

# Evaluation of Fatigue Potential for Crumb Rubber Modified Bitumen in Stone Mastic Asphalt Mixes

Anusha T M, Sharath Kumar M D, H S Jagadeesh



**Abstract:** SMA is a gap graded mix composed of a high concentration of coarse aggregate that is held together in a thick asphalt film by a matrix of mineral filler and stabilizers. Since natural aggregates have become expensive, hence Reclaimed Asphalt Pavement (RAP) can be reused in pavement construction to reduce the environmental hazardous due to disposal problems. Since the RAP contains used aggregates, it is highly prone to fatigue, thermal and reflective cracking effect. Rheological and chemical properties of aged bitumen in RAP can be enhanced by use of untreated waste oils such as waste engine oil as rejuvenators. This research presents a study on fatigue performance of SMA mix with Reclaimed Asphalt Pavement (RAP) materials with and without rejuvenators and results were compared with conventional SMA mix. The materials used were first characterized by common laboratory tests. Then the three SMA mixes are tested using several laboratory test procedures: Marshall Stability, indirect tensile strength, moisture susceptibility, and indirect tension fatigue test. The optimum proportions of the of the mixes with highest stability are selected from the Marshall stability test. The indirect tensile strength test results show that the SMA mix replaced with RAP without rejuvenators showed higher tensile strength ratio and resistance to moisture damage when compared to conventional mix and optimum RAP replacement mix with rejuvenators. The fatigue test was conducted for the three optimum mixes at different temperature and stresses. The fatigue test results showed that at lower temperature and stresses, the RAP replaced SMA without rejuvenator offered better fatigue resistance than those with rejuvenator and conventional SMA mix. At higher temperatures, the RAP replaced SMA mix with rejuvenator offered similar fatigue lifecycle as conventional mix. However, at high stresses, conventional SMA mix offered better fatigue lifecycle. Increase in failure stresses resulted in decrease of number of fatigue cycles and increased in initial tensile strain of the mix. Thus, with the use of RAP substantial decrease in cost can be achieved without compromising the fatigue characteristic of the SMA mix.

**Keywords:** Then the three SMA mixes are tested using several laboratory test procedures: Marshall Stability,

## I. INTRODUCTION

Stone mastic asphalt (SMA) was developed by Dr. Zincher of the Straubag-Bau central laboratory Germany in the 1960s, to resist the damage caused by studded tires.

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SMA is a gap graded mixture containing 70-80% coarse aggregate of total aggregate mass, 6-7% of binder, 8-12% of a filler, and about 0.3-0.5% of fibre or modifier. A skeleton-type structure is formed due to the high amount of coarse aggregate in the mixture providing better stone-on-stone contact between the coarse aggregate particles, which offers high resistance to rutting. The SMA has its deformation-resistant capacity from a coarse stone skeleton providing more stone-on-stone contact than with conventional dense graded asphalt (DGA) mixes. Improved binder durability results from higher bitumen content, a thicker bitumen film, and lower air voids content. The cellulose fibre is used to reduce the air voids this high bitumen content also improves flexibility. The addition of a small quantity of cellulose or mineral fibre prevents drainage of bitumen from the matrix during transport and placement. (Patel et al. 2016) (Yastremsky et al. 2018)

When the pavement grows older, the aged binder becomes more brittle and loses its strength resulting in loss of pavement service life, and under these circumstances, the pavement surfaces can be removed which is generally known as Reclaimed Asphalt Pavement (RAP). However, as the aged bitumen in RAP is more brittle than fresh bitumen and is highly vulnerable to fatigue, thermal, and reflective cracking, experts suggest using RAP content of 10 to 30 percent for new HMA mix (Joni et al. 2019). By using rejuvenators, rheological and chemical properties of RAP binder can be restored and more quantity i.e., up to 80% of RAP can be incorporated in the new HMA mix. As a result, of this construction of pavements with RAP is seeing an increasing trend. The use of RAP in the HMA mix makes it very economical and also provides added environment benefits by making reducing the disposal problem of RAPs. Owing to the aging and climatic cycles, oxidation causes the traffic load to stiffen the bitumen, which in effect contributes to fatigue distress, contributes to pavement cracks, and continues in the pavements layers, resulting in the potholes and stripping of the layers. (Shen et al. 2007) Usually, an asphalt binder that experiences aging of oxidization has a lower concentration of more reactive components [Nitrogen base (N) + first acidifies (A1)] and the higher concentration of less reactive components [Paraffines (P) + second acidifies (A2)]. Generally, a rejuvenator used for restoring the aged asphalt binders has a minimum N/P ratio of 0.5 to ensure the compatibility of the rejuvenator and the aged binder and to prevent syneresis (i.e., contraction of a gel accompanied by the separating of liquid). The condition for bitumen being stiffer is the reduction of the binder's aromatic content while increasing the number of resins (i.e., increase in the asphaltene content).

Rejuvenators can restore the original asphaltenes to maltenes ratio in the aged asphalt pavements to plasticize the aged asphalt and produce a broad-spectrum renovation that compensates the volatile materials and disperses oils while promoting the adhesion. (Tran et al. 2016) (Mazzoni et al. 2018) (Joni et al. 2019).

Crumb rubber (CR) when blended with asphalt binder, yields a product that is generally called asphalt rubber (AR). Enhancement of the anti-fatigue property of the mixture with the addition of crumb rubber into asphalt mixtures can be based on the following two reasons. One is that crumb rubber powder consists of an anti-aging element, such as carbon black, which increases the aging resistance of the mixtures and the other reason is that crumb rubber increases the viscosity and the elasticity of the asphalt binder thereby, improving the asphalt film thickness on the surface of the aggregates and subsequently increases the asphalt mixtures aging resistance. Many studies show that adding crumb rubber could significantly improve the intermediate temperature fatigue life of asphalt binders. (Zaumanis et al. 2016) (Mashaan et al. 2013)

Fatigue cracking is one of the vital distress of asphalt pavement. Fatigue cracking is a phenomenon that occurs in pavements due to repeated applications of traffic loads. Indian traffic is a heterogeneous type. Due to the repeated traffic loading combined with the ultraviolet-irradiation aging, the adhesive and cohesive performance of asphalt mastic deteriorates, leading to the development of fatigue cracks, surface texture roughness, and potholes eventually the disintegration of the whole pavement surface. The fatigue life of asphalt materials can be predicted using the methods such as the Superpave fatigue factor ( $G^*\sin\delta$ ) test and linear amplitude sweep (LAS) test for asphalt binder, the shear fatigue test for asphalt mortar, and the indirect tensile fatigue test (ITFT) and four-point bending beam (4PB) test for asphalt mixture (Wang et al. 2020). Indirect Tensile strength is measured to know the wet and dry load

of the sample and this load is used to calibrate the fatigue distress while testing in the fatigue testing machine. Resilient modulus is one of the important properties in the mechanistic analysis of pavement response under dynamic traffic loads and to measure the quality of the materials. It measures the potential elastic properties of the asphalt mix (Ariyapijati et. al. 2017). The number of factors influencing resilient modulus is test temperature, loading time or loading frequency, rest period, and loading pulse waveforms. Field aging of aged binder can be measured by various methods such as are Thin Film Oven Test (TFOT) and Rolling Thin Film Oven Test (RTFOT) for short term aging while Pressure Aging Vessel (PAV) and Rotating Cylinder Aging Test (RCAT) are specifically for long term aging which involves in measuring Oxidation and Volatile losses. Although resilient modulus includes different parameters, it also changes concerning aging phenomena of asphalt mixtures, which made research into the aging asphalt mixture phenomenon. (Karami et al. 2017) (Li et al.2018) (Xiao et al.2011)

## II. MATERIALS

### A. Natural aggregates

The composite aggregate consists of the coarse, medium, and fine aggregate with a maximum 19 mm thickness. Fine aggregate consists of the manufactured sand resulting from crushing operations going through a sieve of 2,36 mm and held on a sieve of 0,075 mm. Aggregates of for this study are collected from KMS crusher, Bagalur, Tamilnadu. The properties of aggregates are summarised in Table 1.

**B. Reclaimed Asphalt Pavement (RAP)** The RAP materials is procured from NH-206, where the existing 2 lane flexible pavement is removed to construct the cement concrete pavement near the Karnataka-Andhra Pradesh border. The pavement was found to be approximately 15 – 20 years old as per the records. Table I shows the results of common laboratory tests for RAP aggregates.

**Table- I: Properties of natural and RAP aggregates**

Property	Test	Natural Aggregates	RAP aggregates	IRC-SP: 79 (2008) Specifications
Particle shape	Combined EI & FI	10.51%	22.68%	Max 30%
Strength	Aggregate crushing	23%	19.56%	Max 30%
Toughness	Aggregate Impact value	17.51%	9.73%	Max 18%
Water absorption	Water absorption	0.4%	0.55%	Max 2%
Specific gravity	Specific gravity	2.734	2.66	2.5-2.8

### C. Crumb Rubber Modified Bitumen (CRMB)

CRMB is the hydrocarbon binder obtained through physical and chemical interactions of crumb rubber (produced by recycling of used tires) with bitumen and some particular additives. CRMB-55 was collected from the

Mangalore Refineries and Petrochemicals Limited (MRPL). Table II presents the results of common laboratory tests on the CRMB 55 sample obtained.

**Table- II: Physical Properties of CRMB-55**

SL No.	Test	CRMB-55 results	Specifications as per MoRT&H
1	Penetration at 25 °C, min	47	60 (max)
2	Softening point ( R & B), °C	56.75	55 (min)
3	Flash Point, °C	280	220 (min)
4	Elastic Recovery of half thread in ductilometer at 15 °C, %	50	50 (min)
5	Separation test, the difference in softening point, °C	3.5	4 (max)
6	Thin Film Oven Tests and test on residue		
	a) Loss in mass, %	0.7	1.0 (max)
	b) Increase in softening point, °C	1.3	6 ( max)
	c) Reduction in penetration of residue at 25 °C, %	25.20	40 (max)
	d) Elastic Recovery of half thread in ductilometer at 15 °C, %	37	35 (min)

#### D. Rejuvenators - Waste Engine Oil (WEO)

Engine lubricating oil is made from paraffinic base oils with a small dose of specialty compounds added to boost the viscosity, stability, cleaning (ability to extract contaminants from cylinder walls and oil pathways), and flammability. Waste engine oil (WEO) is also made up of short-chain polar molecules that can break apart during lubricating operation. Research has shown that bus/truck engine oil is better suited than engine oil for small vehicles. So, WEO is collected from Hassan Bus Depot for the current work.

#### E. Mineral Filler and Stabilizer Additive

Mineral Filler consists of finely divided minerals such as stone dust or hydrated lime that passes

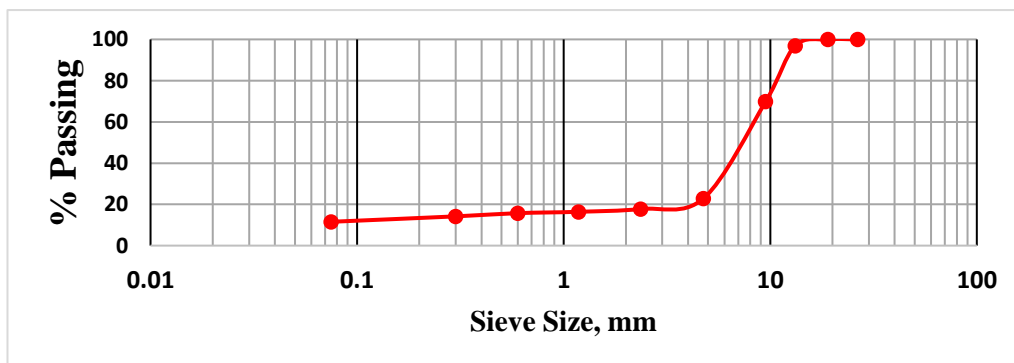
through a sieve of 0.075 mm. The mineral filler is chosen so it meets SMA's grading criteria. Baghouse dust is the dust or particulate matter collected from baghouse filter, bag filter or cloth filter which is an air pollution control system and dust collector that removes particulate matter or gas emitted from commercial establishments from the air. The baghouse dust for this study is acquired from Sri Venkateshwara Crushers, Periyapatna.

Cellulose fibers can be used in the SMA mix only in the pelletized form. The dosage rate for cellulose fibers is 0.3% minimum by weight of the total mix. For this work, it is obtained by "Strategic Marketing and Research Team".

By utilizing the different materials mentioned above, final gradation of conventional SMA mix is arrived and can be observed from the Fig. 1. Table III shows the final proportion of materials in the conventional SMA mix.

**Table-III: Proportion of different aggregate sizes**

Proportion of Materials	20mm down	12mm down	6mm down	2.36 mm down	Baghouse dust	Total
	0.100	0.650	0.060	0.110	0.080	1.000



**Fig. 1: Gradation of conventional SMA mix**

### III. MIX DESIGN

The SMA mix design as per requirements AASHTO PP41-01 and IRC- SP: 79-2008. The measures followed are as shown below

1. Selection of material.
2. Selection of good gradation.
3. Determination of the VCA, aged bitumen content.
4. Determination of the Optimum Binder Content.
5. Performing the Marshall Stability, Indirect Tensile Strength, and Fatigue test.

#### A. Mix Preparation

Natural and RAP aggregates are procured from the quarry and removed pavement surfaces concerning the SMA specifications as recommended by **IRC- SP:79-2008**. The

aggregates are graded using the Roth futch process, and the proportion of the mixture is calculated. Bitumen rheology is performed to identify the concentration of the aged binder on RAP. Marshall moulds are prepared for three different mixture types; Natural Aggregate, Natural Aggregate + RAP, and Natural Aggregate + RAP + rejuvenator (WEO) by mixing with CRMB-55, mineral fillers and stabilizer additives (cellulose fibers). Specimens in triplicates with dimensions of  $101.6 \pm 0.5$  mm diameter & 57-70 mm height were compacted by applying 50 blows on either side according to the **ASTM D 6926** guidelines for Marshall Compaction.



Marshall Stability Test is conducted to determine Optimum Binder Content (OBC), Stability and Flow value of above three different mixes as per **AASHTO T 245 (ASTM D 6927)**. Indirect Tensile Strength test known to be Water Sensitivity test is conducted to find out Voids analysis by using Job Mix Formula and to set the blows which would give voids of  $6 \pm 0.5\%$  in the sample with compliance of **AASHTO T 269 (ASTM D 3203)**. To assess the water sensitivity of the mix as per **AASHTO T 322 (ASTM D 4123)** the ITS test is performed for both conditioned and unconditioned samples. Then ITS dry load is taken using the Marshall assembly which is used as stress values in a repeated loading haversine waveform test apparatus as per **ASTM D 4123** for performing fatigue and resilient modulus test. The preparation of specimens is the same as that prepared for the Marshall moulds with 50 blows on either side to achieve a void ratio of between 3% and 5%

## IV. RESULTS AND DISCUSSION

### A. Marshall Stability Test

The Marshall Stability test is conducted on three SMA samples; conventional SMA mix, SMA mix with RAP replacement and SMA mix with RAP and rejuvenator addition. The test is conducted with various proportions of Binder, RAP and rejuvenators content. From the results, the optimum proportions of three SMA mixes are selected from the samples having highest Marshall Stability. The optimum proportions are

- Conventional SMA mix with binder content (CRMB) of 6%
- SMA mix with 40% of RAP replacement
- SMA mix with 70% of RAP replacement and addition of 25% Waste engine oil (WEO) as rejuvenator

Table IV summarizes the properties obtained from the Marshall Stability test for the optimum samples

**Table- IV: Marshall Properties of SMA mix**

Sl No.	Properties	Conventional SMA mix + 6% CRMB-55	SMA mix + 40% RAP + CRMB-55	SMA mix + 70% RAP + CRMB-55 + 25%WEO
1	Marshall Stability (kN)	8.59	13.20	11.62
2	Flow (mm)	3.8	3.20	3.19
3	Volume of voids (%)	4	4.04	3.99
4	VMA (%)	18	17.96	17.88
5	VFB (%)	77.5	77.50	77.70

### B. Indirect Tensile Strength (ITS)

The ITS test is performed on three optimized SMA samples in both unconditioned and conditioned states for the wearing course. Table V provides the summary of ITS test results for all three samples. The Tensile Strength Ratio, which is the ratio of conditioned sample to unconditioned

sample, for Conventional SMA mix, SMA mix with RAP replacement with and without WEO are 89.83, 91.40 and 90.99 respectively. Thus, it is clear that SMA mix with RAP offers higher moisture resistance and tensile strength than SMA mix with RAP and rejuvenator. Both the RAP replaced samples offer better moisture susceptibility than conventional SMA mix.

**Table-V: Summary of ITS test results of SMA mixes**

SMA mix	Conditioned	Unconditioned	Tensile Strength Ratio (TSR)
Conventional SMA mix + 6% CRMB-55	500.92	557.65	89.83
SMA mix +40% RAP + CRMB-55	840.66	919.76	91.40
SMA mix +70% RAP + CRMB-55 + 25% WEO	716.10	787.03	90.99

### C. Indirect Tensile Fatigue Test

The fatigue test is conducted on the conventional SMA mix and optimized RAP with and without the rejuvenator in ITFT apparatus. The specimen is tested at three different temperature (25°C, 35°C and 45°C) and four stress levels (10%, 20%, 30% and 40% of failure stress). The specimen is deemed to be failed when it undergoes vertical deformation of 5 mm due to fatigue loading. The Figs 2 – 10 shows the log-log plot of fatigue cycles vs Micro strain (horizontal tensile strains) for three types of sample mixes at three temperature. The figures also provides the respective regression equation of the form  $\log N_f = \log k_1 + k_2 \log \epsilon$ . Table 6 gives summary of regression equation obtained from the Fatigue test.

It can be observed from the above figures and summarized data, the y - intercept ( $\log k_1$ ) of regression equation represents the number of fatigue cycle at failure for unit strain. At lower room temperatures (i.e., 25°C and 35°C), the intercept is highest for SMA mix with RAP and WEO followed by SMA mix with RAP and conventional SMA mix respectively. It indicates that, at lower temperature, the mix with RAP and WEO requires more cycle of load to fail than other two and hence is more stable. At higher temperature (i.e., 45°C), the Conventional SMA mixture appears to be more stable than the mix with RAP replacement and have almost similar stability as the SMA mix with RAP and rejuvenator replacement.

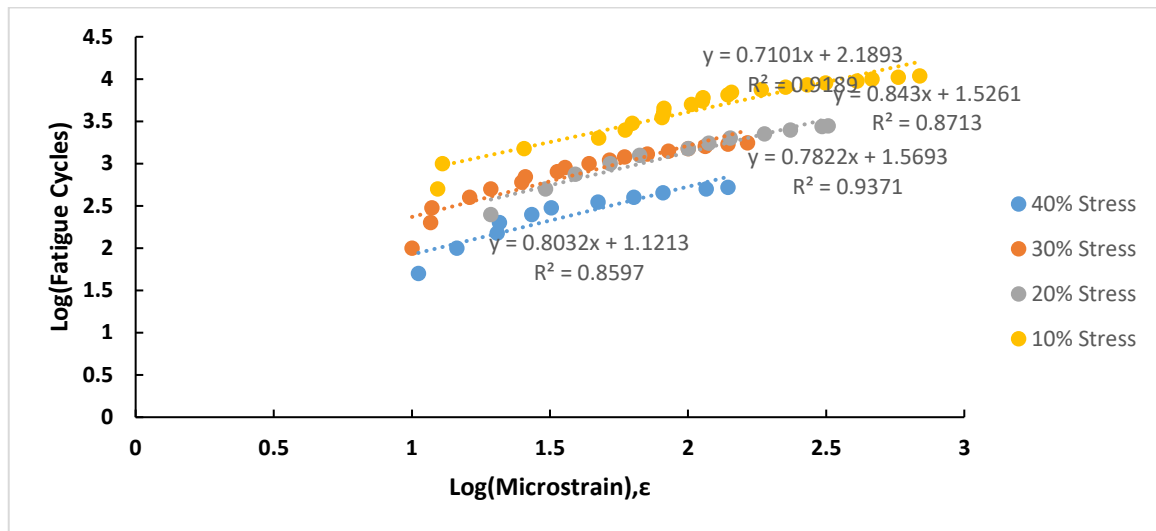


Figure 2: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 25°C

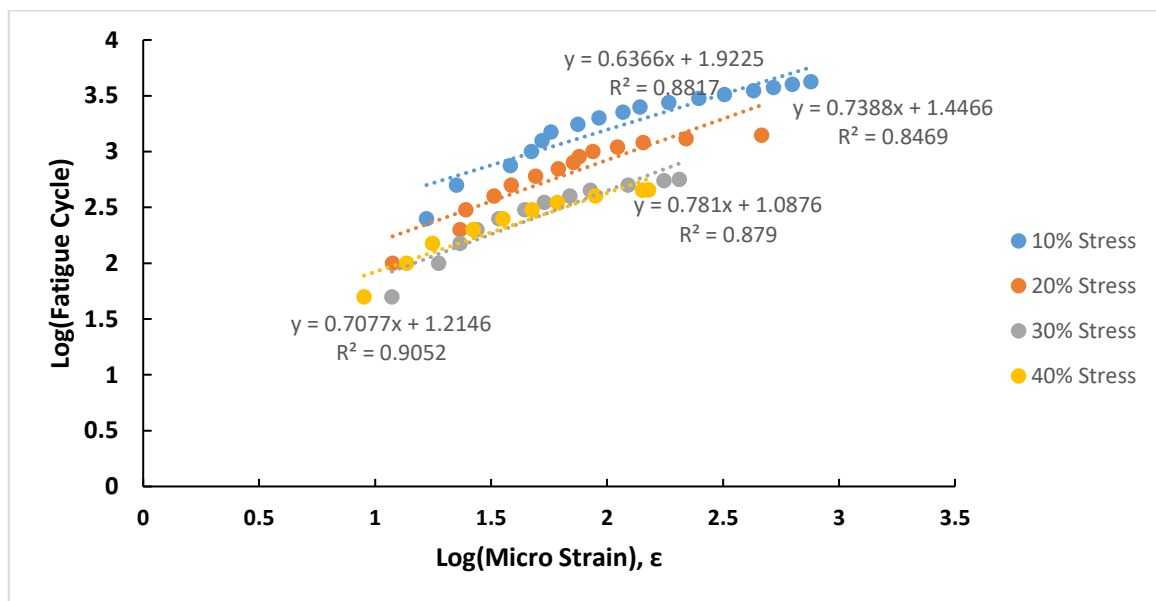


Figure 3: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 35°C

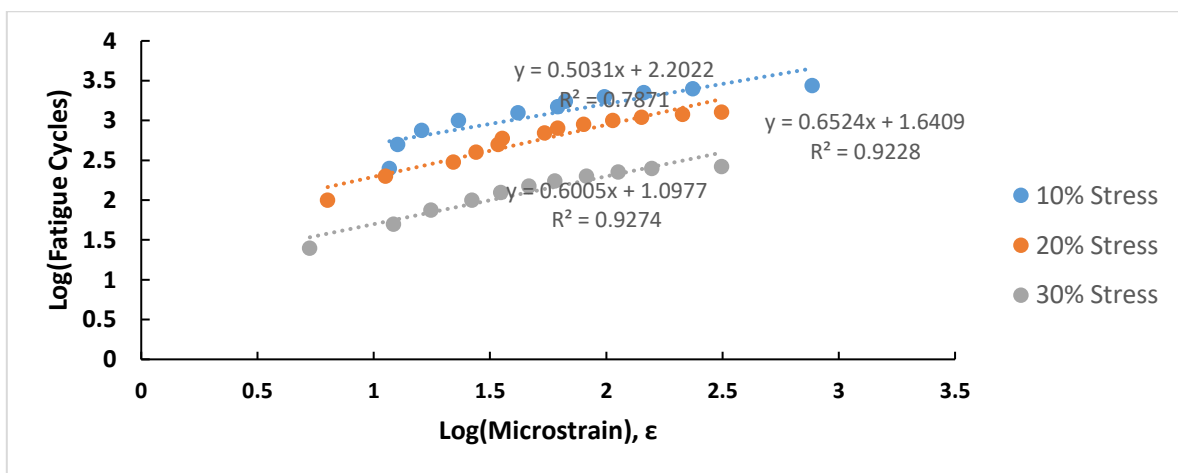


Figure 4: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 45°C

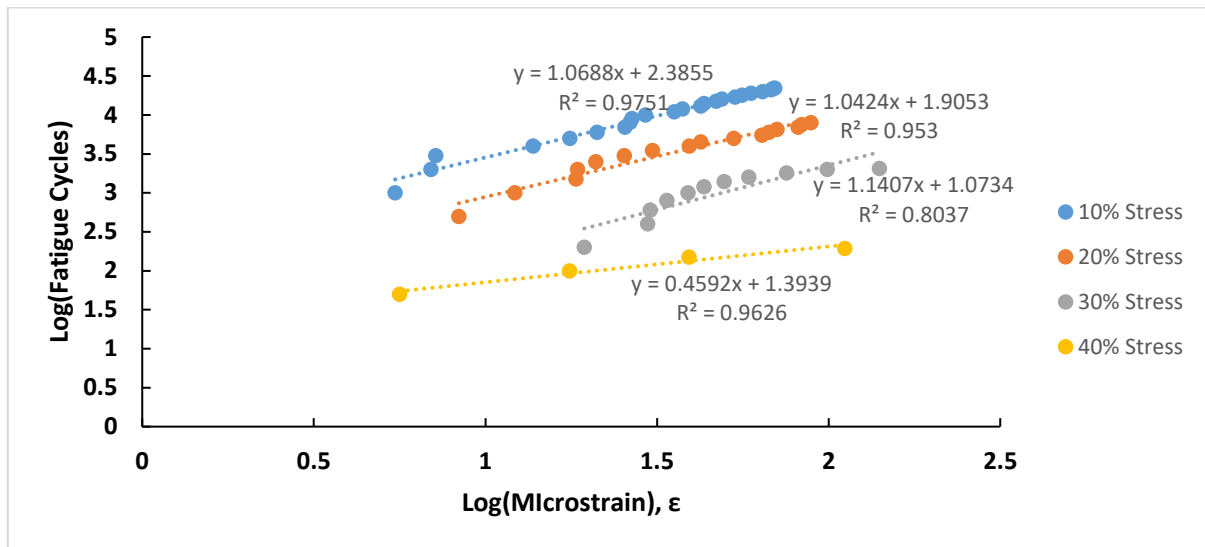


Figure 5: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 40% RAP replacement at 25°C

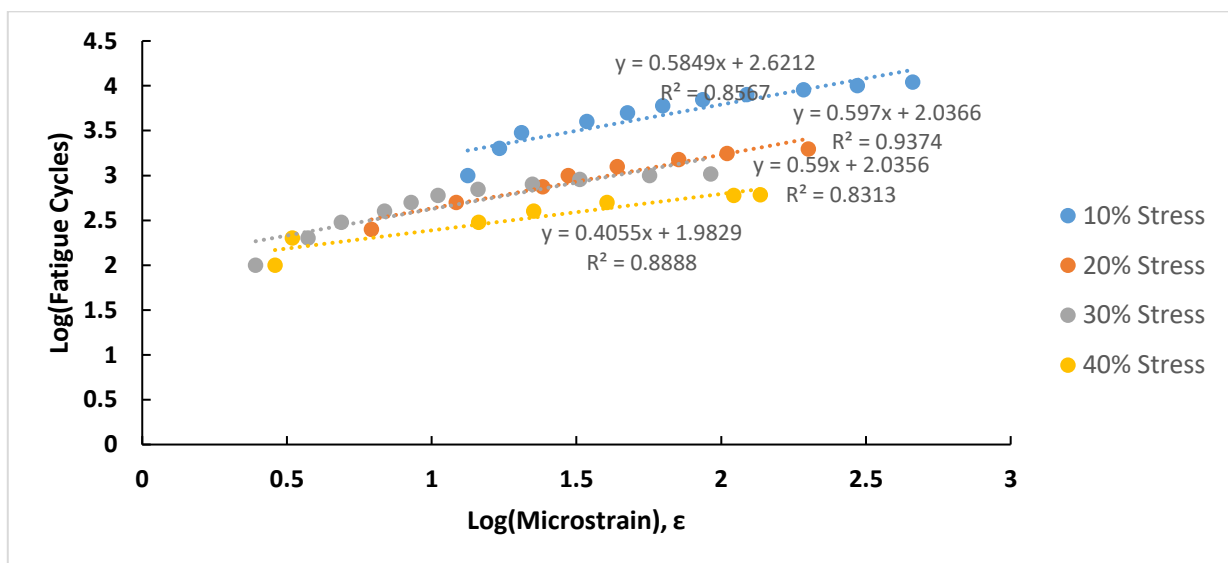


Figure 6: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 40% RAP replacement at 35°C

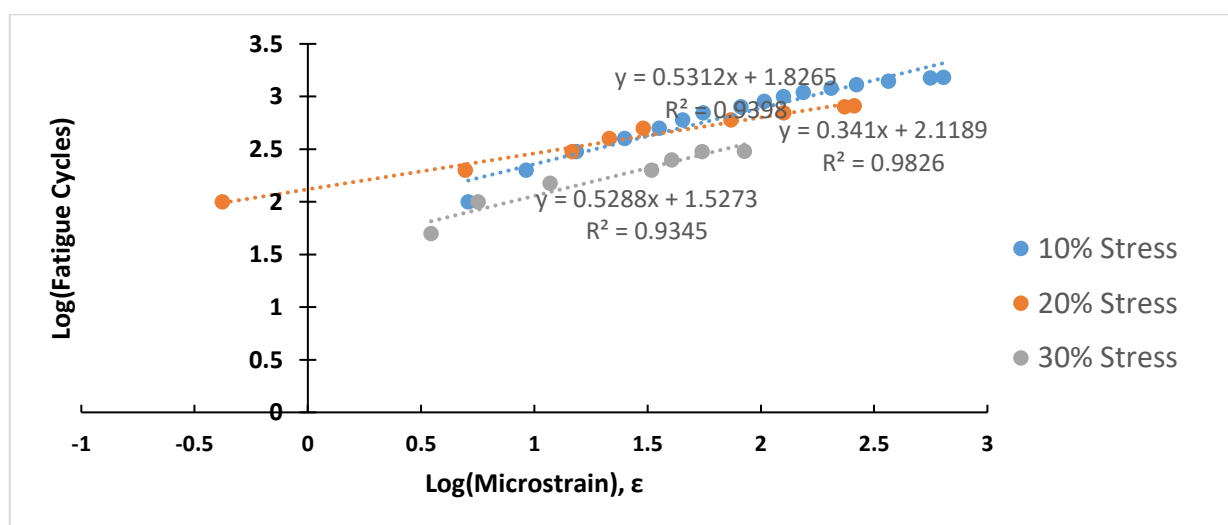


Figure 7: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 40% RAP replacement at 45°C

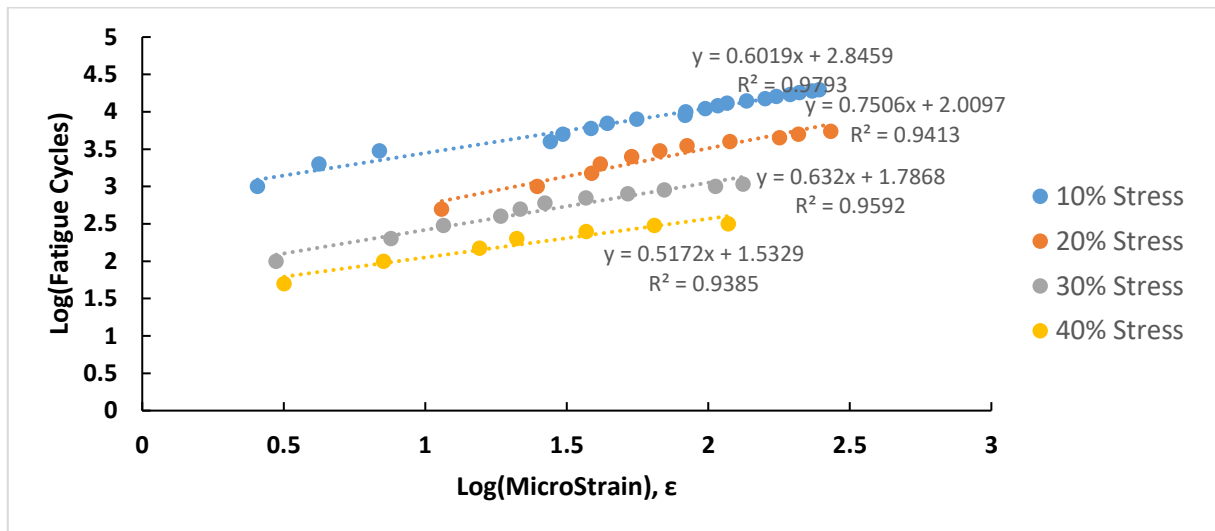


Figure 8: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 70% RAP replacement and 25% WEO at 25°C

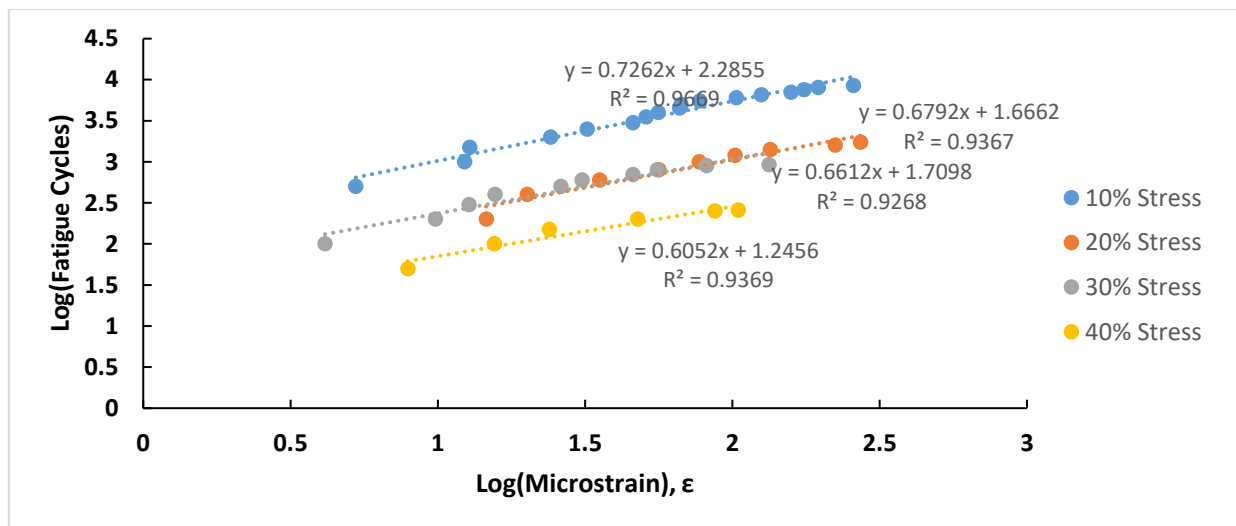


Figure 9: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 70% RAP replacement and 25% WEO at 35°C

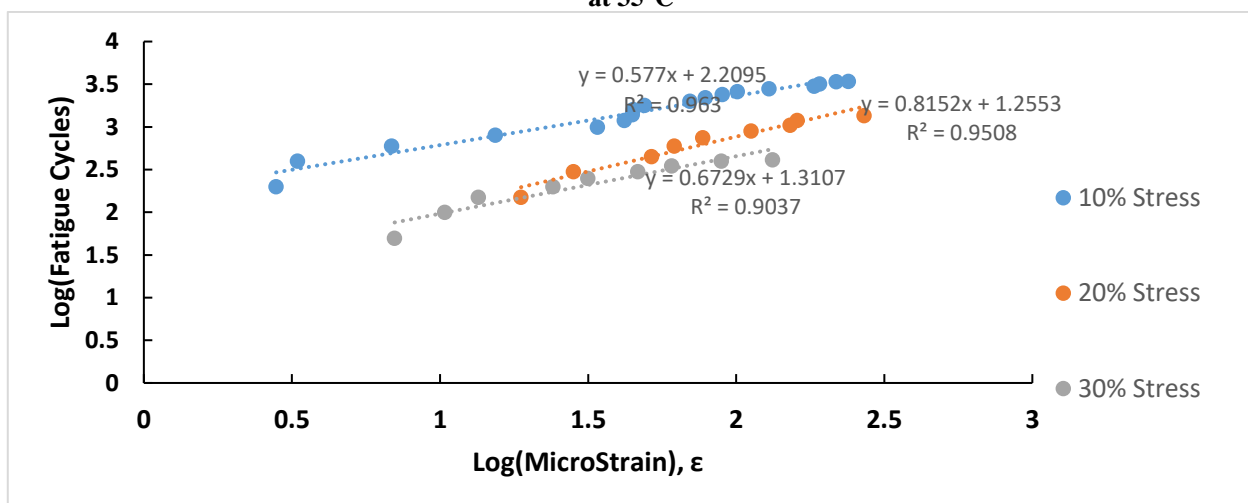


Figure 10: Log – Log plot of Fatigue Cycles vs Micro strain for SMA mix with 70% RAP replacement and 25% WEO at 45°C

Table-VI: Summary of regression equation between Fatigue cycles and Micro Strain from the ITFT test

SMA Mix	Temperature, °C	Stress levels, %	{logN <sub>f</sub> = logk <sub>1</sub> + k <sub>2</sub> logε} or {N <sub>f</sub> =k <sub>1</sub> (ε) <sup>k<sub>2</sub></sup> }			
			logk <sub>1</sub>	k <sub>1</sub>	k <sub>2</sub>	R <sup>2</sup>
Conventional Mix	25	10	2.1893	154.632	0.7101	0.9189
		20	1.5261	33.5815	0.843	0.8713
		30	1.5693	37.0937	0.7822	0.9371
		40	1.1213	13.2221	0.8032	0.8597
	35	10	1.9225	83.6566	0.6366	0.8817
		20	1.4466	27.964	0.7388	0.8469
		30	1.0876	12.2349	0.781	0.879
		40	1.2146	16.3908	0.7077	0.9052
	45	10	2.2022	159.294	0.5031	0.7871
		20	1.6409	43.7421	0.6524	0.9228
		30	1.0977	12.5228	0.6005	0.9274
		40	1.0977	12.5228	0.6005	0.9274
40% RAP SMA mix	25	10	2.3855	242.941	1.0688	0.9751
		20	1.9053	80.4081	1.0424	0.953
		30	1.0734	11.8413	1.1407	0.8037
		40	1.3939	24.7685	0.4592	0.9626
	35	10	2.6212	418.023	0.5849	0.8567
		20	2.0366	108.793	0.597	0.9374
		30	2.0356	108.543	0.59	0.8313
		40	1.9829	96.1391	0.4055	0.8888
	45	10	1.8265	67.0656	0.5312	0.82
		20	2.1189	131.492	0.341	0.9826
		30	1.5273	33.6744	0.5288	0.9345
		40	1.5273	33.6744	0.5288	0.9345
70% RAP + 25% WEO SMA Mix	25	10	2.8459	701.294	0.6019	0.9793
		20	2.0097	102.259	0.7506	0.9413
		30	1.7868	61.2068	0.632	0.9592
		40	1.5329	34.1114	0.5172	0.9385
	35	10	2.2855	192.975	0.7262	0.9669
		20	1.6662	46.366	0.6792	0.9367
		30	1.7098	51.2625	0.6612	0.9268
		40	1.2456	17.6035	0.6052	0.9369
	45	10	2.2095	161.994	0.577	0.963
		20	1.2553	18.0011	0.8152	0.9508
		30	1.3107	20.4503	0.6729	0.9037
		40	1.3107	20.4503	0.6729	0.9037

Fig. 11 shows the no. of fatigue cycle at which the specimen failed for three SMA mixes at various temperature and Stress levels. From the Figure, it can be noticed that the SMA mix with RAP appears to be most resistant to fatigue followed by SMA mix replaced with RAP & WEO and then by conventional SMA mix. At higher temperature and low stresses, the conventional mix appear to perform better than the mix with RAP without rejuvenators. The sample with rejuvenator performs slightly better than the conventional

mix. At higher stresses, irrespective of temperature, the conventional SMA mix performs better than both the RAP replaced samples.

Fig. 12 shows the micro strain (Horizontal tensile Strain) at which the specimen failed for three SMA mixes at various temperature and Stress levels.



It can be seen that at lower stress levels (10% and 20%), substantial reduction in strain at failure can be observed by using SMA mix RAP replacement. The effect is more pronounced in SMA - RAP mix without rejuvenators than

with rejuvenators. As the stress level increases, this effect becomes less and less visible and at about 40% stress all sample exhibit similar failure strain with the conventional mix producing slightly higher strain.

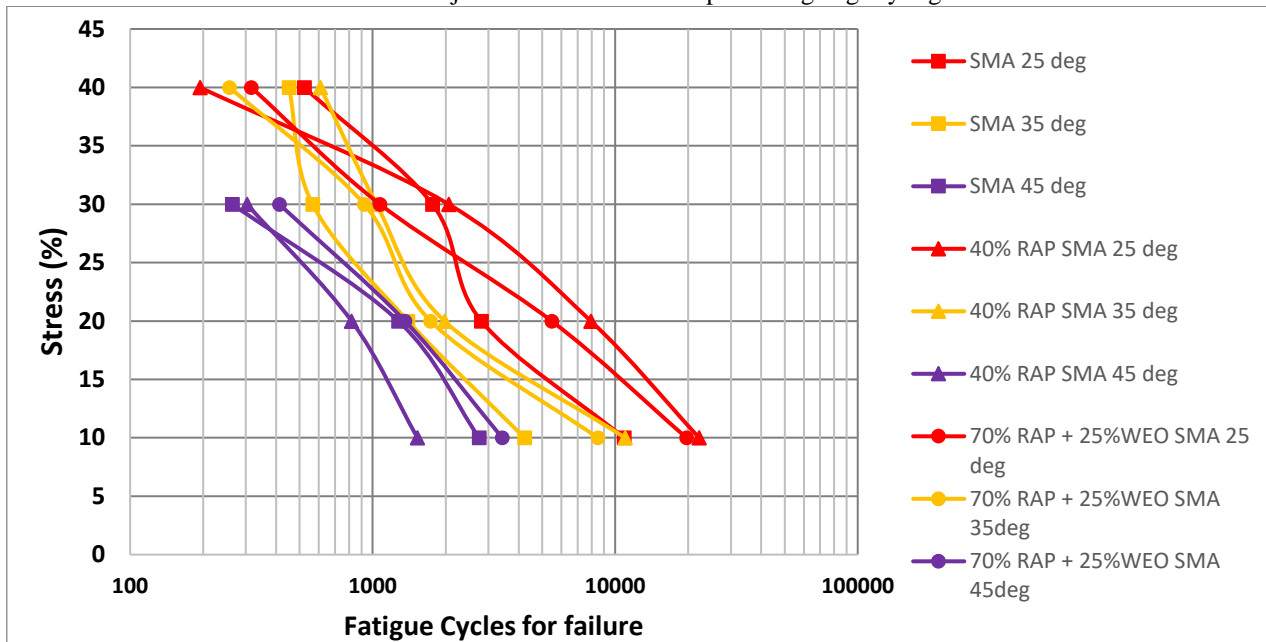


Fig. 11: Fatigue Cycle for failure vs Stress level at various temperature for the three optimum SMA mixes

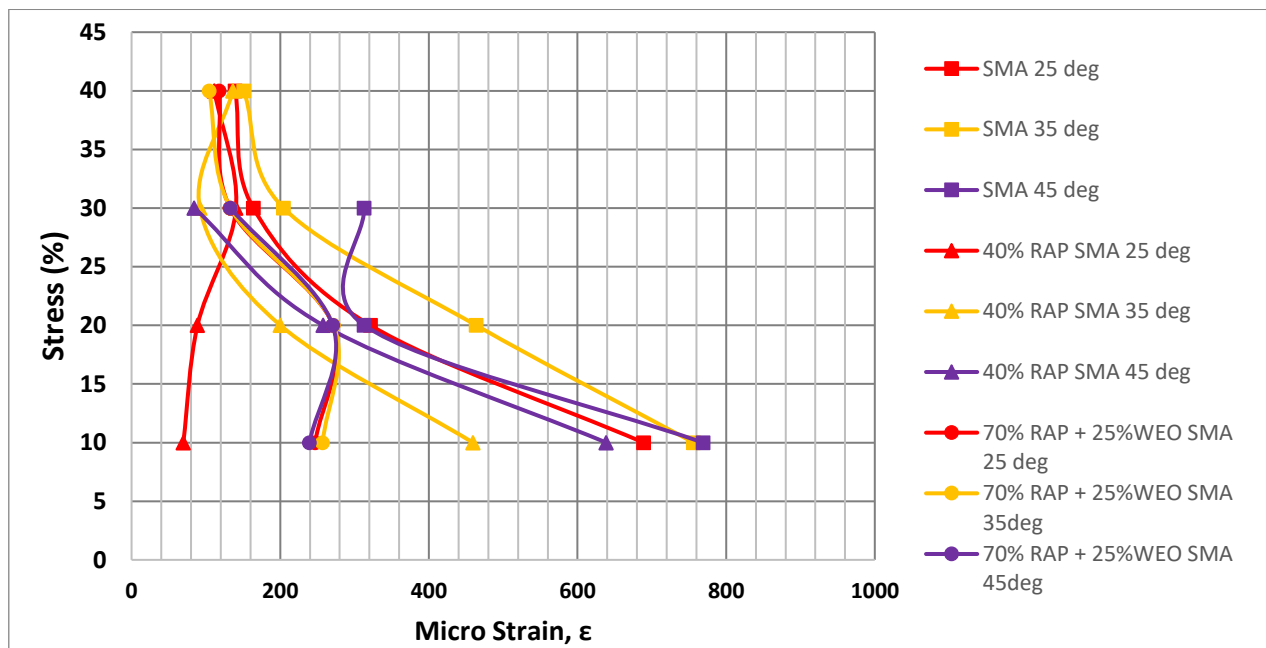


Fig. 12: Micro strain at failure vs Stress level at various temperature for the three optimum SMA mixes

#### D. Resilient Modulus

Fig. 13 - 21 shows a typical variation of resilient modulus with number of fatigue cycles. Table 7 provides the summary of regression equation between Fatigue cycles and resilient modulus. The resilient modulus of the sample mix goes on decreasing with the increase in the fatigue cycles and stress. The y - intercept ( $\log k_3$ ) of regression equation represents the number of fatigue cycle at failure for unit resilient modulus. It can be observed from the figures that at lower room temperature (25°C) and low stress levels, the resilient modulus of RAP replaced SMA mix without

WEO significantly increases the resilient modulus over conventional SMA mix. At intermediate and higher temperatures (35°C and 45°C), conventional SMA mix appears to have higher resilient modulus than RAP replaced optimum mix with and without rejuvenators. The overview of the results show that even the reduction in resilient modulus for most of the conditions is within 5%. It can be further noted that with the increase in stresses, irrespective of temperature, the resilient modulus decreases.

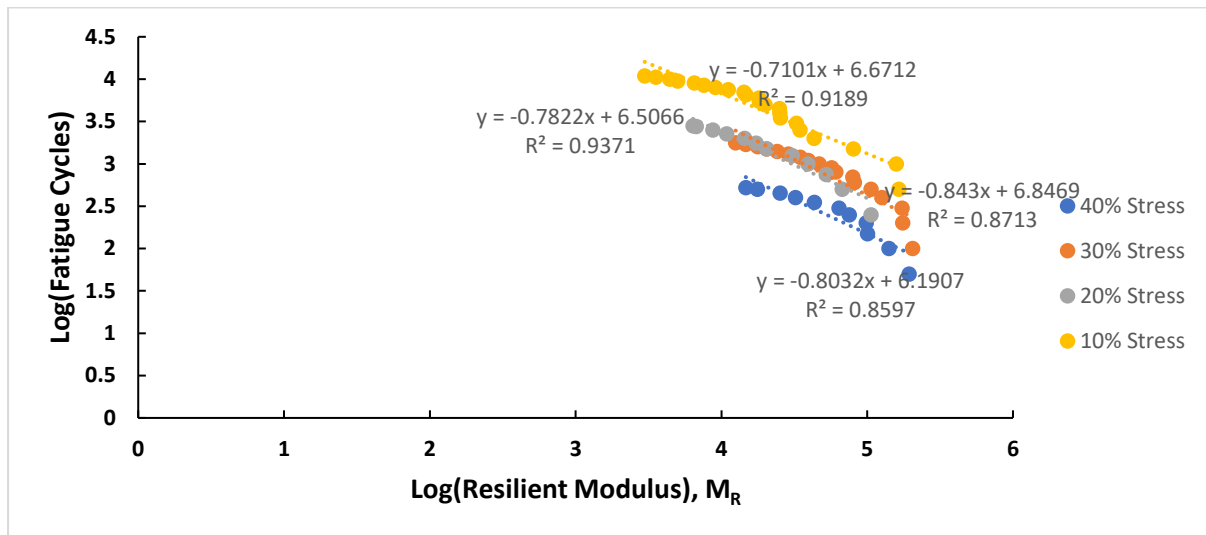


Figure 13: Log – Log plot of Fatigue cycles V/s Resilient Modulus for conventional SMA at 25°C

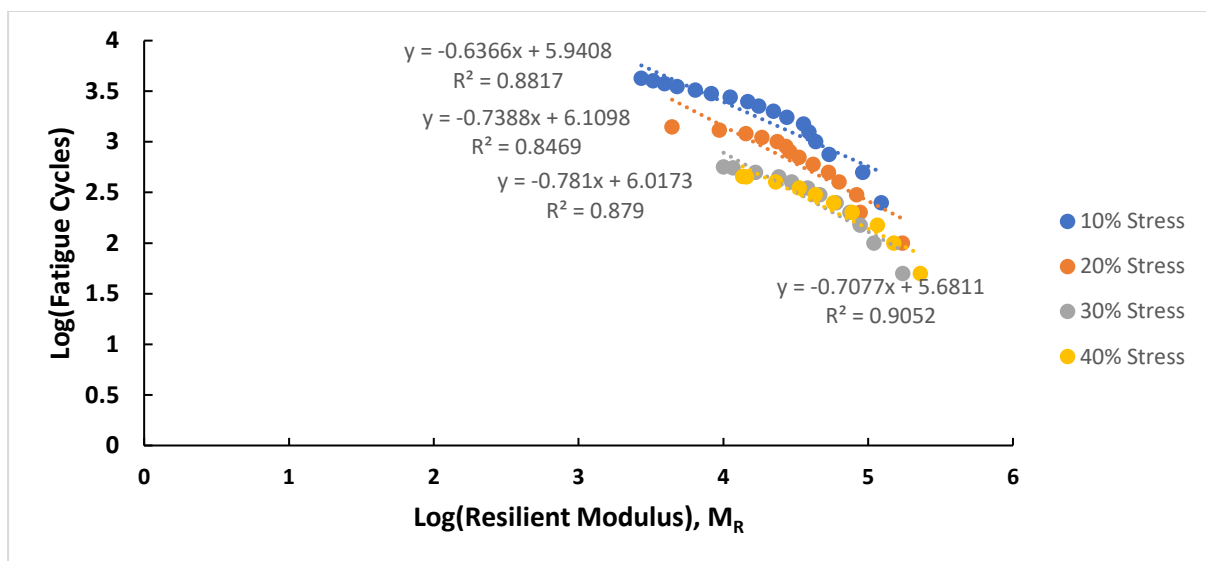


Figure 14: Log – Log plot of Fatigue cycles V/s Resilient Modulus for conventional SMA at 35°C

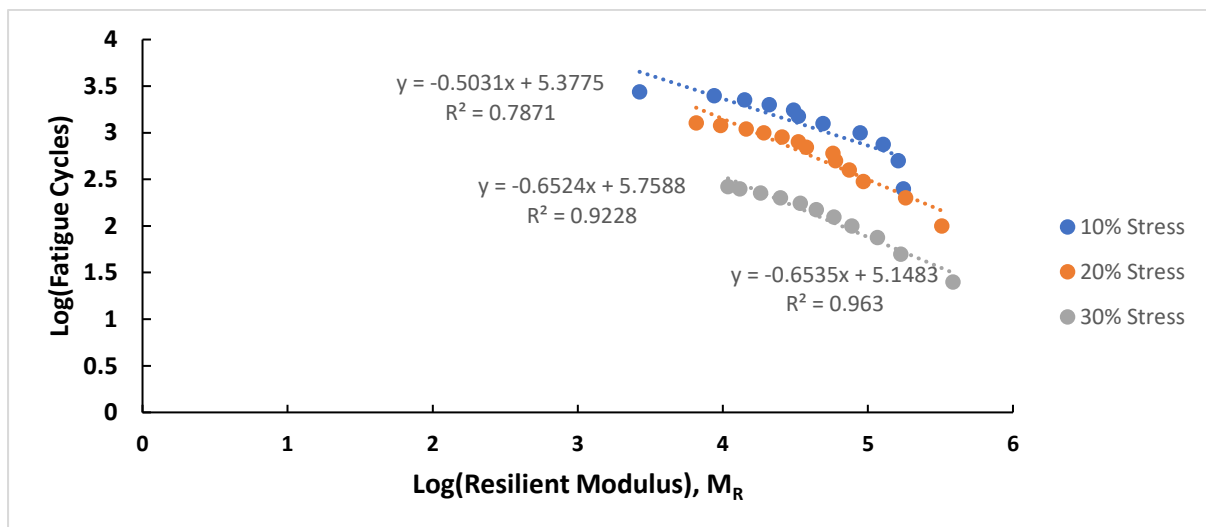


Figure 15: Log – Log plot of Fatigue cycles V/s Resilient Modulus for conventional SMA at 45°C

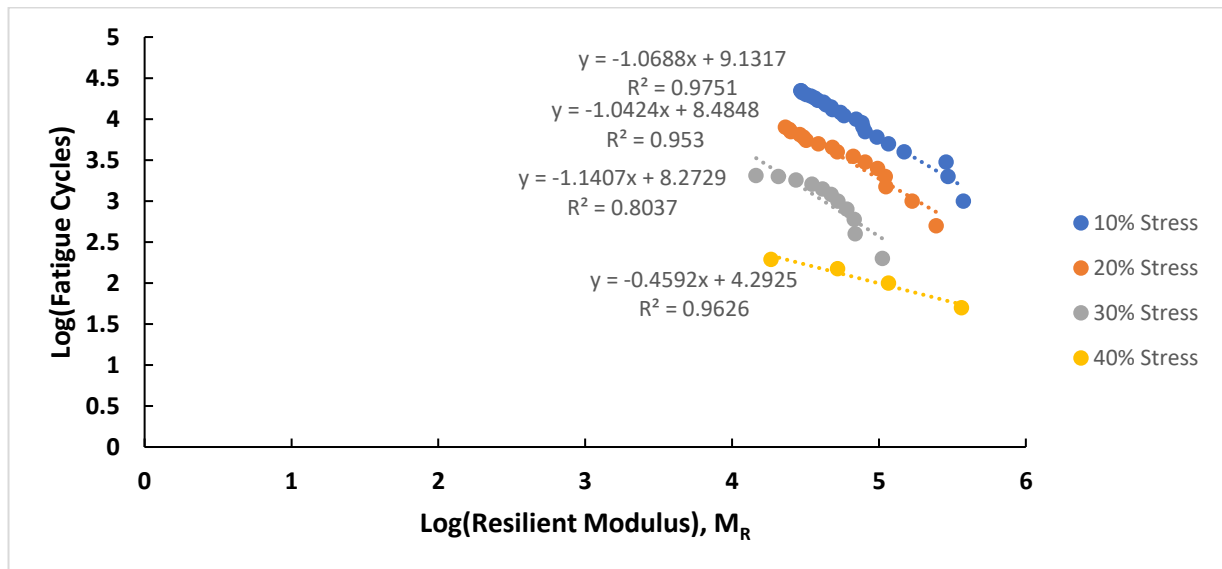


Figure 16: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA with 40% RAP replacement at 25°C

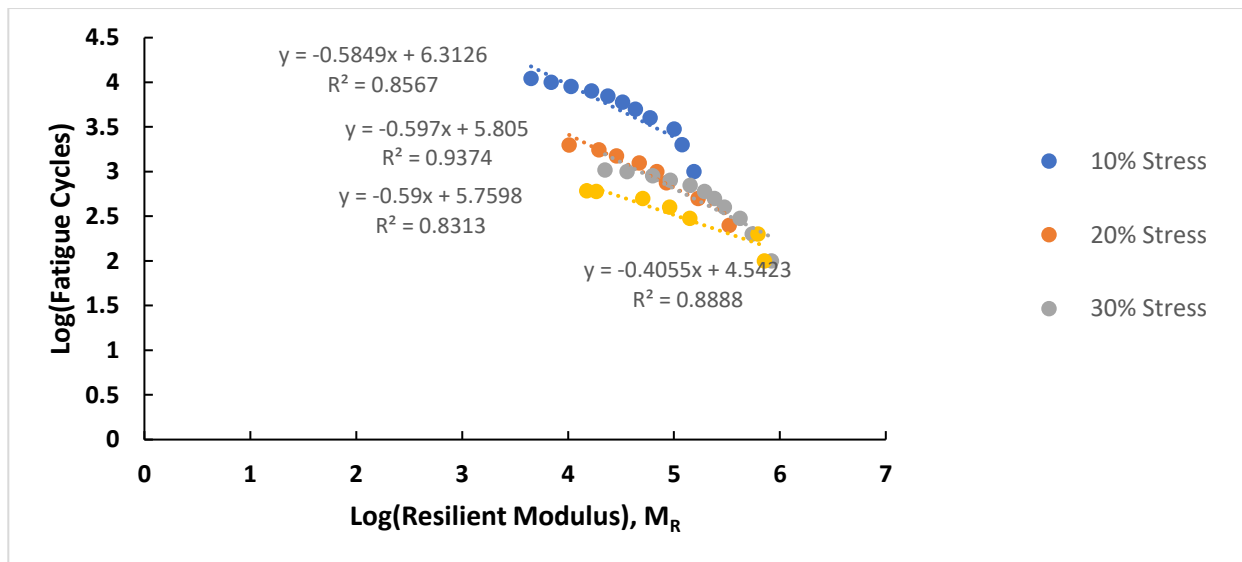


Figure 17: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA with 40% RAP replacement at 35°C

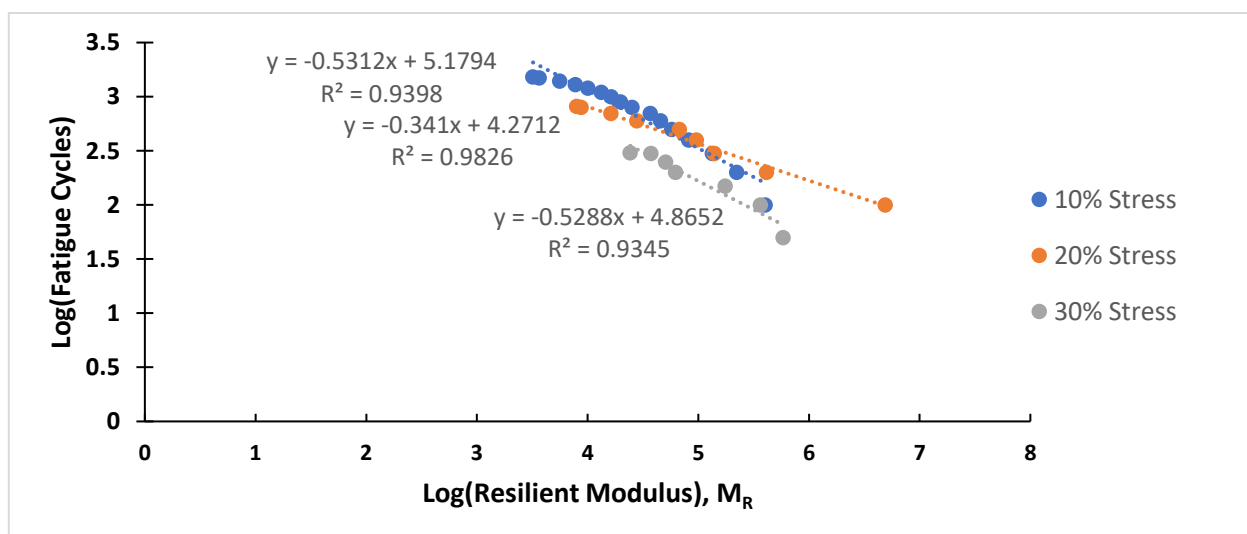


Figure 18: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA with 40% RAP replacement at 45°C

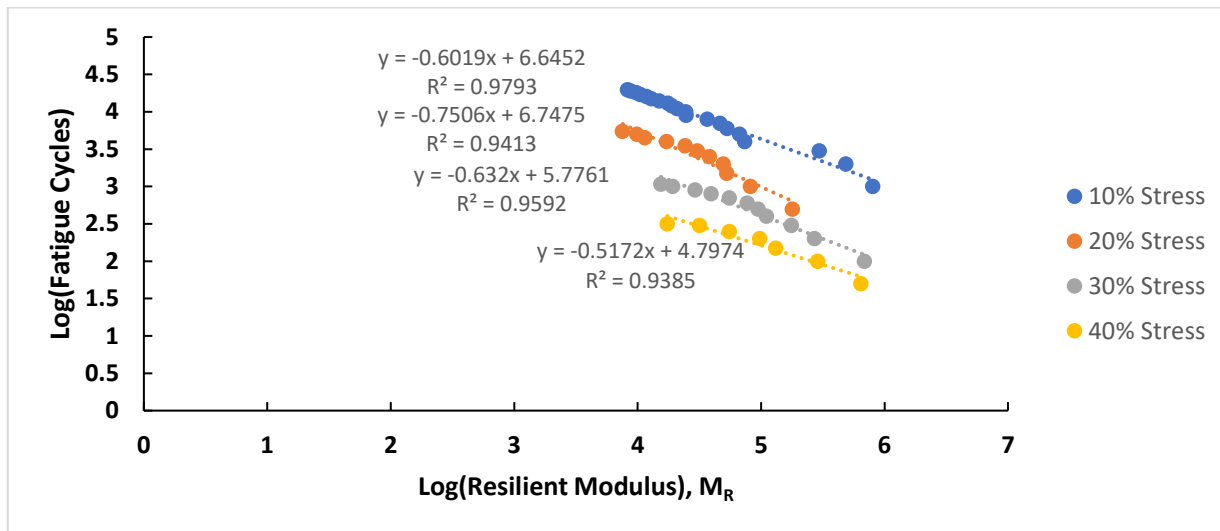


Figure 19: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA mix with 70% RAP replacement and 25% WEO at 25°C

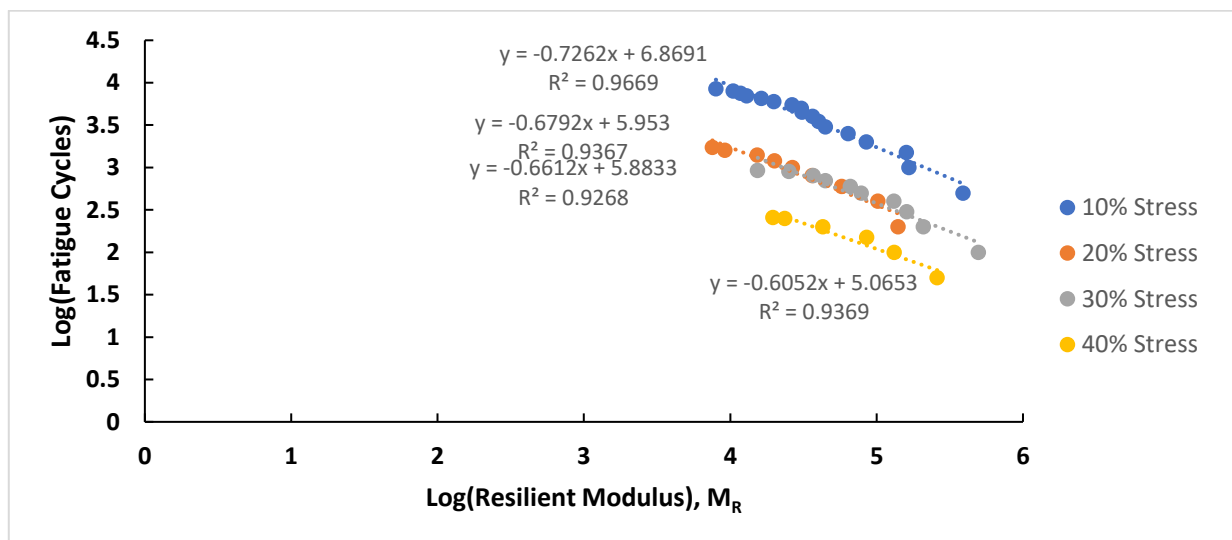


Figure 20: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA mix with 70% RAP replacement and 25% WEO 35°C

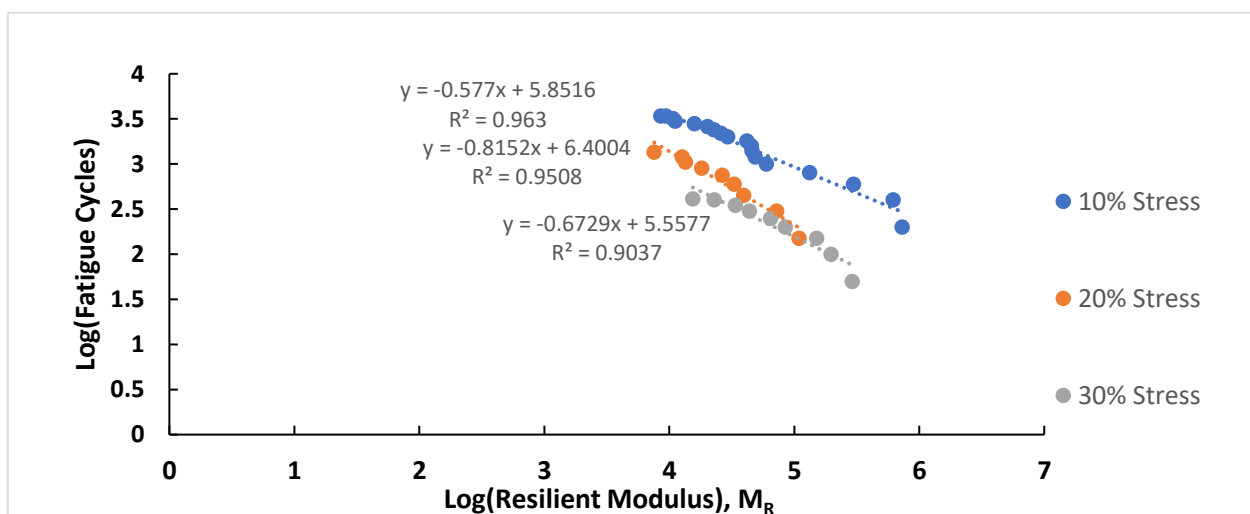


Figure 21: Log – Log plot of Fatigue cycles V/s Resilient Modulus for SMA mix with 70% RAP replacement and 25% WEO 45°C

Table-VII: Summary of regression equation between Fatigue cycles and Resilient Modulus from the ITFT test

SMA Mix	Temperature, °C	Stress levels, %	{ $N_f = k_3(M_R)^{k_4}$ } or { $\log N_f = \log k_3 + k_4 \log M_R$ }			
			$\log k_3$	$K_3$	$K_4$	$R^2$
Conventional Mix	25	10	6.6712	4690293	-0.7101	0.9189
		20	6.5066	3210702	-0.7822	0.9371
		30	6.8469	7029105	-0.843	0.8713
		40	6.1907	1551315	-0.8032	0.8597
	35	10	5.9408	872569	-0.6366	0.8817
		20	6.1098	1287656	-0.7388	0.8469
		30	6.0173	1040639	-0.781	0.879
		40	5.6811	479844	-0.7077	0.9052
	45	10	5.3775	238506	-0.5031	0.7871
		20	5.7588	573852	-0.6524	0.9228
		30	5.1483	140702	-0.6535	0.963
40% RAP SMA mix	25	10	9.1317	1.4E+09	-1.0688	0.9751
		20	8.4848	3.1E+08	-1.0424	0.953
		30	8.2729	1.9E+08	-1.1407	0.8037
		40	4.2925	19611	-0.4592	0.9626
	35	10	6.3126	2053998	-0.5849	0.8567
		20	5.805	638263	-0.597	0.9374
		30	5.7598	575175	-0.59	0.8313
		40	4.5423	34857.8	-0.4055	0.8888
	45	10	5.1794	151147	-0.5312	0.9398
		20	4.2712	18672.4	-0.341	0.9826
		30	4.8652	73316.2	-0.5288	0.9345
70% RAP + 25% WEO SMA MIX	25	10	6.6452	4417738	-0.6019	0.9793
		20	6.7475	5591135	-0.7506	0.9413
		30	5.7761	597173	-0.632	0.9592
		40	4.7974	62719.1	-0.5172	0.9385
	35	10	6.8691	7397756	-0.7262	0.9669
		20	5.953	897429	-0.6792	0.9367
		30	5.8833	764364	-0.6612	0.9268
		40	5.0653	116225	-0.6052	0.9369
	45	10	5.8516	710559	-0.577	0.963
		20	6.4004	2514201	-0.8152	0.9508
		30	5.5577	361160	-0.6729	0.9037

## V. CONCLUSION

- The Marshall stability of the conventional SMA mix is enhanced significantly by RAP replacement with or without rejuvenators. The RAP replaced SMA mix without rejuvenators offers better stability than those with rejuvenators.
- Tensile Strength Ratio and in turn the resistance to moisture susceptibility of SMA mix with RAP offers is higher than SMA mix with RAP and rejuvenator. Both the RAP replaced samples offer better moisture resistance than conventional SMA mix.
- At lower temperature (i.e., 25°C and 35°C), and low stress level (i.e., 10% and 20%), the SMA mix with RAP appears to be most resistant to fatigue followed by SMA mix replaced with RAP & WEO and then by conventional SMA mix. At higher temperature (i.e., 45°C) and low stresses, the conventional SMA mixture appears to be more stable than the mix with RAP

replacement, but have slightly less fatigue susceptibility than SMA mix with RAP and rejuvenator replacement. At higher stresses, irrespective of temperature, the conventional SMA mix performs better than both the RAP replaced samples.

- At lower stress levels (10% and 20%), substantial reduction in failure strain is observed by using SMA mix with RAP replacement with and without rejuvenators. The effect is more pronounced in SMA - RAP mix without rejuvenators than with rejuvenators. At higher stress level (40%) all sample exhibit similar failure strain with the conventional mix producing slightly higher strain



- With the increase in fatigue cycles, the resilient modulus decreases considerable. With the increase in stresses, irrespective of temperature, the resilient modulus decreases.
- At lower temperature (25°C), the resilient modulus of conventional SMA mix is considerably improved by the addition of RAP and rejuvenators. At intermediate and higher temperatures (35°C and 45°C), the conventional SMA offers a higher resilient modulus than with RAP and rejuvenators.

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