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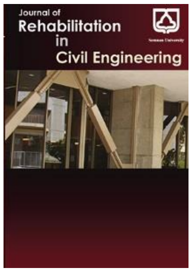

Effect of Emulsified Asphalt Content on Creep Behavior and Mechanical Properties of Cold Recycled Emulsified Asphalt Bases

Sarella Chakravarthi[1*], Galipelli Raj Kumar[2], Sabavath Shankar[3], Radhakrishnan Vishnu[3]

1. Research Scholar, Department of Civil Engineering, National Institute of Technology, Warangal, India
2. Ex-M. Tech, Department of Civil Engineering, National Institute of Technology, Warangal, India
3. Assistant Professor, Department of Civil Engineering, National Institute of Technology, Warangal, India
Corresponding author: *chakravarthi.sarella@student.nitw.ac.in*

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ABSTRACT

Since the beginning of the 21st century, the rapid development of road infrastructure has facilitated enhanced mobility and accessibility that has caused environmental degradation due to the continuous extraction of natural aggregates. To address this increasing problem, recycled aggregates and Reclaimed Asphalt Pavement (RAP) materials have been utilized in road construction worldwide. The studies related to various emulsified asphalt contents on permanent deformation and other parameters are limited. This study examined the performance characteristics of cold recycled emulsified asphalt bases with RAP materials in different proportions, i.e., 25%, 50%, and 75%, and evaluated in terms of the indirect tensile strength, tensile strength ratio, density, water loss, and permanent deformation at lower and higher emulsified asphalt contents than optimum. The results demonstrated that the total residual binder content influences the permanent deformation characteristics of cold mixes. There was no significant variation in the durability and strength with the RAP at the optimum emulsified asphalt content. But, the emulsified asphalt contents other than optimum influence the strength, density, and permanent deformation. The logarithmic and power-law models are best suited to predict the first-stage permanent deformation of cold mixes.

1. Introduction

The utilization of emulsified asphalt in the recycling of deteriorated pavements is a non-hazardous and environmentally-friendly approach. [1]. RAP is the primarily recycled material that has been used in the cold recycling process in which the deteriorated asphalt pavement is recycled with emulsified asphalt. This cold recycling process improves

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the modulus of the base-layer that results in the improvement of structural number [2]. Further, the cold recycled layer can be used as a base layer or binder course with a thin asphalt layer.

The pavement layers subjected to live loads that include construction vehicles and usual traffic that lead to several premature failures like; rutting and cracking. Rutting is one of the primary structural shortcomings of the asphalt pavements that increase with traffic [3]. The leading causes of rutting include inadequate compaction, high-temperature conditions, and higher traffic loads [4]. Besides, the asphalt content significantly influences the mechanical properties of the mix. For instance, higher asphalt content in a mix than optimum asphalt content results in higher fatigue life and lower stiffness [5-6]. Similarly, the lower asphalt contents result in thermal cracking and high permeability [7]. From the extensive literature, it was noticed that minimal studies had been found on the influence of binder content on the permanent deformation of cold mixes as bases. As the cold mix design is entirely different from that of Hot Mix Asphalt (HMA), there is a high requirement to study the rutting characteristics. Rutting characteristics could be evaluated using a dynamic creep rutting test. The test is highly correlated with the field conditions and more reliable in predicting the permanent deformation and simulates field conditions Monismith et al. (1975) [8-10].

Earlier research works on Cold Recycled Emulsified Asphalt Mixes (CREAM) used RAP up to 60% and 100% in the base courses that significantly influenced the mix performance. [11-12]. So, the RAP content and source influence the performance of the mix. The studies on the variation of emulsified asphalt contents significantly affect the fatigue behavior of the cold mixes at different stress levels. Lower emulsified asphalt contents are recommended at lower stress levels, and higher emulsified asphalt contents are recommended for higher stress levels [13]. Dong et al. (2019) proposed a balanced mix design for cement emulsion mixes and evaluated them in cracking and rutting. The results demonstrated that lower emulsified asphalt contents and higher cement contents performed well [14]. However, there are limited studies on the performance of cold mixes with emulsion contents other than Optimum Emulsified Asphalt Content (OEAC). The current research studied the performance of cold mixes comprised of RAP blends that are replaced with Natural Aggregates (NA) using performance tests such as Tensile Strength Ratio (TSR), permanent deformation using dynamic creep rutting test at different emulsified asphalt contents mainly at less than OEAC, at OEAC, and higher than OEAC, and models were developed to determine the permanent deformation of different mixes for multiple repetitions. Though there are different models available predicting the rutting of HMA, a few identified models are helpful to estimate the permanent deformation of cold mixes, such as; three-stage models, logarithmic models, power-law models, and Stephen price models [15-17]. In general, any HMA subjected to the rutting test has three regions. The regions are primary, secondary, and tertiary. The primary and tertiary regions are non-linear, and the second region is linear. In literature, different creep models were proposed for these regions in a combination or separately. Also, the power fit model is recommended for the primary region; linear fit for the secondary region, and an exponential fit for the tertiary region [17]. Further, a logarithmic model for the primary region is recommended [10, 18]. Additionally, a deviation error was created to check the model's. This reiterates the process until the obtained percentage of deviation error is less than 1%. So, both logarithmic and exponential rutting models are tried in the current study.

2. Materials and methodology

RAP was collected from a local district road. In contrast, NA, i.e., aggregates were collected from the local quarry in three different sizes and evaluated for its physical properties according to the Ministry of Road Transport and Highways (MoRTH, 2014) specifications and are presented in Table.1 [19]. Except for the Flakiness and Elongation Index, all the properties are within the specification limits. Since these materials are used for several years under traffic loads, there is a development of a fractured surface while crushing the RAP. Hence, the RAP might have more degradable properties than the NA or may not fall within the specifications. Three different mixes were prepared using RAP which was partially replaced with NA in the ratio of 1:1,1:3 and 3:1 (RAP-50, RAP-25, RAP-75) contents, representing the depth of milling. The gradation curves for different stacks of NA and RAP with the corresponding Nominal Maximum Aggregate Size (NMAS) and RAP blends are shown in Fig.1. All the mixes fall within the upper and lower limits of the Asphalt Academy, 2009 specifications. Additive like 1% to 2% cement helps form a homogeneous mix [20]. The cement content below 1% is ineffective in early strength gain, and excess cement beyond 2.5% results in brittle nature in the mixes [20-21]. Hence, 2% of Ordinary Portland cement (OPC) was adopted to prepare the samples. Cationic Slow Setting (CSS-2) emulsion was selected as a binder for the preparation of the samples. The properties of the CSS-2 are performed according to specifications and are available in Table 2.

A homogeneous mixture was prepared with calculated quantities of dry aggregates and cement. Next, the amount of pre-wetting water was selected based on the minimum degree of coating, i.e., 50% coating [20, 22]. The pre-wetting water was added to the mix, and the degree of the coating was observed to visibly confirm more than 50% coating of the asphalt emulsion [20]. The observed pre-wetting water contents are 2.5%, 2.5%, and 1.5% for 25%, 50%, and 75% of RAP mixes. Next, specimens of size 101 mm diameter and 63 mm height were prepared using the Marshall method of compaction with 75 blows on each side. The prepared samples were cured for 72 h at 40°C in a hot air oven, representing a field curing of 30 days [11, 23]. The specimens were demoulded after one day of curing as samples are weak initially after the preparation.

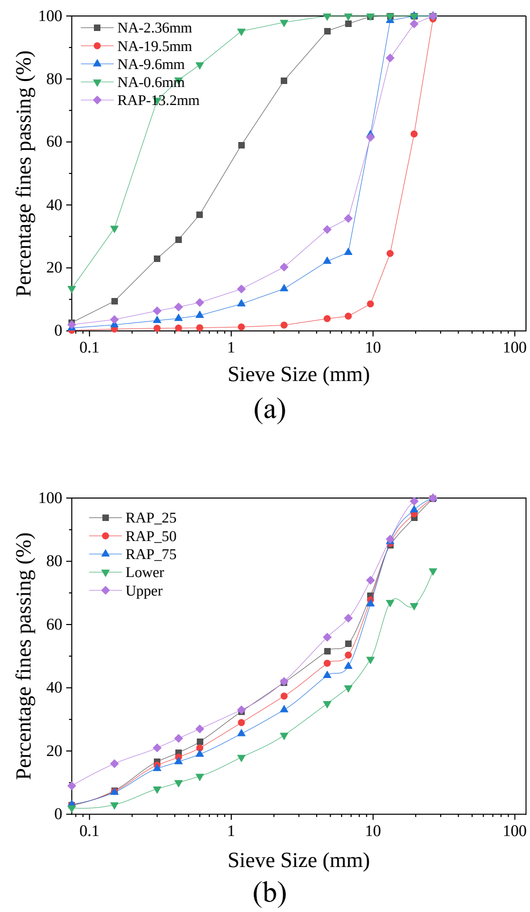


Fig. 1 Gradation curves for (a) Different Stacks of NA and RAP, (b) Blended RAP mixes.

Table 1. Physical Properties of aggregates.

Test	MORTH,2014 Specification	NA	RAP	Test Method [24]
Combined FI and EI (%)	35 (Max)	27	47.66	IS2386-Part I 1963
Aggregate Impact Value (%)	30 (Max)	21.33	19.17	IS2386-Part IV 1963
Water Absorption (%)	2 (Max)	0.12	-	IS2386-Part III 1963
Abrasion value	40 (Max)	29.59	30.12	IS2386-Part IV 1963
Asphalt content (%)	-	-	4.47	

Table 2. Properties of Asphalt emulsion.

Test on Emulsion	Permissible Values	Obtained Result	Test Method
Residue on 0.6 mm IS Sieve, % by mass, Max	0.05	0.02	IS 8887: 2018 [25]
Viscosity (Say bolt furol viscometer), seconds, (at 25°C)	30-100	31	IS 3117: 2004 [26]
Storage stability (24 h), %, Max	2	0.62	IS 8887: 2018 [25]
Particle charge	Positive	Positive	IS 8887: 2018 [25]
Stability to mix with cement (% coagulation), Max	2	1.84	IS 1203: 1978 [27]
Residue by evaporation (%), Min	60	62.66	IS8887: 2018 [25]
Penetration 25°C/ 100g/5, sec	60-120	67	IS1208: 1978 [28]
Ductility,27 °C/cm, Min	50	60	IS8887: 2018 [25]

The preparation of specimens involves the optimization of pre-wetting water and emulsified asphalt content in the mix. The pre-wetting water is added to the mix with 2% cement content. The emulsified asphalt content is varied at an interval of 0.5% weight of the dry aggregate and tested for the indirect tensile strength properties. The initial emulsion content is determined based on the equation given in IRC: SP: 100-2014, based on the mixes' final gradation [29].

$$IEAC\ (\%) = 0.05A + 0.1B + 0.5C \quad (1)$$

Here, A is the percentage weight of sieved material retained on a 2.36 mm sieve, B is the percentage weight of sieved material passing through a 2.36mm sieve and retained on a 0.09 mm sieve, and C is the percentage weight of material passing through a 0.09 mm sieve.

The trial emulsified asphalt content (TEAC) was determined by using the following equation (2)

$$TEAC(\%) = IEAC - \frac{P_{b,RAP} \times (RAP - content)}{P_{b,Emulsion}} \quad (2)$$

IEAC is the Initial emulsified asphalt content calculated from equation (1) $P_{b,\ RAP}$ is the Bitumen content in RAP material (%), *RAP content* is the RAP content in the blended mix (%) $P_{b,\ Emulsion}$ is the residue by evaporation in emulsified asphalt (%).

Indirect tensile strength (ITS): It is an important parameter that has been used to optimize the mix design of asphalt emulsion aggregate mixes. To test ITS, samples were compacted at each emulsified asphalt content and then cured. The cured samples were kept idle for one day at room temperature and tested for ITS as per ASTM D6931 at a loading rate of 50.8 mm per minute [30]. The ITS was determined by using the following equation (3).

$$S_T = \frac{2000P}{\pi D t} \quad (3)$$

Where S_T is the ITS in N/mm^2, D is the diameter of the specimen in mm, t is the thickness of the specimen in mm, and P is the ultimate failure load in kN.

Density and water loss: To understand the variation of the density with mix proportions and asphalt emulsion content, the density of each sample was measured after curing for three days. The percentage of water loss was calculated by measuring the weight at regular intervals (0, 24, 48, and 72 h) during the three days of the curing period. The difference in weight of the sample at respective time intervals will give the percentage of water loss, which is calculated by using the equation (4). The percentage of water loss calculated with equation (4) was used to observe the rate of curing of the cold mixes.

$$\%Water\,loss = \frac{W_{initial} - W_{final}}{W_{initial}} \times 100 \quad (4)$$

Here $W_{initial}$ is the initial weight of the sample after compaction and W_{final} is the weight of the sample after curing.

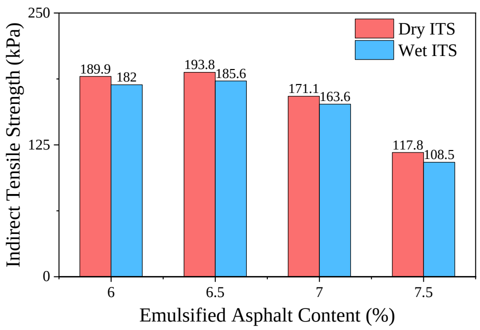
Tensile strength ratio: TSR is the ratio of ITS of the conditioned samples to the ITS of the unconditioned samples. The samples were cured for 72 h at 40^{O}C and conditioned by submerging in a water bath at room temperature for 24 h [23]. These parameters represent the field conditions where the base is exposed to rain before placing a surface layer [31]. This property also embodies the durability of cold mixes. Both the conditioned and unconditioned samples have been tested at temperatures of 25±2^O C according to the guidelines of Asphalt Academy, 2009 [23].

Dynamic creep rutting test: A dynamic creep rutting test was performed on the CREAM bases to determine the rutting potential. The test was conducted at a temperature of 25±2^O C. The dynamic loading was applied at the 0.1 seconds loading period and 0.9 seconds rest period, which represents 1 Hz frequency. The applied loading created stress of 150 ±5kPa, and deformation was measured using a Linear Variable Deformation Transducer (LVDT) with an accuracy of 0.0001 mm [32]. It could be noted from previous studies that there is no consensus in choosing the stress levels that ranges between 69 kPa to 1000 kPa. The temperature conditions ranged from ambient to 60^{O}C, and a majority of the studies have adopted 0.1 seconds as the loading period and 0.9 seconds as the rest period. The test termination is either in a fixed number of cycles or the collapse of the sample due to tertiary flow [11, 32-42].

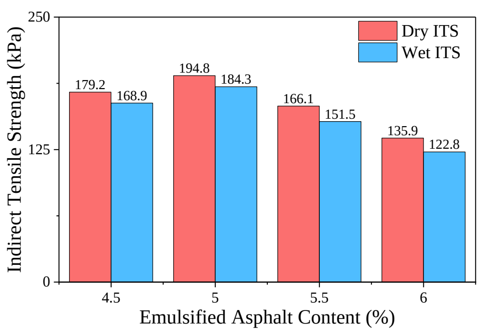
3. Results

The mix design of CREAM involves the preparation of samples using the Marshall method of compaction followed by the determination of the OEAC at which the mix achieves maximum strength. Samples were prepared for different Emulsified Asphalt Contents (EAC) ranging from 4.5% to 7% by dry weight of the aggregate at an interval of 0.5%. Each sample was compacted and oven cured for 72 h at 40^{O}C. Three representative samples have been prepared for each emulsion content to ensure the repeatability of the test results. After curing, the samples were allowed to cool at room temperature ($25 \pm 2°C$) before testing for ITS. The variation of ITS with EAC for mixes with different RAP contents is shown in Fig. 2.

From Fig.2, the maximum dry-ITS is achieved at 6.5%, 5%, and 5% of EAC for the RAP-25%, RAP-50%, and RAP-75% mix, respectively. The EAC corresponding to the maximum strength achieved is called OEAC. The OEAC is different from different RAP contents because the asphalt absorption varies with the presence of NA. Furthermore, the RAP does not act as a black rock, and there is a possibility to rejuvenate the aged binder with asphalt emulsion [11]. The variation in the maximum dry-ITS values corresponding to OEAC is shown in Fig. 3.



(a)



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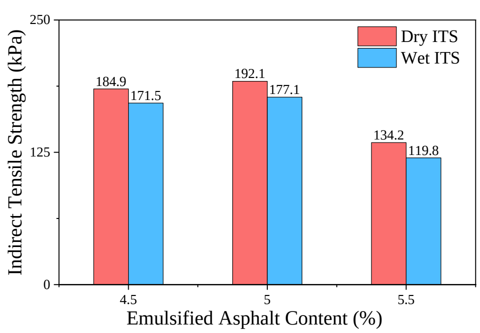


(c)

Fig.2. ITS test of cream for different RAP contents (a) 25% RAP (b) 50% RAP (c) 75% RAP.

The difference in dry-ITS is significantly small at OEAC for different RAP mixes. Maximum dry-ITS is achieved at 50% RAP content due to its good packing density compared to other mixes. The obtained ITS results in dry conditions typically less than the specification limits. But, the strength has been significantly increased with curing periods. The obtained values are much higher than 225 kPa after 60 days of curing, around 250 kPa. [43]. As per the Asphalt Academy, it could be used for traffic levels up to 6 msa [23].

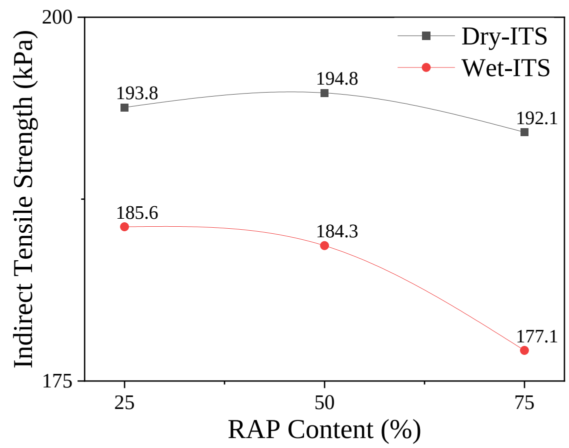


Fig. 3. Variation of ITS with RAP content at OEAC.

The variation in Optimum Total Fluid Content (OTFC), OEAC, and Optimum Residual Binder Content (ORBC) for variation in RAP content are depicted in Fig.4. It was observed that the required OTFC decreased as the RAP content increased from 25% to 75%. The OTFC values were 9%, 7.5%, and 6.5% for 25%, 50%, and 75% RAP mixes, respectively. The decrease in total fluid content with the increase in RAP content is due to the increase in the aggregate surface area of RAP. RAP aggregates have less water absorption due to the presence of asphalt coating, and NA absorbs water and binder initially on its surface. The specimens were observed after the ITS test, as shown in Fig. 5. The samples' failed surfaces were along with the bonding interface, and the samples were completely cured with no free moisture.

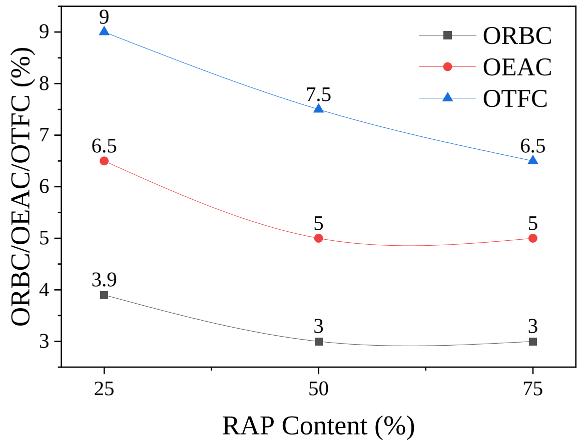


Fig.4. Variation of ORBC/OEAC/OTFC with RAP content.

Fig.5. Failure patterns of RAP blends.

The dry density of cold emulsified asphalt mixes depends on the EAC, RAP content, the natural aggregate amount, and packing density. It is observed that the dry-densities of the RAP-50 and RAP-25 mixes are significantly more than that of RAP-75, where good compaction is achieved, as shown in Fig. 6.

In general, the rate of curing is measured in terms of the percentage of water loss. The percentage of water loss considering the time of curing for each sample is presented in Fig.7. The results indicate that the maximum curing rate was observed in the first 24 h and gradually decreased in the later hours. The same trend has been found in all the mixes. The rate of reaction decreases with an increase in the percentage of RAP in the mixes. The dynamics of moisture loss entirely depend on the composition of the aggregates, cement, water, and asphalt emulsion.

The TSR represents the percentage loss in strength when the material is subjected to prevailing field conditions. From Fig. 8, it is observed that the TSR of all the mixes at the OEAC, below OEAC, and above OEAC exhibited a TSR of more than 80%, which is the permissible limit [29]. This indicates that the water did not affect the strength of the base. In addition, the emulsified asphalt content did not have any significant effect on the durability. Hence, when the emulsion content is less than or more than optimum, there is no significant influence on the TSR of the mixes. In this study, the emulsion contents considered were 0.5% below and above the optimum. Further, the RAP content in the blend does not influence the durability of the mixes.

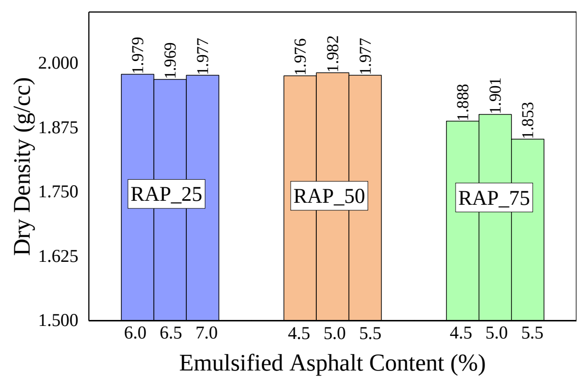
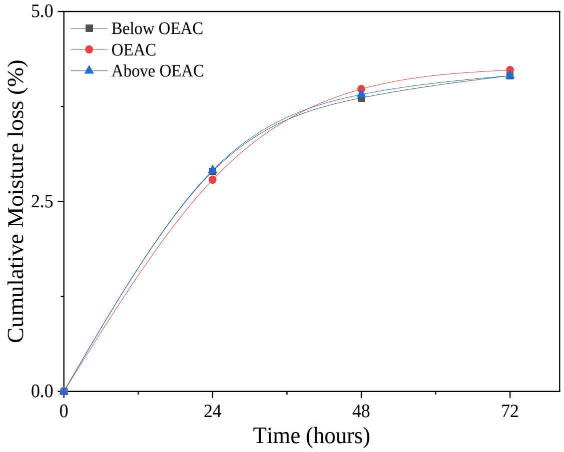
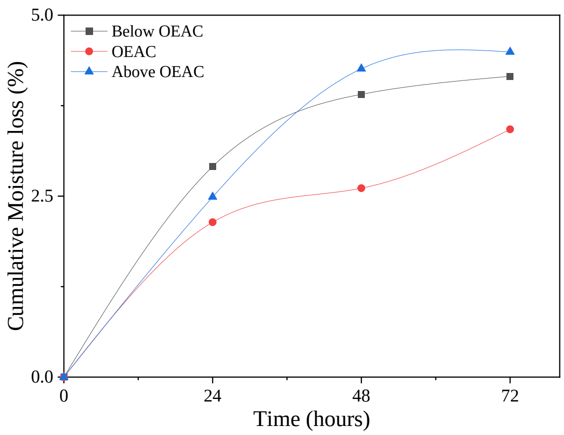


Fig. 6. Variation of density with EAC.



A



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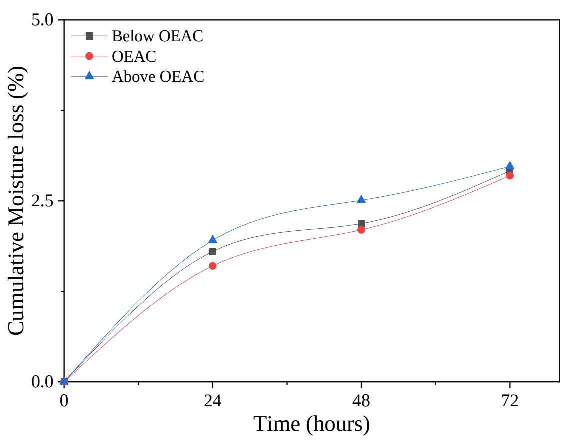


C

Fig. 7. Water loss (%) with time a) 25% RAP b) 50% RAP and 75% RAP mixes.

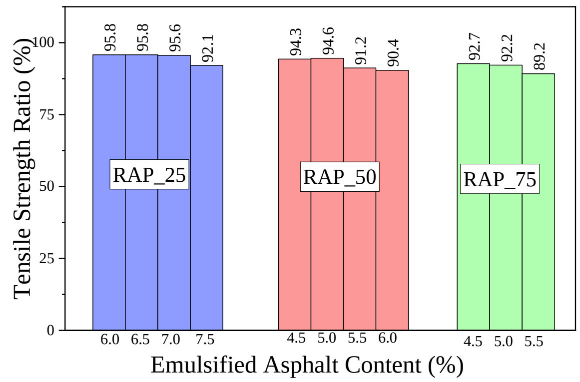
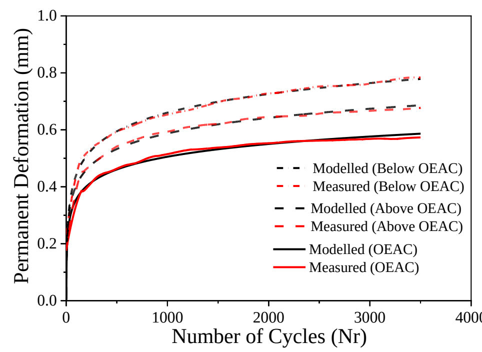


Fig. 8. Tensile strength ratio of RAP mixes.

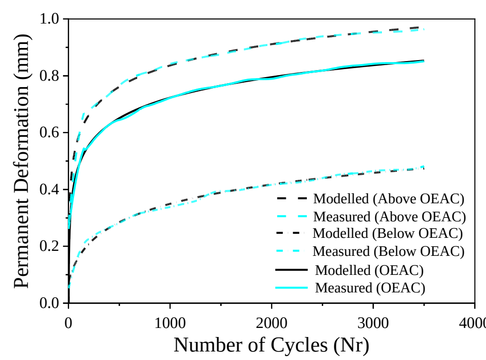
The performance of all the samples under dynamic compressive loading for 3500 cycles was tested and is presented in Fig. 9. In addition to the observed deformation, the corresponding models of permanent deformations have been depicted in the curves. The measured curves were smoothed using the Satitzsky-Golay digital filter technique. This smoothing method involves the least-squares fit of a small set of consecutive data points to a polynomial. It takes the calculated central point of the fitted polynomial curve as the new smoothed data point. The permanent deformation for different mixes is modelled in terms of logarithmic curves and power-law curves. Models were developed for all the RAP blends to understand rutting behavior and validated, as shown in Fig. 9. Lower permanent deformations have been observed at lower emulsified asphalt contents than, and more permanent deformations were observed at higher emulsified asphalt contents than optimum for RAP-50 and RAP-75 mixes. For RAP-25 mixes, more minor permanent deformations were observed at the OEAC, as shown in Fig.9. The observed permanent deformation curves for all the RAP mixes are compared at optimum, lower, and above optimum emulsified asphalt contents, as shown in Fig. 10. It is demonstrated that the RAP-75 mixes have shown higher permanent deformation characteristics of 3.54 mm than RAP-25 and RAP-50. This indicates that the asphalt content present in RAP contributes to the permanent deformation characteristics of the mixes. The emulsified asphalt acts as not only a binder but also a rejuvenator. Hence, the contribution of aged bitumen towards higher permanent deformation characteristics is possible. This statement has been supported by a previous study that explains that RAP does not act as a black rock [11]. The existing bitumen content present in the RAP-75 blend is greater than that of the remaining mixes, and there is a chance of higher binder content, which leads to more rut depth. This could also be due to the combination of RAP-75 having 75% reclaimed material that may not have the same angularity or may not provide the same shear strength due to the angle of internal friction. The RAP 25 mix contains 75% natural aggregates, whose particle shape contributes significantly to higher shear strength and enhanced rut resistance.

Further, the effect of the Total Bitumen Content (TBC) of CREAM on the resistance to permanent deformation at the end of the test is depicted in Fig. 11. The permanent deformation escalates with the RAP content and reaches a maximum at 75%RAP, and the observed lower and higher deformations are 0.48 mm and 3.54 mm, respectively. For the mixes with 50% RAP content, the significant observation is that the highest deformation is twice that of lower deformation. Mixes with 25% RAP content show the highest deformation, with more than 36.8% of the corresponding lowest deformation. It is also observed that the permanent deformation increases with the increase in TBC for mixes blended with RAP-50 and RAP-75. However, in the case of RAP-25 mixes, this trend does not appear.

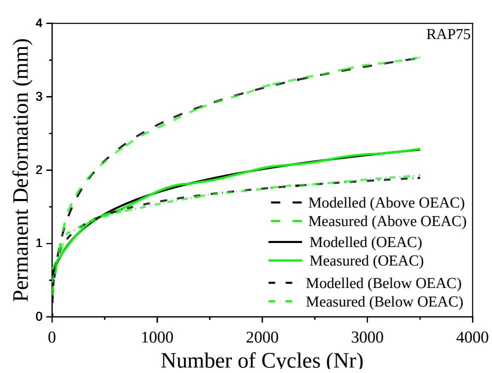
A similar study at OEAC by Dong et al. (2019) observed 2 mm deformation for 2500 cycles at 3.5% emulsified asphalt and 1.5 % cement content [14]. Arimilli et al. (2016) found that less than 3 mm rut depth were observed for cold mixes with RAP for 20000 cycles where the deformation is maximum for conventional mixes around 5.5 mm [11]. Compared with these studies, the obtained rut depths are below 2 mm except 75 RAP at the higher side of OEAC for 3500 cycles.



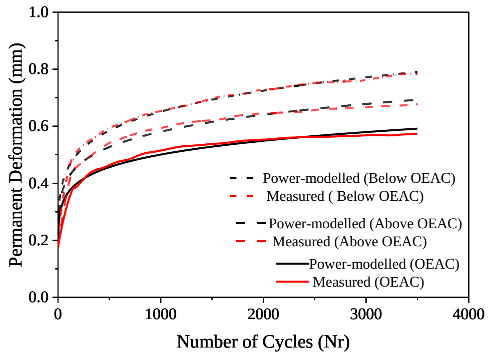
(a) Logarithmic model for RAP-25%.



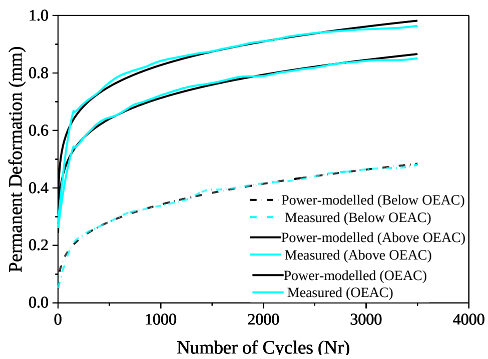
(b) Logarithmic model for RAP-50%.



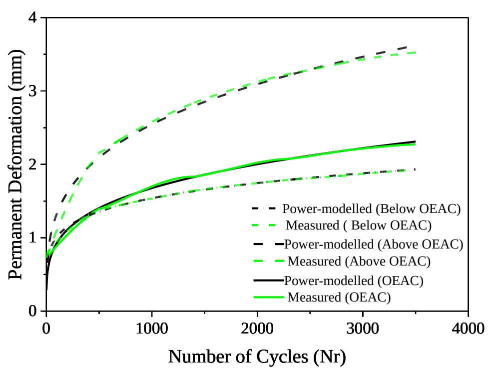
(c) Logarithmic model for RAP-75%.



(d) Power-law model for RAP-25%.



(e) Power-law models for RAP-50%.



(f) Power-law models for RAP-75.

Fig. 9. Permanent Deformation Curves for different Percentage of RAP.

Previously, Ahari et al. (2014) developed a two-stage model for Styrene-Butadiene-Styrene (SBS) modified asphalt mixes [18]. The same method is adopted in cold mix combinations to predict permanent deformation characteristics. A logarithmic equation used to indicate the permanent deformation is shown in equation (5).

$$\Delta = a - b[\ln(Nr + c)] \quad (5)$$

Δ is the permanent deformation or rutting in mm,

a, b, c are constants and Nr are the number of cycles.

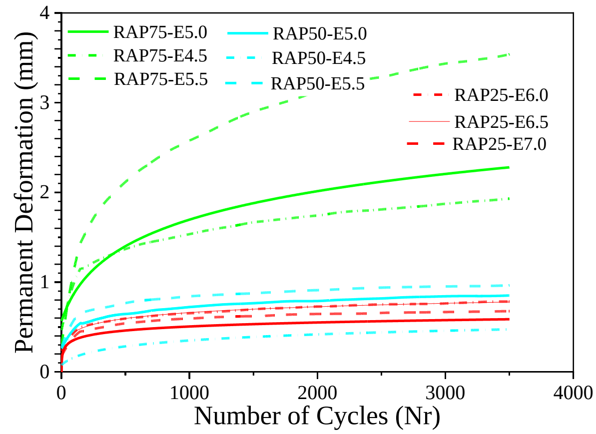


Fig.10. Comparison of permanent deformation curves of different RAP blends at optimum, below optimum, and above optimum emulsion contents.

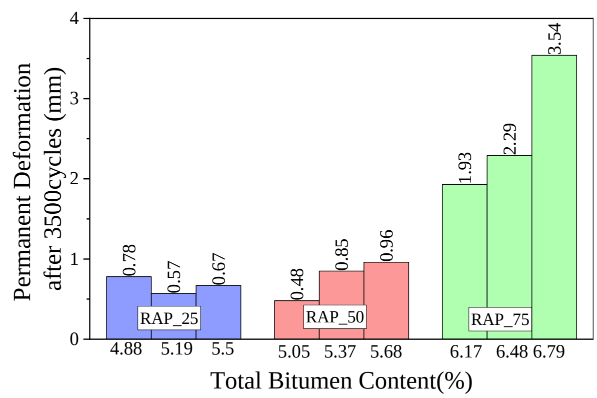


Fig. 11 Effect of Total Bitumen Content (TBC) on Permanent Deformation.

A summary of the statistical analysis of all the models has shown in Tables 3, 4, and 5. The standard error is negligible for each model, and the models are reliable, which indicates the best fit for defining the rutting potential of the RAP mixes. Further, the influence of the constant ‘a’ is negligible in all the mixes.

Table 3. Summary of logarithmic modelling data for RAP-25.

EAC		Value	SE	R2 value
OEAC	a	0.05973	0.00126	0.98
	b	-0.06454	1.74E-04	
	c	-0.81269	0.0294	
<OEAC	a	0.00737	7.98E-04	0.99
	b	-0.09453	1.10E-04	
	c	-0.34664	0.03877	
> OEAC	a	0.04233	0.00119	0.99
	b	-0.0789	1.64E-04	
	c	-0.75495	0.02919	

Table 4. Summary of logarithmic modelling data for RAP-50.

EAC		Value	SE	R^2 value
OEAC	a	-0.00231	0.00114	0.99
	b	-0.10494	1.56E-04	
	c	0.5	0.09098	
<OEAC	a	-0.22848	2.01E-03	0.97
	b	-0.08482	2.77E-04	
	c	0.5	0.19973	
> OEAC	a	0.08023	0.00173	0.99
	b	-0.10936	2.37E-04	
	c	0.5	0.13264	

Table 5. Summary of logarithmic modelling data for RAP-75.

EAC		Value	SE	R^2 value
OEAC	a	-1.78072	0.01197	0.99
	b	-0.49563	1.52E-03	
	c	112.80724	1.96092	
<OEAC	a	-0.23449	3.57E-03	0.99
	b	-0.26084	4.90E-04	
	c	1.10441	0.14279	
>OEAC	a	-2.57575	0.00687	0.99
	b	-0.74692	8.97E-04	
	c	42.55346	0.46929	

Similar to the logarithmic models, power equations were developed to calculate permanent deformation, as shown in equation (6).

$$\Delta = a \times N_r^{\,b} \tag{6}$$

Where Δ is the permanent deformation or rutting in mm, a and b are constants, and Nr is the number of cycles.

A summary of the statistical analysis of all the models has shown in Tables 6, 7, and 8. The standard error is negligible for each model, and the models are highly reliable, which indicates the best fit for defining the rutting potential of the RAP mixes. The equation represents the deformations in the primary region of the creep deformation curve. If the curve stage moves to the secondary region, there is another slope parameter to determine the strain slope of the second region, which is almost in linear form. It is observed that the power-law equations were best fitted to the permanent deformation curves, as observed in previous research works on HMA [17, 42]. When permanent deformation curves have two regions, primary and secondary, then the equation will have a combination of the power equation and straight-line equation. In the present study, only the primary region exists where both the logarithmic and power-law models are best fitted. This reveals that the emulsified asphalt mixes with 2% cement content behave like hot mix asphalts in permanent deformation.

Table 6. Summary of Power-law modelling data for RAP-25.

EAC		Value	SE	R^2 value
OEAC	a	0.1995	0.00101	0.93
	b	0.1332	6.85E-04	
<OEAC	a	0.2236	6.66E-04	0.98
	b	0.1547	4.00E-04	
>OEAC	a	0.2196	0.00107	0.95
	b	0.1408	6.58E-04	

Table 7. Summary of Power-law modelling data for RAP-50.

EAC		Value	SE	R^2 value
OEAC	a	0.24	8.31E-04	0.97
	b	0.16	4.58E-04	
< OEAC	a	0.05	1.97E-04	0.99
	b	0.28	5.15E-04	
> OEAC	a	0.32	0.00132	0.95
	b	0.14	5.53E-04	

Table 8. Summary of Power-law modelling data for RAP-75.

EAC		Value	SE	R^2 value
OEAC	a	0.28626	8.07E-04	0.99
	b	0.2559	3.75E-04	
< OEAC	a	0.43853	1.34E-03	0.98
	b	0.18168	4.09E-04	
> OEAC	a	0.36437	0.00157	0.99
	b	0.28134	5.73E-04	

4. Conclusions

Based on the results of this study, the following conclusions were drawn:

Mixes with 75% RAP have more permanent deformation when subjected to the dynamic creep rutting test. The combined residual binder present in the RAP and emulsified asphalt content influences the rutting characteristics of the cold mixes.

Lower permanent deformation was observed for mixes with lower emulsified asphalt contents than optimum emulsion content, and more permanent deformations are observed at higher emulsion contents than optimum for RAP-50 and RAP-75 mixes. However, lower permanent deformations were observed at the optimum asphalt emulsion content for RAP-25 mixes. Overall, 25%RAP and 50% RAP performed better than that of the 75%RAP at optimum and lower side of optimum.

The rate of curing is high in the first 24 hours after the preparation of the bases and declines in later stages. The failure pattern of the cold emulsified asphalt RAP mixes occurred along with the bonding interface and exhibited higher TSR values, which represent better durability.

The popular power-law models and logarithmic models best fit the primary region of the creep curves.

The indirect tensile strength values for different RAP mixes (25%, 50%, and 75%) at optimum emulsified asphalt content are approximately the same (193.8 kPa, 194.8 kPa, and 192.1kPa). Further, ITS is not a true mix-design parameter that explains the rutting potential of cold recycled emulsified asphalt mixes with reclaimed asphalt pavement material.

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Declaration of Interest Statement

No potential conflict of interest was reported by the author(s).

REFERENCES

[1] James, A., Baumgardner, G., Kadrmas, A., & Simpson, P. (2006). “Asphalt emulsion

technology." Transportation Research Circular, pp.1-15.

[2] Li, Peng, and Juanyu Liu. (2014). "Predictive model for non-linear resilient modulus of emulsified asphalt treated base." Pavement Materials, Structures, and Performance, pp.383-394.

[3] Shafiei, A., & Namin, M. L. (2014). "Experimental investigation on the effect of hydrated lime on mechanical properties of SMA." Construction and Building Materials, Vol. 70, pp. 379-387.

[4] Huang, Y. H. (2004). "Pavement analysis and design." 2 edition. Pearson.

[5] Harvey, J. T., & Tsai, B. W. (1996). "Effects of asphalt content and air void content on mix fatigue and stiffness." Transportation research record, Vol. 1543(1), pp. 38-45.

[6] Minhas, K. S. (2019). "Effect Of Binder Content On Volumetric Properties Of Asphalt Mixes." Elk Asia Pacific Journal Of Civil Engineering And Structural Development, Vol. 5(1), pp. 1-24.

[7] Dave, E. V., DeCarlo, C., Hoplin, C. M., Helmer, B., Dailey, J., & Williams, R. C. (2017). "Impact of low asphalt binder for coarse HMA mixes (No. MN/RC 2017-27)." Minnesota. Dept. of Transportation. Research Services & Library.

[8] Khodaii, A., & Mehrara, A. (2009). "Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test." Construction and Building Materials, Vol. 23(7), pp.2586-2592.

[9] Kaloush, K. E., Witczak, M. W., & Sullivan, B. W. (2003). "Simple performance test for permanent deformation evaluation of asphalt mixtures." In Sixth international RILEM symposium on performance testing and evaluation of bituminous materials, pp. 498-505.

[10] Kalyoncuoglu, S. F., &Tigdemir, M. (2011). "A model for dynamic creep evaluation of SBS modified HMA mixtures." Construction and Building Materials, Vol. 25(2), pp. 859-866.

[11] Arimilli, S., Jain, P. K., & Nagabhushana, M. N. (2016). "Optimization of recycled asphalt pavement in the cold emulsified mixtures by mechanistic characterization." Journal of Materials in Civil Engineering, Vol. 28(2), pp. 04015132.

[12] Sangiorgi, C., Tataranni, P., Simone, A., Vignali, V., Lantieri, C., &Dondi, G. (2017). "A laboratory and field evaluation of Cold Recycled Mixture for base layer entirely made with Reclaimed Asphalt Pavement." Construction and Building Materials, Vol. 138, pp. 232-239.

[13] Pi, Y., Huang, Z., Pi, Y., Li, G., & Li, Y. (2019). "Composition Design and Performance Evaluation of Emulsified Asphalt Cold Recycled Mixtures." Materials, Vol. 12(17), pp. 2682.

[14] Dong, W., & Charmot, S. (2019). "Proposed tests for cold recycling balanced mixture design with the measured impact of varying emulsion and cement contents." Journal of Materials in Civil Engineering, Vol. 31(2), pp. 04018387.

[15] Mounes, S. M., Karim, M. R., Khodaii, A., &Almasi, M. H. (2016). "Evaluation of permanent deformation of geogrid reinforced asphalt concrete using dynamic creep test." Geotextiles and Geomembranes, Vol. 44(1), pp. 109-116.

[16] Lavasani, M., Namin, M. L., &Fartash, H. (2015). "Experimental investigation on mineral and organic fibers effect on resilient modulus and dynamic creep of stone matrix asphalt and continuously graded mixtures in three temperature levels." Construction and Building Materials, Vol. 95, pp. 232-242.

[17] Zhou, F., Scullion, T., & Sun, L. (2004). "Verification and modeling of three-stage permanent deformation behavior of asphalt mixes." Journal of Transportation Engineering, Vol. 130(4), pp. 486-494.

[18] Ahari, A. S., Forough, S. A., Khodaii, A., &Nejad, F. M. (2014). "Modeling the primary and secondary regions of creep curves for SBS-modified asphalt mixtures under dry and wet conditions." Journal of materials in civil engineering, Vol. 26(5), pp. 904-911.

[19] Ministry of Road Transport and Highways. (2013). “Specifications for Road and Bridge works, 2013.” FifthRevision, Ministry of Road Transport and Highways, New Delhi, India.

[20] Asphalt Institute Manual, A. B. A. E. (1997). Manual Series No. 19.

[21] Bessa, I. S., Almeida, L. R., Vasconcelos, K. L., & Bernucci, L. L. (2016). “Design of cold recycled mixes with asphalt emulsion and portland cement.” Canadian Journal of Civil Engineering, Vol. 43(9), pp. 773-782.

[22] Joni, H. H., & Hashim, M. S. (2018). “Evaluation silica fume addition on some properties of cold bitumen emulsion mixtures (CBEMs).” In IOP Conference Series: Materials Science and Engineering, Vol. 433(1), pp. 012021. IOP Publishing.

[23] Asphalt Academy. (2009). “Technical guideline: Bitumen stabilised materials.” A guide for the design and construction of bitumen emulsion and foamed bitumen stabilised materials.

[24] IS 2386 (Part I, Part II, Part III and Part IV) (1963). “Tests on Aggregates.” Bureau of Indian Standards, Manak Bhavan, New Delhi.

[25] IS 8887 (2018). “Bitumen Emulsion for Roads (Cationic type) Specification.” Indian Roads Congress.

[26] IS 3117. (2004). “Bitumen Emulsion for Roads and allied Applications (Anionic type).” Bureau of Indian Standards, Manak Bhavan, New Delhi.

[27] IS 1203. (1978). “Indian standard methods for testing tar and bituminous materials(Determination of Penetration).” Bureau of Indian Standards.

[28] IS 1208. (1978). “Indian standard methods for testing tar and bituminous materials (Determination of ductility).” Bureau of Indian Standards.

[29] Congress, Indian Roads. (2014). "Use of Cold Mix Technology in Construction & Maintainance of Roads Using Bitumen Emulsion IRC: SP-100: 2014." In Indian Roads Congress, New Delhi. 2014.

[30] ASTM D6931. (2012). “Standard test method for indirect tensile (IDT) strength of bituminous mixtures.” ASTM, West Conshohocken, PA. 2012.

[31] Behnood, A., Gharehveran, M. M., Asl, F. G., & Ameri, M. (2015). “Effects of copper slag and recycled concrete aggregate on the properties of CIR mixes with bitumen emulsion, rice husk ash, Portland cement and fly ash.” Construction and Building Materials, Vol. 96, pp. 172-180.

[32] NCHRP 465. (2002). “Simple performance test for Superpave mix design.” National Cooperative Highway Research Program (NCHRP) Rep. No. 465.

[33] Daryaee, D., Ameri, M., & Mansourkhaki, A. (2020). “Utilizing of waste polymer modified bitumen in combination with rejuvenator in high reclaimed asphalt pavement mixtures.” Construction and Building Materials, Vol. 235, pp. 117516.

[34] Goli, H., & Latifi, M. (2020). “Evaluation of the effect of moisture on the behavior of warm mix asphalt (WMA) mixtures containing recycled asphalt pavement (RAP).” Construction and Building Materials, Vol. 247, pp. 118526.

[35] Sobhi, S., Yousefi, A., & Behnood, A. (2020). “The effects of Gilsonite and Sasobit on the mechanical properties and durability of asphalt mixtures.” Construction and Building Materials, Vol. 238, pp. 117676.

[36] Chew, J. W., Poovaneshvaran, S., Hasan, M. R. M., Hamzah, M. O., Valentin, J., & Sani, A. (2020). “Microscopic analysis and mechanical properties of Recycled Paper Mill Sludge modified asphalt mixture using granite and limestone aggregates.” Construction and Building Materials, Vol. 243, pp. 118172.

[37] Al-Khateeb, G. G., Al-Suleiman Obaidat, T. I., Khedaywi, T. S., & Elayan, M. S. (2018). “Studying rutting performance of Superpave asphalt mixtures using unconfined dynamic creep and simple performance tests.” Road Materials and Pavement Design, Vol. 19(2), pp. 315-333.

[38] Babagoli, R., Ameli, A., & Shahriari, H. (2016). "Laboratory evaluation of rutting performance of cold recycling asphalt mixtures containing SBS modified asphalt emulsion." Petroleum Science and Technology, Vol. 34(4), pp. 309-313.

[39] Zhu, T., Ma, T., Huang, X., & Wang, S. (2016). "Evaluating the rutting resistance of asphalt mixtures using a simplified triaxial repeated load test." Construction and Building Materials, Vol. 116, pp. 72-78.

[40] Mounes, S. M., Karim, M. R., Khodaii, A., & Almasi, M. H. (2016). "Evaluation of permanent deformation of geogrid reinforced asphalt concrete using dynamic creep test." Geotextiles and Geomembranes, Vol. 44(1), pp. 109-116.

[41] Lavasani, M., Namin, M. L., & Fartash, H. (2015). "Experimental investigation on mineral and organic fibers effect on resilient modulus and dynamic creep of stone matrix asphalt and continuous graded mixtures in three temperature levels." Construction and Building Materials, Vol. 95, pp. 232-242.

[42] Ziari, H., Nakhaei, M., Akbari Nasrekani, A., & Moniri, A. (2016). "Characterization of rutting resistance of EBS-modified asphalt mixtures." Petroleum Science and Technology, Vol. 34(13), pp. 1107-1112.

[43] Congress, I. R. (2001). "Guidelines for the design of flexible pavements." Indian code of practice, IRC, 37.