not digested in the asphalt will maintain their integrity, interweave together, and form a three-directional network when distributed uniformly in the mixtures. This spatial reinforcing network could reinforce the mixtures and resist damage propagation.

As can be seen in Figures 3(a)–3(d), incorporating trans-polyoctenamer as a cross-link dispersant agent in preparation of rubberized binder indicates a significant enhancement in the behaviour of mixtures as showed by 12R 4.5V mixtures. This implies that trans-polyoctenamer improves the rheological properties of rubberized binder by activating the crumb rubber and asphalt to form a chemical reaction. The reaction permits cross-linking with the sulfur associated with the asphaltenes and maltenes in the asphalt to create a macro-polymer network. Finally, a uniform, low tack, rubber-like composite is produced which is capable of improving the rutting resistance of the mixtures [24].

5.2. Ultimate Strain. Results of ultimate strain after 1800 load cycles are illustrated in Figure 4. As can be seen in the figure, the ultimate strain of rubberized mixtures improves remarkably compared to the control mixtures. In all test conditions, specimens prepared with 12R 4.5V show the lowest ultimate strain followed by 12R and control mixture. It implies that incorporating crumb rubber and trans-polyoctenamer in asphalt provides significant impact on susceptibility of mixtures to permanent deformation.

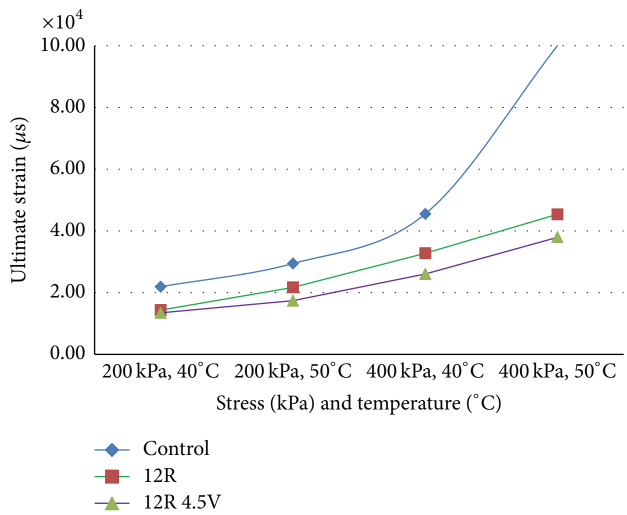

Figure 4: Ultimate strains for control and rubberized mixtures at different stress level and temperature.

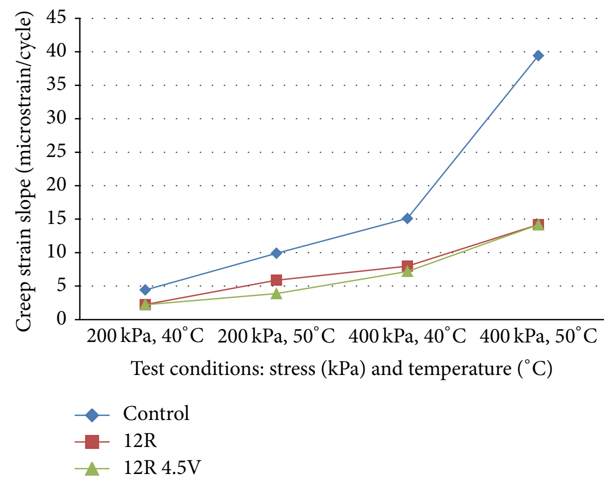

Figure 5: CSS results for control and rubberized mixtures versus test conditions.

It is important to note that the ultimate strain increases at higher temperature. For instance, at 200 kPa stress, in case of control mixture when the temperature increases from 40°C to 50°C, the strain value rises from 21901.06 μs to 29418.91 μs which is 1.34 times higher in comparison with 40°C. However, dependency of ultimate strain on temperature in rubberized mixtures is considerably lower than that of control mixtures, especially specimen with addition of trans-polyoctenamer. For example, at stress level 200 kPa and 400 kPa, increase in 10°C (from 40°C to 50°C) the ultimate strain for control mixture increases 1.34 and 2.20 times, while 12R 4.5V rises at lower rates compared to control mixture that is, 1.29 and 1.46 times, respectively.

The similar trend was observed by rising stress level in which the ultimate strain increases by an increment in stress (from 200 kPa to 400 kPa) for both 40°C and 50°C temperatures. In control mixtures, the rate of increment is more than rubberized mixtures. Results show that the ultimate strain increased 3.40, 2.09, and 2.18 times for control, 12R, and 12R 4.5V, respectively, as stress increased from 200 kPa to 400 kPa at 50°C. This means that control mixtures deform more than three times while rubberized mixtures show better resistance to deformation as stress increases.

Moreover, control mixture deforms very fast at highest test condition (400 kPa, 50°C). In other words, increase in stress and temperature has caused a dramatic growth in the ultimate strain of control mixtures so that these samples faced a total destruction of 100,000 μs. On the contrary, in the rubberized mixtures, the ultimate strain is much lower which is 45359.73 μs and 37915.94 μs for 12R and 12R 4.5V, respectively, which is equivalent to 2.20 and 2.64 times less compared to control mixture. Thus, efficiency of crumb rubber was clearly observed at highest test condition which the rubberized mixtures deform much lower compared to control mixture.

5.3. Creep Strain Slope (CSS). CSS is the slope of the secondary phase of typical repeated load creep test results. It is calculated from the regression line that excludes the primary stage and therefore perfectly reflects the rate of deformation affected by the load cycling. For constant stress loading conditions, the creep strain rate is approximately constant during the secondary creep phase. Hence, CSS is another permanent deformation characteristic that shows the developing rate of deformation [25, 26].

Figure 5 shows the CSS results for control and rubberized mixtures under different stress level and temperature. Similar to ultimate strain results, Figure 5 manifests that modifying asphalt mixtures with rubber and trans-polyoctenamer decreases the temperature and stress susceptibility of the mixtures. In other words, dependency of permanent deformation on temperature and stress in rubberized mixtures is considerably lower than that of control mixture.

As seen in Figure 5, increasing the temperature from 40°C to 50°C at stress level of 200 kPa in control mixtures increases the CSS 2.24 times (from 4.42 to 9.90). Moreover, at stress level of 400 kPa, 10°C increase in temperature results in rises CSS 2.61 times (from 15.10 to 39.44) for control mixture. However, in rubberized mixtures at 200 kPa and 400 kPa stress level, an increase 10°C in temperature can lead to 1.74 times and 1.97 times increase, respectively (from 2.22 to 3.87 and from 7.19 to 14.16), considerably lower than control mixture. Rubberized mixtures at both stress levels, therefore, are less sensitive to temperature increase than control mixture.

Further, by rising stress level, the same finding was observed. Increase in load stress leads to increase in CSS for all mixtures. Result obtained by control mixture shows that increasing the stress level from 200 kPa to 400 kPa at 40°C rises the CSS around 3.42 times (from 4.42 to 15.10) and 3.98 times (9.90 to 39.44) at 50°C. CSS for rubberized mixtures also increases as stress level increases; however the rate is lower compared to control mixture. For instance, at the same test condition as above, the CSS for rubberized mixtures increases 3.24 times (from 2.22 to 7.19) and 3.66 times (from 3.87 to 14.16), which is slightly lower than the control mixture.

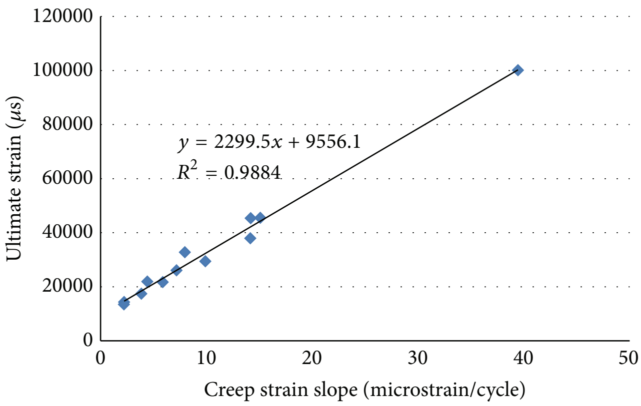

Figure 6: Ultimate strain versus creep strain slope for control and rubberized mixtures.

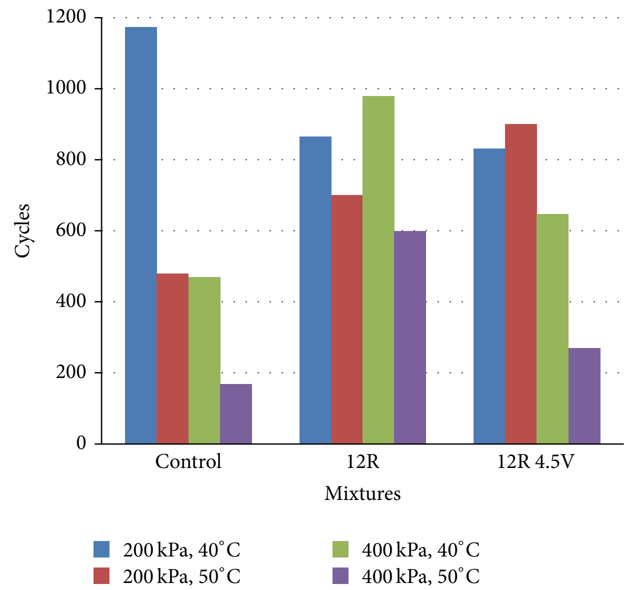

Figure 7: Number of load cycles at first stage for control and rubberized mixtures at all test conditions.

The above findings show that the rubberized mixtures are less susceptible to stress level compared to control mixture.

It is important to note that comparison of CSS between control and rubberized mixtures becomes more significant as stress level and temperature increase. For instance, the rate of CSS for control mixtures is 1.99, 2.56, 2.10, and 2.78 times that of the 12R 4.5V for 200 kPa, 40°C; 200 kPa, 50°C; 400 kPa, 40°C; and 400 kPa, 50°C, respectively. However, it seems that low temperature and low stress level did not reveal the benefits of rubberized asphalt. Above phenomenon is probably due to the behaviour of crumb rubber particles that do not dissolve entirely in asphalt; it swells and adsorbs the certain components of the asphalt. Therefore the crumb rubber maintains their integrity and acts as flexible filler in the mixtures. At high temperature, the crumb rubber is stiffer than the asphalt while at low temperature the asphalt is stiffer whereas the crumb rubber properties do not change significantly. Thus, at low temperature and stress level, the strength of mixture is not attributable to the role of rubberized binder but rather more to the contact points in the aggregate skeleton. As seen in Figure 5, at 200 kPa stress level and 40°C temperature, the CSS for all mixtures is not much different; thus it supported above justification.

Relationship between ultimate strain and CSS is shown in Figure 6. There is a good correlation between these two parameters. The relationship coefficient of the fitted curve, R^2, is 0.9884. It is apparent that ultimate strain increases with an increase of CSS. Therefore if the creep strain slope of the mix is being enhanced; then its susceptibility to permanent deformation will increase as the consequence. Thus ultimate strain and CSS are considered to be useful parameters for evaluating the permanent deformation susceptibility of the mixtures.

6. Zhou Three-Stage Model

In this study, Zhou three-stage model was used for better understanding of permanent deformation behaviour of the mixtures. Regression analysis as explained by Zhou et al. [10] was utilized to determine the mathematical functions as well as transition points between each stage and use it for modelling each stage.

The results are presented in Tables 7 and 8. Achieved results show that all curves obey the Zhou model. Similar strain values are observed when predicted strains calculated via mathematical functions based on Zhou model were comparable with measured strain.

As seen in Tables 7 and 8, results show that control and rubberized mixtures only achieve the secondary stage. This is due to short loading cycles (1800); tertiary stage was not achieved. However, at 400 kPa stress and 50°C, the control mixtures enter the tertiary stage after 829 loading cycles whereas the rubberized mixtures are still at the second stage.

Figure 7 shows number of load cycles at first stage also known as transition point from first stage to second stage for all mixtures. Generally, the number of load cycles decreases as stress level and temperature increase. As first stage presents recoverable elastic and second stage presents viscoelastic behaviour of the mixture, it means that specimen changes to viscoelastic behaviour faster as stress level and temperature increase. At 40°C, for instance, increasing stress level from 200 kPa to 400 kPa leads the control mixture to enter the second stage from 1173 cycles to 469 cycles which is 2.5 times faster.

From Figure 7, it can be illustrated that length of first stage for rubberized mixture is longer than control mixture. This shows that rubberized mixtures sustain the first stage longer compared to control mixture. For example, at 400 kPa and 40°C, transition point for 12R mixture is 979 cycles while control mixture is 469 cycles which is more than two times longer. Although the length of first stage of modified mixtures is generally longer than control mixture, exception is observed at low test condition (200 kPa stress level and 40°C temperature).

Table 7: Three-stage models and boundary points for control and modified mixtures at 200 kPa stress.

Test temperature	Sample	Primary stage				Secondary stage		Tertiary stage
		Model	End point	Measured strain, μs	Predicted strain, μs	Model	End point	Model
40°C	Control	$\varepsilon_p = 2979.3N^{0.2628}$	$N = 1173$	19100.08	19086.48	$\varepsilon_p = 19086.48 + 4.422\,(N\text{-}1173)$	a	a
	12R	$\varepsilon_p = 2331.3N^{0.2486}$	$N = 865$	12222.56	12523.92	$\varepsilon_p = 12523.92 + 2.235\,(N\text{-}865)$	a	a
	12R 4.5V	$\varepsilon_p = 2169.4N^{0.248}$	$N = 831$	11294.98	11492.13	$\varepsilon_p = 11492.13 + 2.223\,(N\text{-}831)$	a	a
50°C	Control	$\varepsilon_p = 2513.8N^{0.3004}$	$N = 479$	16116.79	16051.05	$\varepsilon_p = 16051.05 + 9.904\,(N\text{-}479)$	a	a
	12R	$\varepsilon_p = 2505.7N^{0.2737}$	$N = 701$	15183.12	15059.21	$\varepsilon_p = 15059.21 + 5.886\,(N\text{-}701)$	a	a
	12R 4.5V	$\varepsilon_p = 2227.5N^{0.2673}$	$N = 901$	13865.05	13728.26	$\varepsilon_p = 13728.26 + 3.865\,(N\text{-}901)$	a	a

[a]Not found at the end of 1800 load cycle.

Table 8: Three-stage models and boundary points for control and modified mixtures at 400 kPa stress.

Test temperature	Sample	Primary stage				Secondary stage		Tertiary stage
		Model	End point	Measured strain, μs	Predicted strain, μs	Model	End point	Model
40°C	Control	$\varepsilon_p = 4088N^{0.2949}$	$N = 469$	25185.27	25074.93	$\varepsilon_p = 25074.93 + 15.1\,(N\text{-}469)$	a	a
	12R	$\varepsilon_p = 3740.9N^{0.2823}$	$N = 979$	26216.27	26138.10	$\varepsilon_p = 26138.10 + 7.977\,(N\text{-}979)$	a	a
	12R 4.5V	$\varepsilon_p = 2891.4N^{0.277}$	$N = 647$	17659.15	17367.15	$\varepsilon_p = 17367.15 + 7.19\,(N\text{-}647)$	a	a
50°C	Control	$\varepsilon_p = 5146.9N^{0.307}$	$N = 169$	25046.38	24860.33	$\varepsilon_p = 24860.33 + 39.439\,(N\text{-}169)$	$N = 829$	$\varepsilon_p = 50890.1 + 2789.6(e^{0.0046(N\text{-}829)} - 1)$
	12R	$\varepsilon_p = 4100.3N^{0.2983}$	$N = 599$	27859.29	27626.26	$\varepsilon_p = 27626.26 + 14.184\,(N\text{-}599)$	a	a
	12R 4.5V	$\varepsilon_p = 3923.8N^{0.2462}$	$N = 269$	15792.31	15556.50	$\varepsilon_p = 15556.5 + 14.162\,(N\text{-}269)$	a	a

[a]Not found at the end of 1800 load cycle.

7. Statistical Analysis

Statistical analysis was performed using SPSS software to analyse the relationships between permanent deformation of the mixtures and the parameters. The two-way analysis of variance (ANOVA) was used with a confidence interval of 95% ($\alpha = 0.05$). To present permanent deformation of the mixtures, ultimate strain was selected as dependent variable while temperature, stress, and additive (rubber and trans-polyoctenamer) were selected as independent variables. The result of two-way ANOVA is tabulated in Table 9, which indicates that temperatures, stress, and additive have a significant effect on the ultimate strain when the P value is less than 0.05. The interaction effect between the chosen parameters also has a significant effect on the ultimate strain.

8. Conclusion and Recommendations

Based on the findings, use of crumb rubber in construction of pavement deserves serious consideration as it significantly improves the resistance to deformation compared to unmodified mixtures. The effect of crumb rubber is more significant at high stress and temperature. This fits in with Malaysia's conditions which observe tropical weather and high traffic volume. Moreover, addition of trans-polyoctenamer increases the resistance to deformation of rubberized mixtures.

Conclusion has been drawn as follows.

(1) Trans-polyoctenamer improves the properties of rubberized asphalt as best resistance to permanent deformation shown by 12R 4.5V at all test conditions.

(2) At higher stress level and temperature, permanent deformation resistance of both control and rubberized mixtures decreased.

(3) Methods to analyse the permanent deformation by dynamic creep curve, ultimate strain, and CSS are consistent.

Table 9: Two-way ANOVA on ultimate strain.

Source	SS	df	MS	F	P value
Corrected model	1.727E10	11	1.570E9	575.347	0.000
Intercept	3.410E10	1	3.410E10	12495.654	0.000
Stress	6.012E9	1	6.012E9	2203.268	0.000
Temperature	2.126E9	1	2.126E9	779.059	0.000
Additive	3.795E9	2	1.897E9	695.332	0.000
Stress ∗ temperature	8.442E8	1	8.442E8	309.402	0.000
Stress ∗ additive	1.361E9	2	6.806E8	249.424	0.000
Temperature ∗ additive	8.831E8	2	4.416E8	161.829	0.000
Stress ∗ temperature ∗ additive	7.231E8	2	3.616E8	132.513	0.000
Error	5.457E7	20	2728588.943		
Total	5.663E10	32			

a. R Squared = 0.997 (adjusted R Squared = 0.995).

(4) Creep curve observes the Zhou model trend. Predicted strain calculated by Zhou model is similar to measured strain.

(5) Based on Zhou model, length of first stage of creep curve increased considerably in rubberized mixtures.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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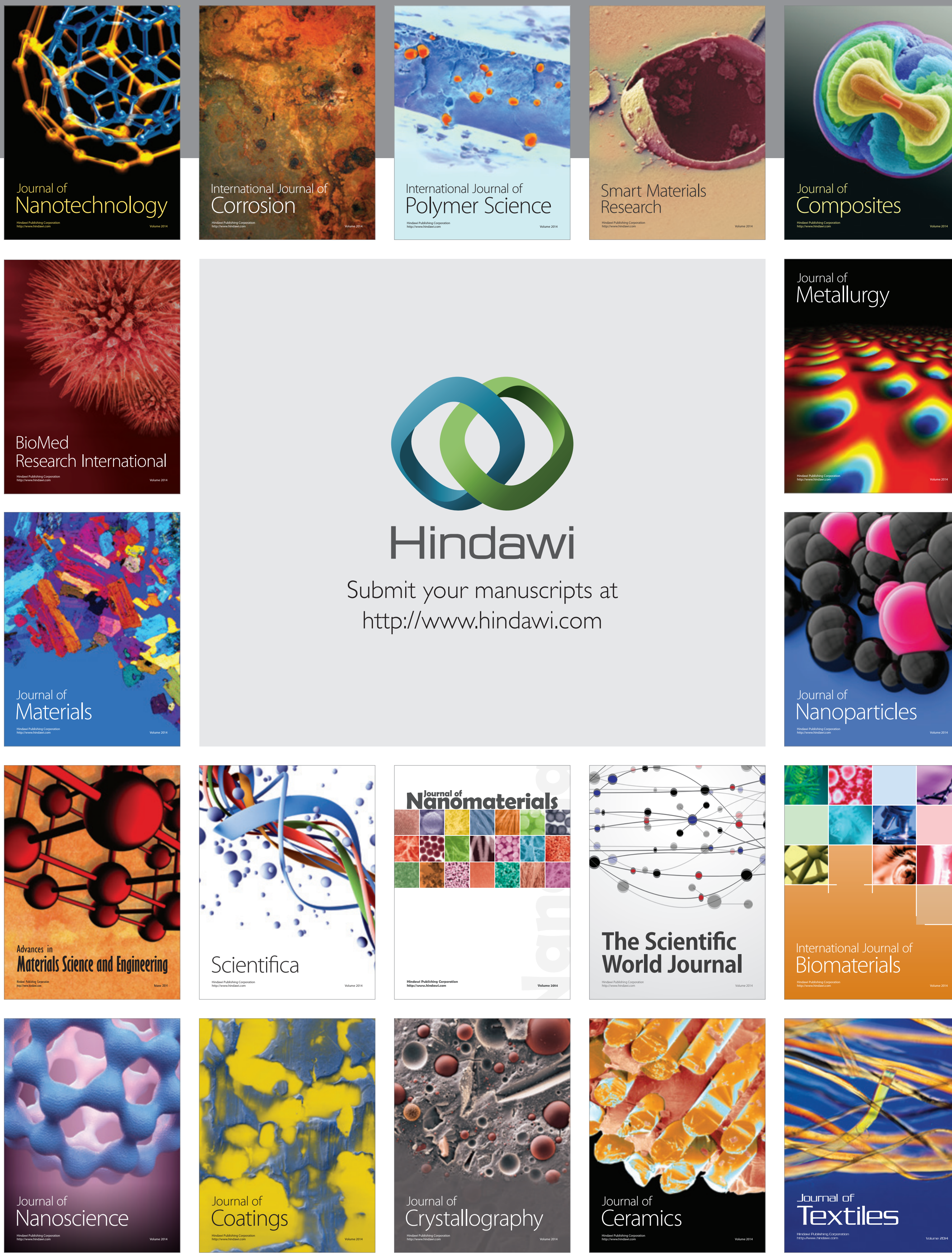
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