International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

# Performance Evaluation of Crumb Rubber Modified Bitumen on Binder Course of Stone Mastic Asphalt Mix

Anusha T M [1], Jagadeesh H S [2]
[1]Research Scholar, Dept of Civil Engineering, BMS College of Engineering, Bangalore, Karnataka- 560019, India.
[2]Professor, Dept of Civil Engineering, BMS College of Engineering, Bangalore-19, Karnataka- 560019, India.

***Abstract*:- Utilization of crumb rubber modified bitumen for wearing course in stone mastic asphalt mix pavement has been widely researched by many researchers due to its enormous benefits. This present paper focuses on the performance of binder course in stone mastic asphalt mixes using Crumb Rubber Modified Bitumen (CRMB) as a binder at five different levels, namely 5.7%, 6%, 6.3%, 6.6% and 6.9% respectively by weight of bituminous mixes. The optimal of crumb rubber modified bitumen was identified by carrying out Marshall stability test, Indirect tensile strength, fatigue and Rutting test. Based on the results obtained, it was observed 6.3% of crumb rubber modified bitumen improves the performance of binder course in stone mastic asphalt mix.**

***Key words : Crumb rubber, Stone mastic asphalt mix, Indirect tensile strength, Fatigue, Rutting, binder course.***

## 1. INTRODUCTION

Bituminous concrete mix is a combination of aggregates and binder. The aggregates acts as the structural skeleton of the pavement and bitumen acts as the glue of the mix. The properties of the aggregates have direct and significant effect on the performance of the pavement Patel et al. (2016) and Sun et al. (2018). The utilization of commercial by-products and recycled materials in construction as secondary and alternative materials has gained widespread acceptance and is becoming more important. The demands for industrial by-products and recycled materials are increasing per annum Joni et al. (2019). Using industrial by-products in pavement engineering not only provides construction materials with possible savings over new materials, but it also reduces demands on natural construction materials. It also protects the environment and save money through reducing the amount of waste materials requiring disposal. An asphalt pavement, which is designed and constructed properly will eventually undergo various types of failures due to various reasons such as number of years pavement served, type of paving materials used and due to other environmental factors etc Tran et al. (2015) Irfan et al. (2018) and Wang et al. (2019). Among various types of pavement failures rutting or grooving on the top layer is the major type of failure reduces the life of the flexible pavements. This may be due to the insufficient compaction of base/sub-base layer or bituminous layers during construction. The type of mix used in pavement construction plays an important role for minimizing the rut depth. Stone Mastic Asphalt or Stone Matrix Asphalt (SMA), is one such mix that provides tough and a durable asphalt mix. It is highly used as a rut-resistant mix for wearing and intermediate courses.

SMA is a gap graded asphalt mix that has a stone-on-stone contact to provide strength and has a rich mortar binder to provide durability. Generally, SMA is more expensive than conventional bituminous mixes because SMA requires high asphalt content, more durable aggregates and fibers as a stabilizer. The cost of stone matrix asphalt is found to be 20-25 % higher than the typical dense graded mixes. Thus, there is a need for the study of alternate materials which can reduce the cost of SMA mix. Reclaimed Asphalt Pavement (RAP) is the scarified pavement material containing aggregates and asphalt. Large quantities of RAP materials are generated during construction and maintenance of the highway Hanumantharao et al. (2019) and Joni et al.(2019).. The use of reclaimed asphalt pavement materials can substitute the high consumption of coarse aggregates and asphalt for SMA mix. On the other hand recycling of RAP also reduces the use of depleting natural aggregates and solves the disposal issues of reclaimed asphalt material generated from pavement rehabilitation.

**Problem statement and aim of the study:** Virgin Bitumen (VG 30) is commonly used in most part of India, and moreover, Indian roads subjected to higher traffic loading and hot weather conditions. The weather conditions in India leads to variation of temperature of about 60°C at surface to 30°C at subgrade during summer. The main objective of this study was to evaluate the effect of crumb rubber modified bitumen in binder course of stone mastic mix. Which involves the study of volumetric properties and mechanical properties of SMA mix in the binder course.

## 2. MATERIALS AND METHOD

The experimental program in this research studies aim to evaluate the effect of CRMB for binder course by evaluating the mechanical properties of crumb rubber modified stone mastic asphalt mixes.

2.1 Materials: asphalt binder with penetration grade 40/60 and average softening point of 56°C was utilized. Table 3 and 4 illustrate the physical and chemical properties of crumb rubber modified bitumen respectively. In the present studies crumb rubber with grade 55 is selected based on the climate condition in southern part of India I S 15462 (2004) and

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

density of CRMB was found to be 1.11 (gm/cm$^3$). CRMB 55 was procured from Mangalore Refineries and Petrochemicals Limited, Mangalore , Karnataka , India.

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.

Table 1: Physical Properties of 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 |

The gradation for 19mm SMA is carried out as per Indian Road Congress SP: 79: 2008 as illustrated in table 2.

Table 2: Aggregate gradation adopted for SMA (Binder course) as per MORT&H

| IS Sieve Size (mm) | Percentage passing | | | | | Desired Gradation | | Obtained gradation |
|---|---|---|---|---|---|---|---|---|
| | 20mm down | 12mm down | 6.3mm down | Baghouse dust | dust | upper limit | lower limit | |
| 26.5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19 | 89.4 | 100 | 100 | 100 | 100 | 100 | 90 | 95.44 |
| 13.2 | 11.7 | 100 | 100 | 100 | 100 | 70 | 45 | 62.0 |
| 9.5 | 0 | 69.5 | 100 | 100 | 100 | 60 | 25 | 51.20 |
| 4.75 | 0 | 0 | 30 | 100 | 99.6 | 28 | 20 | 23.96 |
| 2.36 | 0 | 0 | 6 | 100 | 81.2 | 24 | 16 | 17.32 |
| 1.18 | 0 | 0 | 0 | 100 | 67.8 | 21 | 13 | 14.78 |
| 0.6 | 0 | 0 | 0 | 100 | 60.4 | 18 | 12 | 14.04 |
| 0.3 | 0 | 0 | 0 | 100 | 53 | 20 | 10 | 13.3 |
| 0.075 | 0 | 0 | 0 | 96 | 42.6 | 12 | 8 | 11.94 |

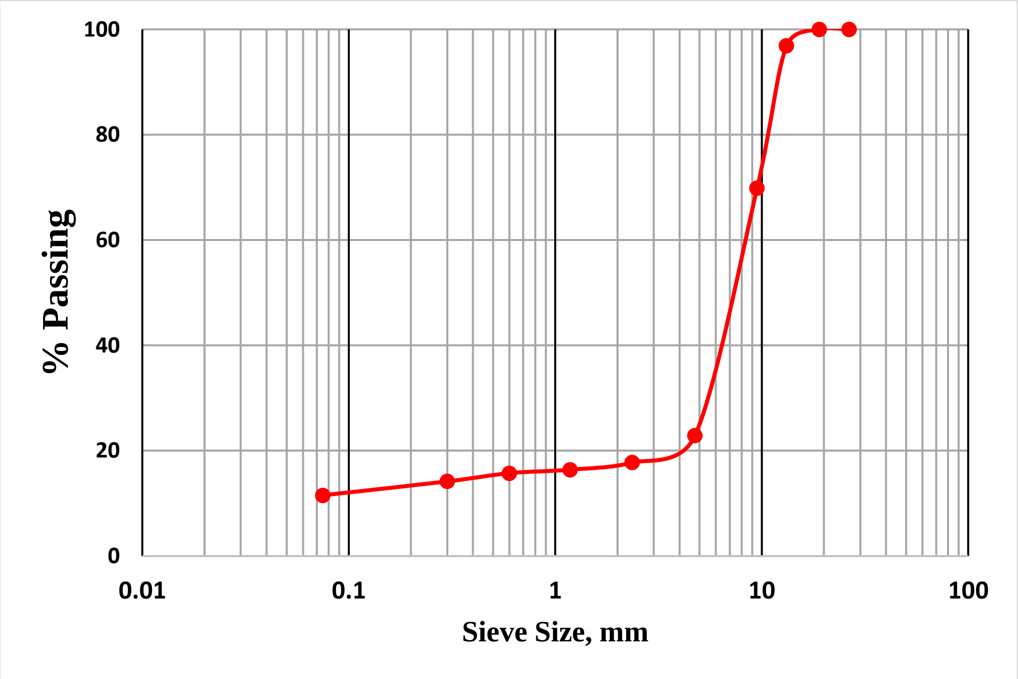


Fig. 1: Gradation of 19mm SMA mix

Table 3: Physical Properties of CRMB-55

| Bitumen test | Bitumen grade CRMB-55 | Standard test |
|---|---|---|
| Penetration @ 25 °C | 57 | ASTM D5 |
| Softening point @ °C | 56 | ASTM D36 |
| Flash Point @ °C | 280 | ASTM D92 |
| Elastic Recovery @15 °C | 35 | ASTM D6084 |
| Separation @ 3°C | 2.9 | ASTM D7173 |
| Viscosity @ 135°C (mPas) | 301.5 | ASTM D4402 |
| Ductility @ 25°C | >100 | ASTM D113 |
| Specific Gravity | 1.03 | ASTM D972 |

Table 4: Chemical Properties of CRMB-55 Mahrez (1999)

| Chemical Components | Test result |
|---|---|
| Acetone extract (%) | 23.1 |
| Rubber hydrocarbon (%) | 46.6 |
| Carbon black content (%) | 25.08 |
| Ash Content (%) | 5.2 |
| Natural rubber content (%) | 43.85 |
| Particle size µ | 425 |

2.2 Sample Preparations and test Method: In the design of bituminous mixes, the Marshall method of mix design is generally being practiced in India. It is a former design method developed by Bruce Marshall. In this method, the plastic deformation resistance of the cylindrical sample of the bituminous mix is measured when the mix is loaded at 5 cm/minute on its lateral surface. Marshall Stability is defined as the load carrying capacity of the specimen in kg or kN at the standard temperature of 60 °C. In the Present studies CRMB is added to SMA mix at different percentages of 5.3%, 5.7%, 6%, 6.3% and 6.6.% by the weight of total mix and filler of 10% is added to preparing SMA mixes, approximately 1200gm of aggregates are weighed and heated to a temperature of 175°C to 190°C and required a quantity of bitumen is heated to a temperature of 120°C to 165° C. Heated bitumen is added to the heated aggregates and mixed thoroughly at the specified mixing temperature by hand mixing or using a mechanical mixer. The prepared mix is placed in a pre-heated mould of 95°C to 165°C and compacted using a hammer by applying 50 blows on either side. Compacted moulds are kept for one day without disturbance, then samples are extracted from moulds and the dimensions and weight of samples are noted down. After that samples are kept in water bath maintained at 60°C for half an hour. Then the specimens are tested in Marshall testing machine and stability, flow are noted. Then the specimen properties are calculated and illustrated.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Marshall test results

3.1.1. Marshall stability. The results obtained for different percentage CRMB 55 is tabulated in table 6 and illustrated in figures 2, 3, 4 and 5. Pavement may subjected to number of repeated stresses, deformation and also fatigue cracks due to the movement of heavy traffic loads on the pavement so, it is necessary that the mix design used for the pavement construction should be done properly in order to withstand stresses coming from the vehicles. Mix design should possess resistance to low temperature cracking, moisture damages and also permanent deformation. In the design of SMA mix, several properties are considered such as percentage of air voids, voids in mineral aggregates binder content, voids in aggregates are should be within the permissible limit [23].

Table 5 SMA mix requirements as per IRC: SP: 79-2008

| **Mix Design Parameters (%)** | **Requirements** |
|---|---|
| **Air void content** | 4 |
| **Bitumen content** | 5.8 min |
| **Cellulous fibres** | 0.3% minimum by weight of total mix |
| **Voids In mineral Aggregates (VMA)** | 17 min |
| **Tensile Strength Ratio (TSR)** | 85 min |

Table 6 Marshall stability test results for different content of CRMB

| **Bitumen Content** | **Air voids $A_V$ (%)** | **Voids in the mineral aggregates VMA (%)** | **Flow value (mm)** | **Stability (kN)** |
|---|---|---|---|---|
| **5.7** | 5.79 | 17.97 | 2.07 | 8.85 |
| **6** | 4.95 | 17.80 | 2.50 | 9.88 |
| **6.3** | 4.12 | 17.64 | 3.18 | 11.10 |
| **6.6** | 3.88 | 17.98 | 4.23 | 9.33 |
| **6.9** | 3.64 | 18.33 | 5.06 | 8.38 |

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

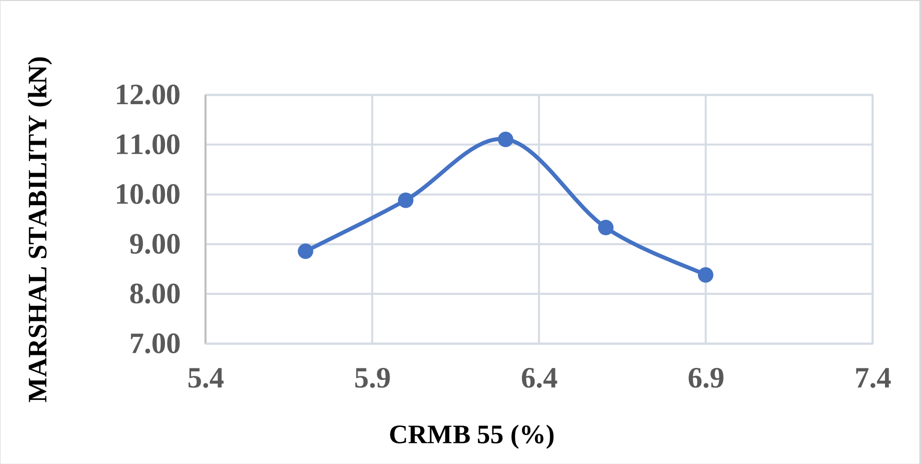


Figure 2 Stability values versus CRMB Content

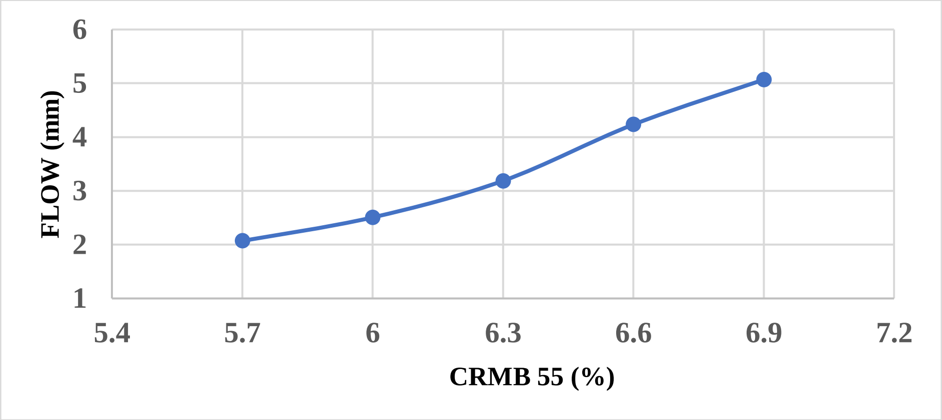


Figure 3 Flow results versus CRMB Content

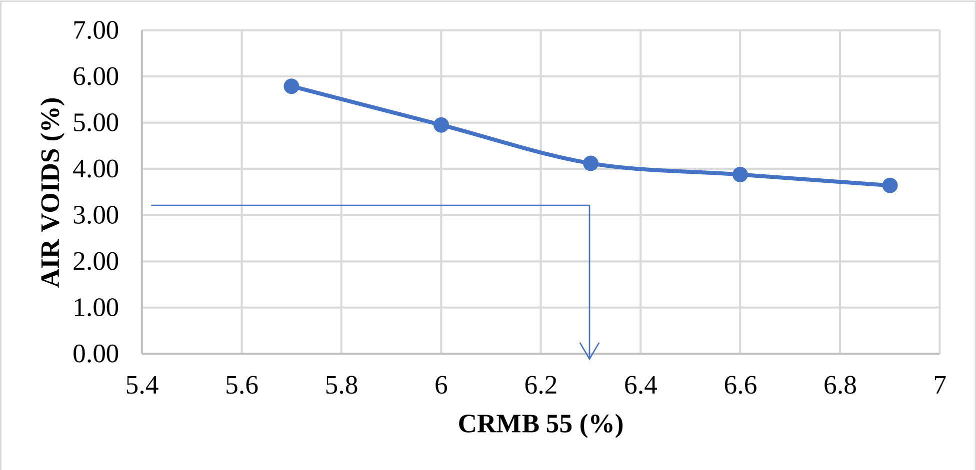


Figure 4 Air void results versus CRMB Content

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

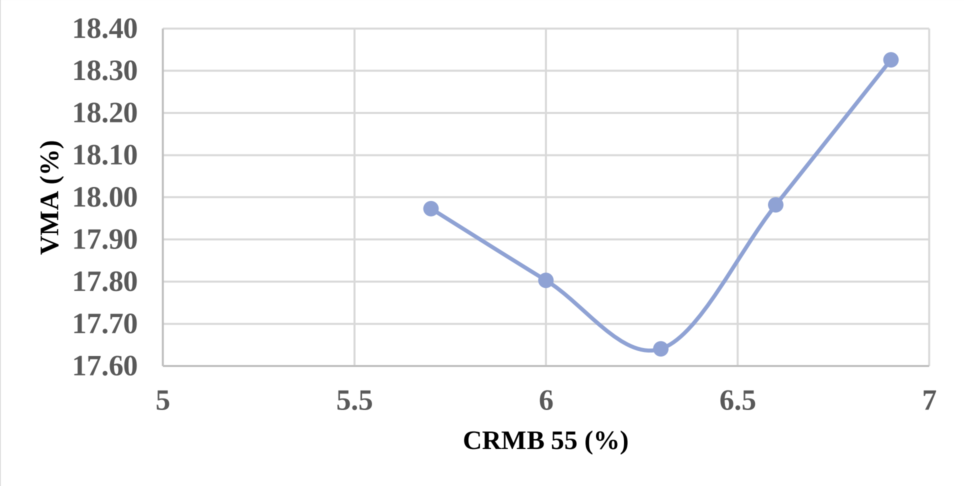


Figure 5 VMS results versus CRMB Content

As per table 5, which explains the mix design parameters for typical SMA mix [23]. The Marshall stability test results satisfies all the volumetric properties such stability, flow, VMA and air voids which is tabulated in table—and illustrated in figure 2, 3, 4 and 5. Among all the percentages of CRMB 55 , the stability value obtained for 6.3% of CRMB55 was higher compare to other percentages of CRMB 55 and further increase in CRMB 55 content the stability value started decreasing.

In the case of Marshall flow value and CRMB 55 content, 6.3% of CRMB 55 achieved the desired flow value further increase in binder content leads to increase in flow value which in turn leads to increase in voids. With respect to voids filled in mineral aggregates (VMA) and Air voids ($A_v$) i.e. VMA should be min 17% and AV should be 4% respectively , both the mix design parameter was satisfied by 6.3% of CRMB 55. Further SMA mixes samples with 6.3% CRMB 55 is prepared using Marshall mix design method which is designed and developed by Bruce Marshall and Indirect tensile strength , fatigue and rutting test is carried out.

3.2 Indirect Tensile Strength: The bituminous mixes are tested for long term stripping susceptibility through the indirect tensile strength test. The specimens are tested for the change in diametrical tensile strength due to the effects of water saturation and accelerated stripping phenomenon observed due to freezing and thawing. The test is carried out for 6 sets of compacted asphalt mix. 3 mixes are tested for ITS in a dry condition and the other 3 are tested after subjecting to a freeze-thaw cycle. Test is carried out as per ASTM D 6931 (2012). ITS test is conducted for the marshall specimens having air voids of 7+/- 0.5%. The required percentage of air voids can be obtained by adjusting the number of blows for the marshall specimens. Six specimens having air void content of 7% are casted. Three of them are tested for dry. The other 3 are subjected to vacuum pressure of 13-67 kPa then wrapped through plastic film and placed in a freezer for 16 hrs at 18+/-3°C. After freezing of the specimens, they are subjected to thawing by keeping them in a water bath maintained at 60+/-1°C for 24 hours. Both dry and wet specimens are placed in a water bath at 25+/-0.5°C for 2hour then tested for indirect tensile strength. Table – explains ITS results. Referring to table 7 illustrates 6.3% CRMB 55 content showed higher tensile strength and tensile strength ratio compare to remaining percentage of CRMB 55 i.e. 5.7%, 6%, 6.6% and 6.9%.

Table 7 ITS test results for conventional SMA mix (CRMB 55)

| **Samples** | Average height of the sample (mm) | Average diameter of the sample (mm) | Maximum load (N) | Tensile strength (kPa) | Average tensile strength (kPa) |
|---|---|---|---|---|---|
| Unconditioned | | | | | |
| S1 | 73.90 | 101.05 | 4470 | 381.01 | |
| S2 | 73.37 | 102.57 | 3050 | 257.97 | 349.87 |
| S3 | 73.54 | 101.17 | 4800 | 410.65 | |
| Conditioned | | | | | |
| S1 | 71.96 | 101.37 | 3582 | 312.56 | |
| S2 | 71.44 | 101.42 | 2945 | 258.73 | 308.39 |
| S3 | 69.86 | 102.42 | 3978 | 353.88 | |
| Tensile Strength Ratio (TSR) | | | | | 88.14% |

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

Immersion Wheel Tracking Test / Rutting test. For rutting test the aggregates and bitumen are preheated for specified temperature and mix is prepared in the pan. The prepared mix is poured into the rutting mould having dimensions of 600mm × 100 mm × 200 mm. The specimens are compacted using UTM for the required thickness. Then the prepared mould is fixed in the testing equipment and tested for the tyre pressure of 5.6 kg/cm$^2$ with speed of the wheel as 25 passes/minute. The rut depth is taken for every 500 passes until 10000 passes or the rut depth is equal to 12mm (whichever is encountered first). The rut depth readings are taken on either side of the specimen at a distance of 15 cm from the edges and average rut depth is calculated. Figure 6 and Figure 7 shows 6.3% content of CRMB 55 played a key role in reducing the rut depth compared to 5.7%, 6%, 6.6%, 6.9% of CRMB 55 content of in SMA mix

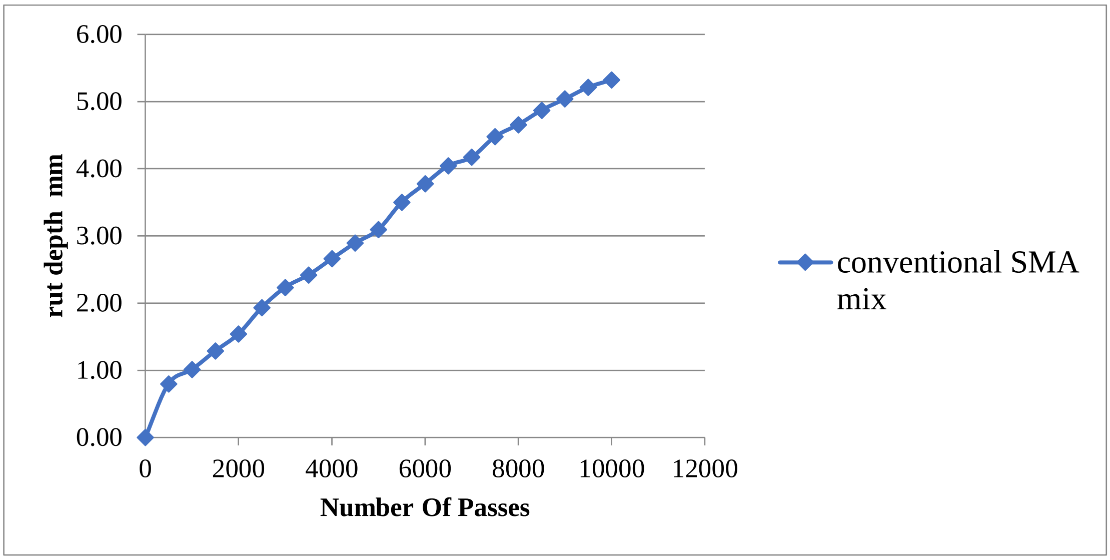


Figure 6 Rut Depth Values for 45 mm thickness specimen

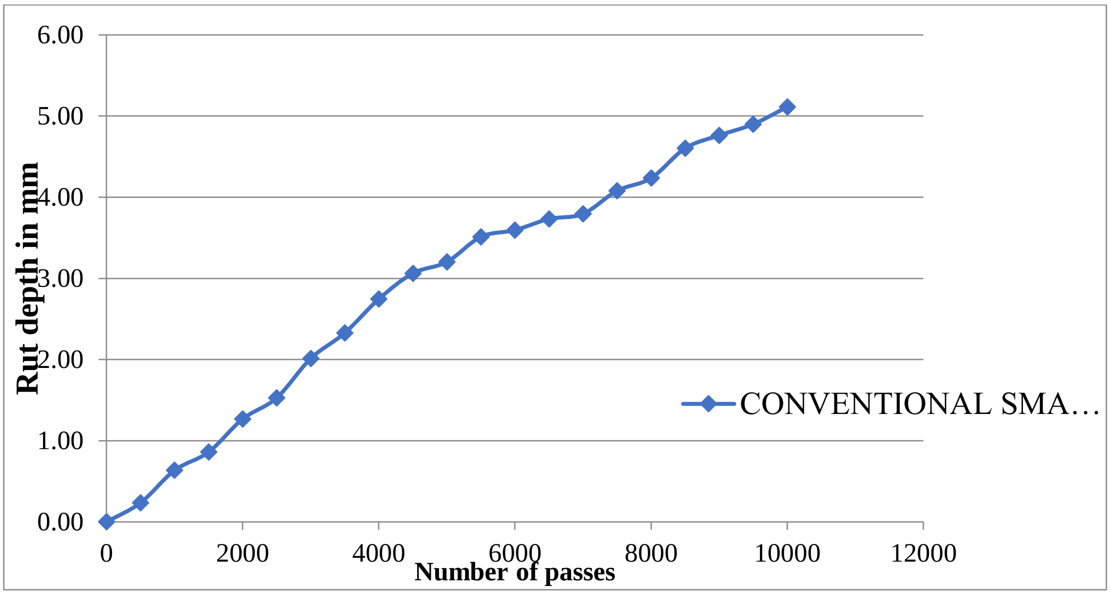


Figure 7 Rut Depth Values for 45 mm thickness specimen

3.3 Indirect Tensile Fatigue Test / Fatigue Test

The fatigue test is conducted on the conventional SMA mix with 6.3% of CRMB 55 ITFT apparatus. In the indirect repeated load testing, the fatigue value is determined using recoverable horizontal and vertical deformation that occurred by applying dynamic loading on the specimen. The specimen is tested at three different temperature (25ºC, 35ºC and 45ºC) and four stress levels (10%, 20%, 30% and 40% of failure stress). The specimen of 6.3% CRMB 55 content is deemed to be failed when it undergoes vertical deformation of 5 mm due to fatigue loading. The Figs 8 – 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 $\log N_f = \log k_1 + k_2 \log \varepsilon$. 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., 25ºC and 35ºC), the intercept is highest for SMA mix with 6.3% CRMB 55 yielded good results compare to SMA mix @ 45 ºC.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

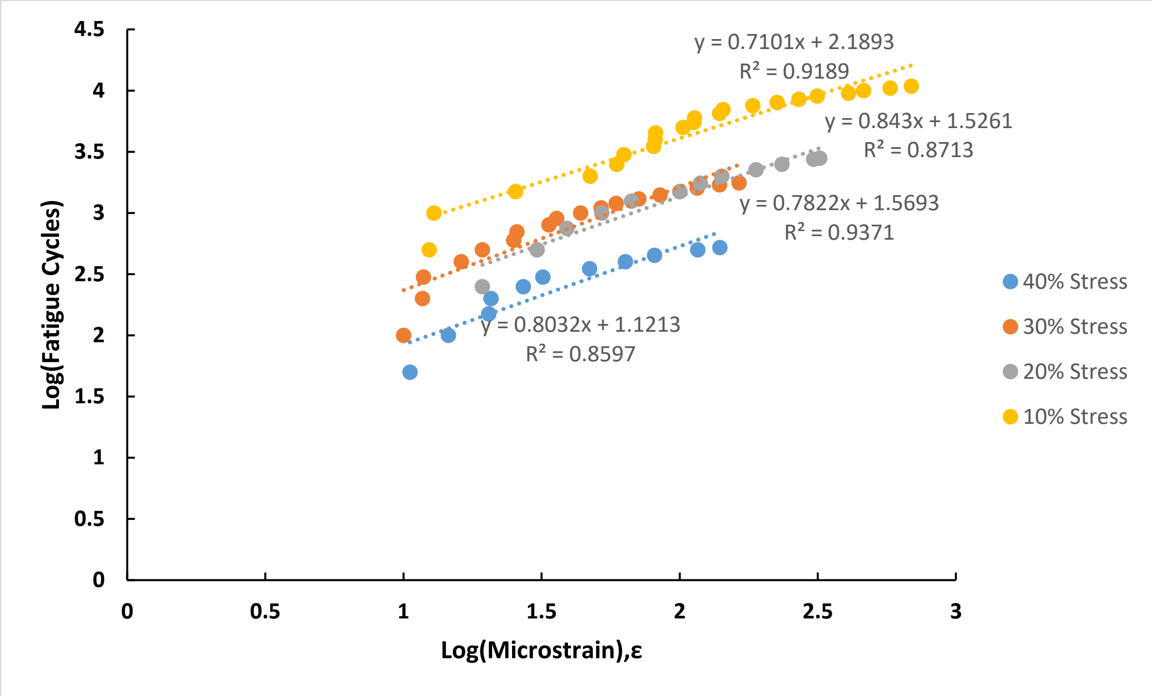


Figure 8: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 25ºC

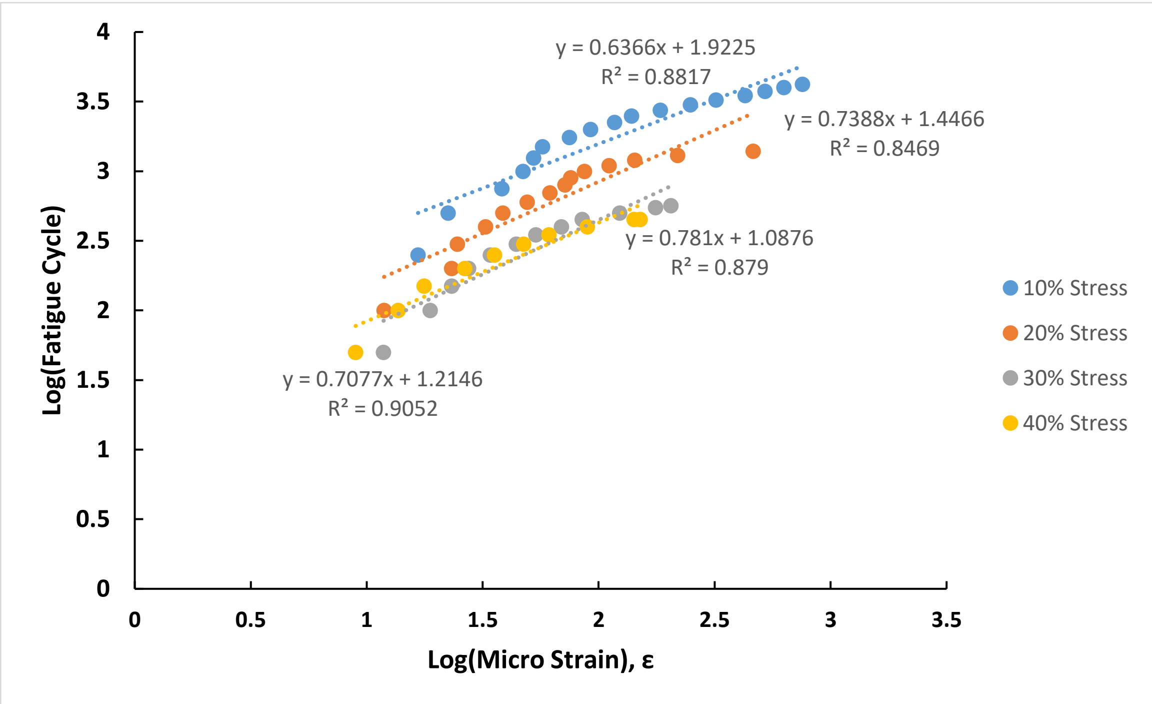


Figure 9: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 35°C

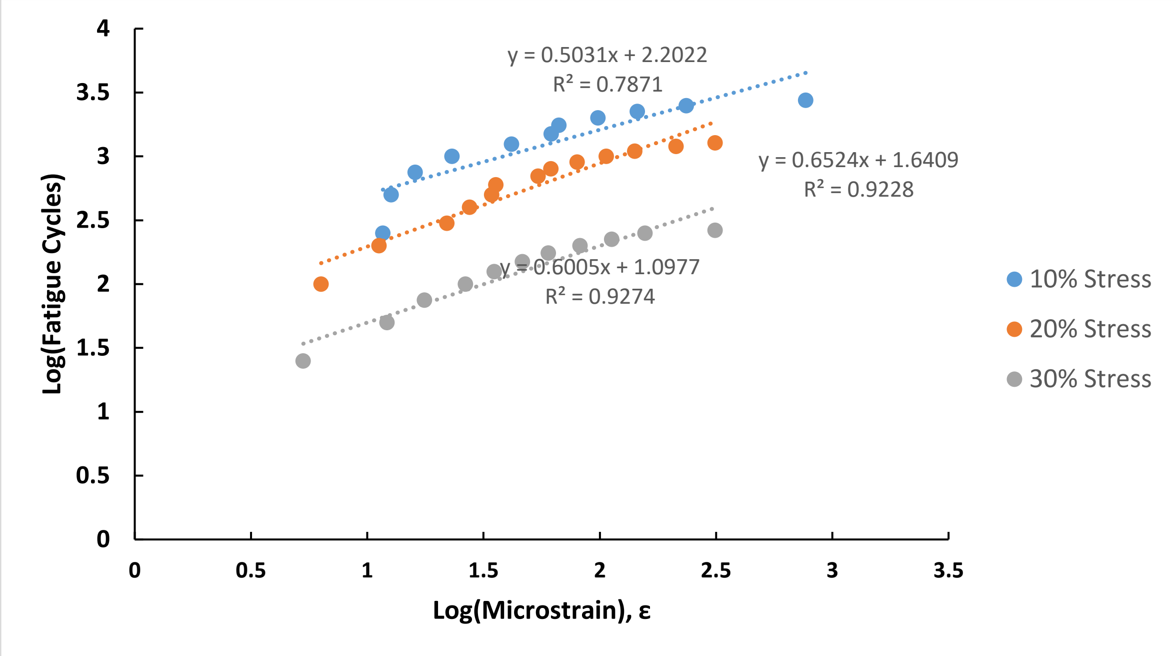


Figure 10: Log – Log plot of Fatigue Cycles vs Micro strain for conventional SMA mix at 45°C

## 4. CONCLUSIONS

Based on the laboratory studies carried out, following conclusions can be derived.

1) Stability / Strength of stone mastic asphalt mix is increased by adding 6.3% of CRMB 55.
2) The volumetric properties of CRMB 55 in SMA mix for binder course, satisfies the standard requirements.
3) Addition of 6.3% of CRMB55 increases the fatigue life of SMA mix at various temperature and stress levels, the mixture found to achieve higher fatigue life for 6.3% CRMB 55 compared to other percentage of CRMB 55.
4) Addition of 6.3% of CRMB55 to SMA mix plays important role in improving the rutting resistance.
5) Use of different modified binders, aggregate gradation and recycled materials are recommended for future studies.

**ORCID**
0000-0002-7549-7723

## 5. REFERENCES

[1] Al-bared M A M and A. Marto (2019), *Evaluating the compaction behaviour of soft marine clay stabilized with two sizes of recycled crushed tiles, In: Pradhan B. (eds) GCEC 2017. GCEC 2017. Lecture Notes in Civil Engineering, vol 9. Springer, Singapore*. Springer Singapore.
[2] Ariyapijati R H, S. P. Hadiwardoyo, and R. J. Sumabrata (2017), "Contributions crumb rubber in hot mix asphalt to the resilient modulus," *AIP Conf. Proc.*, vol. 1855,doi: 10.1063/1.4985475.
[3] ASTM D1559-89 (1992), "Standard test method for resistance to plastic flow of bituminous mixtures using Marshall Apparatus".
[4] Hanumantharao C, T. Anil Pradhyumna, K. Durga Prasad, N. Naveenkumar, G. Shantha Kumar Reddy, and M. Hemanth Vardhan (2019), "Crumb rubber modified bitumen and quarry dust in flexible pavements," *Int. J. Recent Technol. Eng.*, vol. 8, no. 1, pp. 2868–2873.
[5] Huang B, G. Li, D. Vukosavljevic, X. Shu, and B. K. Egan (2005), "Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1929, no. 1, pp. 37–45, doi: 10.1177/0361198105192900105.
[6] I S 15462 (2004), " Polymer and Rubber Modified Bitumen", Bureau of Indian Standards, 2004.
[7] I S 15462, " Polymer and Rubber Modified Bitumen", Bureau of Indian Standards.
[8] IRC:SP:79-2008 (2008), "Tentative Specifications for Stone Matrix Asphalt", Indian Road Congress.
[9] Irfan M, Y. Ali, S. Ahmed, and I. Hafeez (2018), "Performance Evaluation of Crumb Rubber-Modified Asphalt Mixtures Based on Laboratory and Field Investigations," *Arab. J. Sci. Eng.*, vol. 43, no. 4, pp. 1795–1806, doi: 10.1007/s13369-017-2729-2.
[10] Joni H H, R. H. A. Al-Rubaee, and M. A. Al-zerkani (2019), "Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils," *Case Stud. Constr. Mater.*, vol. 11, p. e00279, doi: 10.1016/j.cscm.2019.e00279.
[11] Kök B V and H. Çolak (2011), "Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt," *Constr. Build. Mater.*, vol. 25, no. 8, pp. 3204–3212, 2011, doi: 10.1016/j.conbuildmat.
[12] Mahrez A (1999), "Properties of rubberised bitumen binder and its effect on the bituminous mix [M.S. thesis], Faculty of Engineeering, Univeristy of Malaya, Kuala Lumpur, Malaysia.
[13] Mazzoni G, E. Bocci, and F. Canestrari (2018), "Influence of rejuvenators on bitumen ageing in hot recycled asphalt mixtures," *J. Traffic Transp. Eng. (English Ed.*, vol. 5, no. 3, pp. 157–168, doi: 10.1016/j.jtte.2018.01.001.
[14] Patel A ka, S. Gupte, and N. B. Parmar (2016), "Stone Matrix Asphalt (SMA) Mix Design Using Different Filler," vol. 3, no. 3, pp. 179–182.
[15] Shen J, S. Amirkhanian, and J. Aune Miller (2007), "Effects of rejuvenating agents on superpave mixtures containing reclaimed asphalt pavement," *J. Mater. Civ. Eng.*, vol. 19, no. 5, pp. 376–384, 2007, doi: 10.1061/(ASCE)0899-1561(2007)19:5(376).
[16] Sun Y, C. Fang, D. Fan, J. Wang, and X. Yuan (2018), "A Research on Fatigue Damage Constitutive Equation of Asphalt Mixture," *Math. Probl. Eng.*, vol. 2018, doi: 10.1155/2018/3489082.

[17] Talati Aand V. Talati (2014), “Study of Stone Matrix Asphalt For The Flexible Pavement,” *Int. J. Eng. Dev. Res.*, vol. 2, no. 1, pp. 789–792, [Online]. Available: www.ijedr.org.
[18] Tran N, A. Taylor, P. Turner, C. Holmes, and L. Porot (2016), “Effect of rejuvenator on performance characteristics of high RAP mixture,” *Asph. Paving Technol. Assoc. Asph. Paving Technol. Tech. Sess.*, vol. 85, pp. 283–313, doi: 10.1080/14680629.2015.1266757.
[19] Wang H, X. Liu, M. van de Ven, G. Lu, S. Erkens, and A. Skarpas (2020), “Fatigue performance of long-term aged crumb rubber modified bitumen containing warm-mix additives,” *Constr. Build. Mater.*, vol. 239, p. 117824, doi: 10.1016/j.conbuildmat.2019.117824.
[20] Wang H, Z. Dang, L. Li, and Z. You (2013), “Analysis on fatigue crack growth laws for crumb rubber modified (CRM) asphalt mixture,” *Constr. Build. Mater.*, vol. 47, pp. 1342–1349, doi: 10.1016/j.conbuildmat.2013.06.014.
[21] Xiao F and S. N. Amirkhanian (2008), “Resilient modulus behavior of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement,” *Road Mater. Pavement Des.*, vol. 9, no. 4, pp. 633–649, doi: 10.3166/rmpd.9.633-649.
[22] Xiao F, S. Amirkhanian, and C. H. Juang (2007), “Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures,” *J. Mater. Civ. Eng.*, vol. 19, no. 6, pp. 475–483, doi: 10.1061/(ASCE)0899-1561(2007)19:6(475).
[23] Xiao F, S. N. Amirkhanian, J. Shen, and B. Putman (2009), “Influences of crumb rubber size and type on reclaimed asphalt pavement (RAP) mixtures,” *Constr. Build. Mater.*, vol. 23, no. 2, pp. 1028–1034, doi: 10.1016/j.conbuildmat.2008.05.002.
[24] Zaumanis M, R. B. Mallick, L. Poulikakos, and R. Frank (2015), “Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures,” *Comput. Chem. Eng.*, vol. 71, pp. 538–550, 2014, doi: 10.1016/j.conbuildmat.2014.08.073.
[25] Zaumanis M, R. Mallick, and R. Frank (2013), “Evaluation of rejuvenator’s effectiveness with conventional mix testing for 100% reclaimed Asphalt pavement mixtures,” *Transp. Res. Rec.*, no. 2370, pp. 17–25, doi: 10.3141/2370-03.