University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering
journal homepage: www.jcoeng.edu.iq
Number 5 Volume 24 May 2018

Civil and Architectural Engineering

Performance Evaluation of Plant Produced Warm Mix Asphalt

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ABSTRACT

Warm mix asphalt (WMA) is relatively a new technology which enables the production and compaction of asphalt concrete mixtures at temperatures 15-40 °C lower than that of traditional hot mix asphalt HMA. In the present work, six asphalt concrete mixtures were produced in the mix plant (1 ton each) in six different batches. Half of these mixes were WMA and the other half were HMA. Three types of fillers (limestone dust, Portland cement and hydrated lime) were used for each type of mix. Samples were then taken from these patches and transferred to lab for performance testing which includes: Marshall characteristics, moisture susceptibility (indirect tension test), resilient modulus, permanent deformation (axial repeated load test) and fatigue characteristics (third point flexural beam test). The obtained results indicated that the performance of WMA is enhanced when using the hydrated lime as filler in comparison with the limestone dust and Portland cement fillers. Better fatigue life was obtained for WMA using hydrated lime filler in comparison with HMA. Regardless the filler type, the Marshall properties of WMA satisfy the requirement of local specification, other properties of WMA were relatively lower than the HMA.

Keywords: WMA, HMA, Moisture susceptibility, Resilient modulus, Permanent deformation, Fatigue.

تقييم الأداء للخرسانة الإسفلتية الدافئة المنتجة في المعمل

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الخلاصة

تعتبر الخلطات الإسفلتية الدافئة تقنية حديثة نسبيا والتي تمتاز بقابلية إنتاجها ورصها بدرجات حرارة اقل ب 15 -40 درجة مئوية مقارنة بالخلطات الإسفلتية التقليدية الحارة. لقد تم في هذا البحث إنتاج ستة خلطات مختلفة في معمل الإسفلت زنة واحد طن لكل منها, نصف هذه الخلطات كان من النوع الدافئ والنصف الاخر من النوع الحار. وقد تم استخدام ثلاثة أنواع من المادة المالئة (حجر الكلس المطحون, السمنت البورتلاندي والجير المطفأ) لكلا النوعين. تم اخذ عينات من هذه الخلطات لغرض أجراء فحوصات الأداء لها في المختبر والتي تتضمن خصائص مارشال, التأثر بالرطوبة (فحص الشد الغير المباشر), معامل الرجوعية , التشوهات الدائمية (فحص التحميل المحوري المتكرر) وخصائص الكلل (فحص انحناء العتبة الثلاثي). بينت النتائج المستحصلة من هذا البحث بان أداء الخلطات الإسفلتية الدافئة تتحسن باستعمال الجير المطفأ كمادة مالئة مقارنة بحجر الكلس المطحون والسمنت البورتلاندي وان عمر الكلل لهذه الخلطات أكثر من مثيلاتها من الخلطات الحارة. وبغض النظر عن

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2018.05.10

نوع المادة المالئة, خصائص مارشال للخلطات الدافئة قد حققت متطلبات المواصفات المحلية بينما كانت بقية خصائص الاداء اقل نسبيا من مثيلاتها من الخلطات الحارة.

الكلمات المفتاحية :الخلطات الدافئة, الخلطات الحارة, التأثر بالرطوبة, معامل الرجوعية, التشوهات الدائمية, الكلل

1. INTRODUCTION

Recently, the asphalt concrete production industries worldwide have focusing in the incorporation of sustainability in the pavement construction process throughout the use of warm mix asphalt (WMA). The production of this type of asphalt concrete differ than that of hot mix asphalt concrete (HMA) since the mixing temperature as well as compaction temperature approximately lower than that of HMA by 15-40 degree Celsius depending on the type of additives adopted to produce WMA. This reduction resulted in economical and environmental advantages due to the reduction of fuel cost for heating the raw materials which combined with low emission of carbon dioxide. Although, millions of tons of the WMA has been produced worldwide since the late of 1990th and excessively used for paving works, this type of mix does not used in Iraq, yet.

Generally, there are three distinct technologies to produce WMA. The first one include the use of organic additives such as Sasobit, which is paraffin wax material added in a dosage of 0.8 to 3 percent by weight of asphalt cement resulted in a lower viscosity of asphalt cement. The second type includes the use of chemical additives like Evotherm, the mechanism of this type of additives is to improve the bonding between the aggregate and asphalt cement, the addition rate is 1 to 2 percent by weight of asphalt cement. The third type consists of using foaming additives like Aspha-min or Advera (synthetic zeolite materials), the addition rate is vary from 0.2 to 0.3 percent by weight of the total mixture, at mixing temperature the zeolite release water which reduce the viscosity of asphalt cement.

Based on the aforementioned, the necessity has been a rise to examine the performance of this type of mixture using locally available aggregate and asphalt cement under local climatic condition. For this purpose, six types of asphalt concrete mixtures were produced in mixing plant to directly consider the effect of short term aging since the WMA short term aging does not addressed in current guidelines for mixture aging **AASHTO R30** of the laboratory produced mixes. Each mix batch has approximately 1000 kg weight. Three WMA batches as well as three control HMA batches were produced in the mix plant using pre-prepared job mix formula for the asphalt concrete wearing course with aggregate maximum size of 19mm (0.75 inch). Three types of mineral fillers (limestone dust, Portland cement and hydrated lime) were used in the preparation of the WMA and HMA mixtures, the WMA produced using Aspha-min foaming additives. Samples were then taken from these patches and transferred to lab for performance testing which includes: Marshall characteristics, moisture susceptibility (indirect tension test), resilient modulus and permanent deformation (axial repeated load test) and fatigue characteristics (third point flexural beam test).

2. BACKGROUND

The concept to produce WMA traced back to 1997, during that time the suggested approach was to combine asphalt cement with different grades in the asphalt concrete production process. **Koenders, et al., 2000,** proposed the use of soft asphalt cement which has low viscosity at warm temperature for coating the aggregate, the following step in the production process includes the use of hard grade asphalt cement in form of powder or foam to enhance the stability of the produced mixtures. In 2004, the use of synthetic zeolite additive to produce WMA was introduced by **Barthel, et al., 2006**. The synthetic zeolite (Aspha-min or Advera) is sodium aluminum silicate with 21 percent water by mass of crystallization which creates a foaming affect as the temperature rises above 100°C resulting in a higher workability of the mix due to the reduced binder viscosity, **D'Angelo, et al., 2008**. The typical dosage of the Aspha-min is 0.3 percent by weight of total mix added to the mix shortly before or at the same time as the binder. Although WMA was first developed in Europe, but its production and uses in the paving works was dramatically increase in the United States. Nowadays, approximately one third of total asphalt concrete mix produced in USA is WMA, **Agnieszka, 2017.**

Despite the economical and environmental reasons for using the WMA technologies, the existing literature appeared noticeable differences in the performance of this type mix against the rutting, fatigue and moisture damage, these difference mainly could be attributed to the adopted technology to produce WMA combined with the variability of mixing and compaction temperatures, **Agnieszka, 2017.**

Hurley, et al., 2006, inspected the effect of using Aspha-min on the performance related properties of WMA, Mixes were compacted at 149°C, 129°C, 110°C, and 88°C, with the mixing temperature about 19°C higher than the compaction temperature. They concluded that the rutting potential and the resilient modulus did not effected by the addition of Aspha-min. But the resilient modulus decreased as the compaction temperature decreased. Also, the moisture damage in term of tensile strength ratio was lower for WMA as compared to HMA.

Goh, et al., 2007, examined the performance of WMA prepared using Aspha-min with control HMA, the adopted dosages of the aspha-min was 0.3 and 0.5 percent by weight of total mix. The WMA mixes were compacted at 100°C and 120°C whereas the HMA mix was compcted at 120°C, PG 64-22 was adopted in their study. The main conclusions indicated by the authors reveal that the aspha-min additives does not effect the value of asphalt concrete dynamic modulus for all the examined mixtures. Also, they reported that WMA mixes have lower predicted rut depth in comparison with HMA, the difference in rut depth about 44 percent.

Bhusal, 2008, conducted a laboratory study for the evaluation of the potential of moisture damage as well as the rutting properties and dynamic modulus for WMA using two types of additives (Sasobit and Aspha-min), the results were compared with a control HMA, the obtained results revealed that non of the mixes (WMA and Control HMA) satisfy the minimum requirement of TSR of 80 percent, the Sasobit yield the highest conditioned indirect tensile strength and TSR values. Hamburg wheel tracking results indicate that the WMA with Sasobit have the highest rut resistance in comparison with control HMA and WMA with Aspha-min. Also, the results reflected no significant influence of WMA additives on the dynamic modulus results at test temperature of 4.4°C, but as the testing temperature increase (21.1°C, 37.8°C and 54 °C.) Sasobit showed an improved value for dynamic modulus than both the Aspha-min and Control mix

Jun Zhang, 2010, used three additives type to produce WMA and compare the performance with the HMA contains the same additives, the additives were Advera (Synethetic zeolite), Evotherm and Sasobit. Various laboratory tests were conducted by the author to evaluate the dynamic modulus, moisture susceptibility and rutting potential. It was concluded that all the mixtures present a very similar results regarding the dynamic modulus, the tensile strength ratio which was used to evaluate the moisture damage indicate that all the WMA mixtures yield TSR values below 80 percent (failure criterion), the TSR value for the WMA with Sasobit is higher than that of Advera or Evotherm. Better rut resistance obtained using the WMA in comparison with the HMA, the WMA with Sasobit yield the highest rut resistance in comparison with the other two additives type.

Al-Jumaili and Jameel ,2015, examined the performance of WMA produced using two types of additives (Aspha-min® and Sasobit®), the WMA specimens prepared using 125-135 °C mixing temperature and 120-125 °C compaction temperature, they indicated that the WMA resulted in lower indirect tensile strength, lower resilient modulus, higher rut depth and low fatigue resistant as compared to the HMA, also the researchers concluded that the WMA produced using Sasobit performed better than that produced by Aspha-min.

3. MATERIALS AND JOB MIX

Since it was decided to use plant produced asphalt concrete mixtures (WMA and HMA). Therefore as a first step, the raw materials which consists of aggregate, filer (limestone dust, Portland cement and hydrated lime) and asphalt cement were brought form the mix plant to the lab and a routine type of tests were conducted for them to evaluate the suitability of these materials to be used in the job mix for asphalt concrete production, the obtained results will be compared by the specification limit of State Corporation for Roads and Bridges, **SCRB, R/9, 2003,** except the asphalt cement results it will be compared by the American Association for State Highway and Transportation Official **(AASHTO) M320** requirement since the asphalt cement performance grade requirement does not existed in the local SCRB specification.

3.1 Asphalt Cement

The asphalt cement supplied to the mixing plant was brought from the Doura refinery, south-west of Baghdad. The asphalt cement properties as per the Superpave performance grade requirement are shown in **Table 1**. The results indicated that the asphalt cement has performance grade of PG 64-16. Photographs while testing are shown in **Fig.1**.

3.2 Aggregate

The aggregate used by the mix plant was crushed quartz; its source is Al-Nibaie quarry, north-west of Baghdad. This type of aggregates is locally available and widely used for asphalt concrete production in Baghdad. Four aggregate fractions were used by the mixing plant to produce asphalt concrete, namely; coarse agg, midsize agg, crusher sand and natural sand, the gradation for each one beside the blending ratio of aggregate and specification limits for wearing course mixture (Type III A with 19 mm max agg. size) are shown in **Table 2**. The final gradation of the aggregate is shown in **Fig.2**. The tests results of the physical properties for the coarse and fine aggregate are shown in **Table 3**.

3.3 Mineral Filler

Three types of filler were used in the mix plant for the production of asphalt concrete mixtures, these are; limestone dust, Portland cement and hydrated lime. The chemical composition as well as the physical properties of these fillers is shown in **Table 4**. The limestone dust and hydrated lime were supplied to the mixing plant from lime factory in Kerbala governorate, south east of Baghdad. Whereas the Portland cement supplied from Almas factory in Sulaimanya governorate, north of Iraq.

3.4 Aspha-min

Aspha-min powder was used as an additive for the production of WMA in mix plant; it is Sodium aluminosilicate hydrothermally crystallized into fine powder. Aspha-min (containing approximately 21 percent water by weight) was added manually with 0.3 percent (by the weight of total mix) to the heated aggregate in the mix plant mixer, the blend was thoroughly mixed for approximately 30 second then the asphalt cement is poured to the mixer. The aspha-min as well as the addition process is shown in **Fig.3**. The physical and chemical properties of the Aspha-min are presented in **Table 5**.

3.5 Mix Design

Marshall mix design method was used to design the control mixes (HMA) with the three types of fillers in the laboratory and the results was forwarded to the mix plant for the production of both types of asphalt concrete mixtures, HMA and WMA. For each type of filler, five Marshall specimens were prepared with different asphalt content. For the mixes with limestone dust, Portland cement and hydrated lime, the following asphalt cement contents (percent by weight of total mix) were used (4.1, 4.4, 4.7, 5.0 and 5.3 percent), (4.4, 4.7, 5.0, 5.3 and 5.6) and (4.7, 5.0, 5.3, 5.6 and 5.9), respectively. The starting asphalt cement content are differs for each type of filler since it was noticed earlier during the mix design that some low asphalt cement contents did not provide the proper coating for aggregate in case of Portland cement and hydrated lime mixes. The Marshall properties plots are shown in **Fig.4**.

As per the procedure outlined in the AI's manual series No.2, **AI, 1981**, the optimum content for the asphalt cement is obtained by averaging the three asphalt cement contents which yield the maximum stability, maximum unit weight and 4 percent air voids. Hence, the optimum asphalt cement content were 4.8, 5.1 and 5.4 percent for mixes with limestone dust, Portland cement and hydrated lime, respectively.

3.6 Plant Produced Mixtures

All the mixes used in this research were prepared in the mix plant type Linnhoff CmopactMix (capacity 120 ton/hr). WMA and HMA were produced according to the job mix formula presented in the above articles. For each type of filler, limestone dust, Portland cement and hydrated lime, one ton of WMA and one tone of HMA were produced. Totally, six tones of asphalt concrete were produced in the mix plant in six different batches.

For the HMA production, the aggregate in drying drum was heated to approximately 150°C and the asphalt cement in tank was heated to temperature of 155 °C which is corresponding to a viscosity of 170 c.St obtained from the viscosity-temperature relationship shown in **Fig.5**. The produced mixture has at temperature of 155 °C. Whereas for the WMA production, the asphalt cement temperature was 155 °C and that for aggregate was 120 °C and the resulting WMA mixture has a temperature of 125°C.

Photographs showing the delivery of WMA as well as HMA batched from the mix plant hoper beside those showing the temperature of WMA and sampling of asphalt concrete are presented in **Fig.6**.

After the sampling of asphalt concrete mixtures, the samples were transferred to the laboratory and the following tests were conducted for each type of mixes. For the loose mixes the extraction test to obtain the aggregate gradation and ignition test to determine the asphalt cement content. For the laboratory compacted specimens Marshall Properties, indirect tensile test, repeated axial compression test as well as third-point flexural loading test.

The results obtained from the sieve analysis for the extracted samples as well the asphalt cement content determined by using ignition method are compared with the job mix limit, the results which presented in **Table 6** indicates that there are very slight difference in aggregate gradation in some sieves between the plant produced mixtures and job mix formula where as for asphalt cement content the obtained results match well those determined in mix design.

4. PERFORMANCE TESTING AND RESULTS

4.1 Marshall Properties

Marshall specimens were prepared using the samples brought from the mix plant. From each sample, three specimens with 100mm (4 in) diameter and 63 mm (2.5 in) height were compacted at temperature of 145°C in case of HMA (within viscosity range of 280±30 c.St.) and 115 °C in case of WMA (10°C minus mixing temperature) and the average test results were recorded. The compaction was achieved by 75 blows/end as per the ASTM D 6927-15 requirements. The compacted specimens were immersed in water at 60°C for 45 minutes before testing for stability and flow, as shown in **Fig.7**.

The effect of mix type on Marshall properties are presented in **Table 7** and graphically shown in **Fig.8**. The results indicate that both of WMA and HMA specimens satisfy the minimum stability requirement presented in the SCRB specification (8 kN). The stability value for WMA (averaged for the three types of fillers) is lower than that of HMA by 11.6 percent, the highest stability value in WMA mixes belong to the hydrated lime filler. The minimum difference between the WMA and HMA stability belong to the hydrated lime filler (0.6 kN) whereas the highest difference belongs to the limestone dust filler (1.7 kN).

Based on the Marshall flow values, the WMA mix with limestone dust has the lowest value in comparison with Portland cement and hydrated lime WMA mixes, the average flow value for WMA mixes is higher than that of HMA, it was 3.56 for the former and 3.23 for the latter. This could be attributed to the higher air voids value for the WMA as compared to the HMA mixes, which reflect the better level of compatibility of the HMA than that of WMA mixes. Nevertheless, all the flow values that belong either to WMA or HMA satisfy the requirement for the SCRB specification flow requirement (2-4 mm). In view of density results, generally the HMA regardless of filler type have higher density than WMA, the lowest difference between the density of WMA and HMA belong to the lime stone dust filler whereas the highest difference belong to the hydrated lime filler. Due to insufficient compaction which reflects the further need of compaction, the hydrated lime filler in WMA or HMA yield the lowest density values as compared to the limestone dust or Portland cement filler types.

As demonstrated in the nix type relationship with air voids values, which exactly has the same trend as per the flow, the average air void values for WMA mixes (4.21 percent) is higher than that of HMA by 3.3 percent. The WMA mix with Portland cement filler has the lowest air voids value as compared to the WMA mixes with limestone dust or hydrated lime filler. The highest difference between the WMA and HMA mixes belongs to the hydrated lime filler type; since this type of filler have a higher surface resulted in a difficulty of compaction as indicated also by the voids in mineral aggregate (VMA) values. All the air voids values for WMA as well as HMA within the range of SCRB specification requirement (3-5 percent). Based on the VMA results, the WMA mixes with limestone dust have had the lowest value (14.4 percent) as compared to the WMA mixes with Portland cement or hydrated lime filler, the lowest difference between air VMA values of WMA and HMA also belongs to this type of filler, the average VMA value for the WMA mixes (15.03 percent) is higher than that of HMA by 2.2 percent, this results indicates that the compaction level achieved by the HMA is better than that of WMA. Nevertheless, all the VMA values for WMA as well as HMA are satisfy the requirement of SCRB specification (Min. 14 percent).

4.2 Moisture Susceptibility

The adopted procedure to evaluate the moisture susceptibility of WMA and HMA specimens is ASTM D 4867. For each mix type, six specimens were compacted (Marshall compaction method) to an air void level range 6 to 8 percent, one subset of the specimens (three specimens) were tested in temperature of 25°C (unconditioned specimens) in indirect tension test, whereas the other subset subjected to one cycle of freezing and thawing (16 hrs in -18 ± 2°C and then 24 hrs in 60 ± 1°C) and then tested same as the first subset (conditioned specimens). During the indirect tension test, the specimen is loaded along the diameter and the splitting force is recorded (as shown in **Fig.9**. The test parameters calculated as follow;

$$ITS = \frac{2P}{\pi h D} \quad \text{...... eq. 1}$$

$$TSR = \frac{C.ITS}{UC.ITS} \quad \text{...... eq. 2}$$

Where
P = Splitting load
h = Specimen height (thickness)
D = Specimen diameter
C. ITS = Conditioned indirect tensile stress
UC. ITS = Unconditioned indirect tensile stress

Based on the results presented in **Table 8** and exhibited in **Fig.10** and **Fig.11,** its obvious that the WMA mixes more susceptible to moisture damage than HMA, The average tensile strength ratio (TSR) for the WMA mixes (77 percent) is lower than that of HMA by approximately 14.2 percent. Reminding that the minimum acceptable limit for the TSR is 80 percent, it's clear that the WMA mix with hydrated lime filler is the only WMA which satisfy the specification requirement for this type of damage in comparison with WMA mixes with limestone or Portland cement.
Also, it's interesting to notes from **Fig.10** and **Fig.11**, together, that the unconditioned indirect tensile stress for WMA is less sensitive to filler types than conditioned indirect tensile strength, since the variability of TSR is higher than that of unconditioned tensile strength stress. The minimum difference in TSR between the WMA and HMA belongs to the hydrated lime filler whereas the maximum difference belongs to the limestone dust filler. Generally, the obtained results high lighted the role in hydrated lime in enhancing the resistance of WMA as well as HMA against moisture damage.

4.3 Uniaxial Resilient Modulus

The cylindrical specimens 101.6 mm (4 inch) in diameter and 203.2 mm (8 inch) in height were prepared using the samples brought from the mix plant, the specimens preparation were conducted according to the procedure described elsewhere, **Albayati, 2006**. The uniaxial repetitive compressive stress (20 psi) were applied during the test with 0.1 sec. loading time and 0.9 sec. rest time (loading frequency of 1 Hz), the tests were conducted at a temperature of 40°C (104°F). The resilient modulus was calculated according to the following equation:

$$M_r = \frac{\sigma}{(rd)/h} \quad \text{...... eq. 3}$$

Where

Mr= Resilient modulus
σ = The applied axial stress
rd= Axial resilient deflection (at the load repetition of 50 to 100)
h= Specimen height

The resilient modulus test results are shown in **Table 9** as well as **Fig.12**, it's obvious that the average resilient modulus for WMA (29250 kPa) is lower than that of HMA by 23.8 percent.
For the WMA, the highest resilient modulus belong to the hydrated lime filler, also this type of filler shows the minimum difference in resilient modulus with the corresponding HMA mixes, whereas the highest difference in resilient modulus between the WMA and HMA belongs to the limestone dust filler type.

4.4 Permanent Deformation

For the same loading conditions and specimens described above in uniaxial resilient modulus test, the test of uniaxial repeated load test were continued until the failure of specimens and the permanent deformation parameters intercept (I) and slope (b) were calculated from the plots of permanent deformation versus number of load repetition after representing them in log-log scale as described, **Albayati, 2006**. The test setup and deformation reading is shown in **Fig.13**.
The test results of permanent deformation are exhibited in **Fig.14** which is based on the data presented in **Table 10**. As the figure demonstrated, the highest permanent strain belongs to the WMA with limestone dust filler followed by WMA with Portland cement and WMA with hydrated lime. As an average, the intercept value corresponding to the WMA is higher than that of HMA by 4.3 percent whereas the slope (rate of permanent deformation accumulation) of the WMA is approximately 3.05 percent higher than that of HMA. The minimum difference for the slope values between the WMA and HMA belongs to the limestone dust whereas the highest difference belongs to the Portland cement filler.

4.5 Flexural Fatigue

The fatigue performance was evaluated using the third-point flexural bending fatigue test. The tests were conducted at a temperature of 20°C (68°F) for the beam specimens 76 mm (3 in) x 76 mm (3 in) x 381 mm (15 in) prepared in the laboratory according to the procedure described in **Alkishaab, 2009**. During the test, a controlled stress was applied to the specimen with 0.1 sec. loading time and 0.4 sec. rest time (2Hz frequency) and the initial tensile strain was recorded in the 50th load repetition as well as total number of load repetition to entire failure. The test was repeated for six times with different stress level in order to establish the relationship between the log scale of initial tensile strain and the log number of load repetition to failure. The plot can be fitted by a straight line with a form shown in eq.6 below after calculating the initial tensile strain by eq. 5 shown below.

$$\varepsilon_t = \frac{\sigma}{Es} = \frac{12h\Delta}{3L^2 - 4a^2} \quad \ldots\ldots \text{ eq. 5}$$

$$N_f = k_1(\varepsilon_t)^{-k2} \quad \ldots\ldots \text{ eq. 6}$$

Where
ε_t = Initial tensile strain

Es =Stiffness modulus based on center deformation
σ =Extreme flexural stress
h =Height of the specimen
Δ =Dynamic deformation at the center of the specimen.
L = span length between the supports.
a =Distance from the load to the support (beam length over three)
N_f = Load repetition to failure
k_1 = The fatigue constant which represent N_f when ε_t = 1
k_2 = Inverse slope of the fitted line between the log of initial tensile strain and log number of load repetition to failure.

The fatigue coefficient k_1 and exponent k_2 are presented in **Table 11** whereas the fitted line of fatigue characteristic for the different types of WMA and HMA are presented in **Fig.15**. These parameters can be used to evaluate the fatigue life, the smaller the exponent k_2 value the shorter fatigue life whereas the higher the coefficient k_1 value indicating the longer the fatigue life.
As per the presented data in table 11, the WMA with hydrated lime filler dust has a the highest value k_1 in comparison with the Portland cement and the limestone dust, for the limestone dust and Portland cement the k_1 values for the WMA are lower than that of HMA mixes and vise versa for the hydrated lime. The highest k_2 value for the WMA mixes belong to the hydrated lime, the k_2 values for WMA mixes with limestone dust and hydrated lime are lower than that of HMA by 10.1 and 4.78 percent, respectively. But for the Portland cement filler the k_2 value is higher than that of HMA by 5.39 percent. The examination of fatigue performance shown in **Fig.15** indicated that the shortest fatigue life belong to the WMA with limestone filler whereas the longest fatigue life belong to the WMA with hydrated lime filler, the latter one is even better performed than the HMA with hydrated lime filler.

5. CONCLUSIONS

According to the presented works in this research and within the limitation of test program and the materials used, the following salient conclusions can be drawn:

1. The Marshall properties at optimum asphalt cement content showed that all the examined WMA mixes with Limestone dust, Portland cement or hydrated lime fillers satisfy the requirement of the local SCRB specification.
2. Regardless of filler type, the average stability for WMA is lower than that of HMA by 11.6 percent, the average flow, air voids and voids in mineral aggregate for WMA is higher than that of HMA by 3.56, 3.3 and 2.2 percent, respectively.
3. The WMA mixes are more susceptible to moisture damage than HMA, The average tensile strength ratio (TSR) for the WMA mixes (77 percent) is lower than that of HMA by approximately 14.2 percent.
4. Among the three types of filler, the WMA mix with hydrated lime filler was the only one which satisfy the specification requirement for moisture damage (Min. TSR = 80 percent). Also, the unconditioned indirect tensile stress for WMA is less sensitive to filler types than conditioned indirect tensile strength
5. At test temperature of 40°C (104°F), the average resilient modulus for WMA (29250 kPa) is lower than that of HMA by 23.8 percent, the WMA with hydrated lime yields the

highest resilient modulus in comparison to WMA with limestone or Portland cement filler.

6. The average intercept value for permanent deformation test at 40°C (104°F) corresponding to the WMA is higher than that of HMA by 4.3 percent whereas the slope (rate of permanent deformation accumulation) of the WMA is approximately 3.05 percent higher than that of HMA. The better resistance for permanent deformation for WMA was achieved using hydrated lime filler.
7. The fatigue exponent k_2 value for WMA mixes with limestone dust and hydrated lime are lower than that of HMA by 10.1 and 4.78 percent, respectively. But for the Portland cement filler the k_2 value is higher than that of HMA by 5.39 percent.
8. The shortest fatigue life belong to the WMA with limestone filler whereas the longest fatigue life belong to the WMA with hydrated lime filler which is even better than the corresponding HMA.

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Table 1. Physical properties of asphalt cement based on performance grade.

Binder	Parameters	Temperature Measured	Measured Parameters	Specification Requirements, AASHTO M320-05
Original	Flash Point (°C)	-	310	230 °C, min.
	Viscosity at 135 °C (Pa.s)	-	0.487	3 Pa.s, max.
	DSR, G/sinδ at 10 rad/s (kPa)	58	3.3515	1.00 kPa, min.
		64	2.02	
		70	0.899*	
RTFO Aged	Mass Loss (%)	-	0.651	1%, max.
	DSR, G/sinδ at 10 rad/s (kPa)	58	4.1592	2.2 kPa, min.
		64	3.1489	
		70	1.9813*	
PAV Aged	DSR, G.sinδ at 10 rad/s (kPa)	28	4692	5000 kPa, max.
		25	6481*	
	BBR, Creep Stiffness (mPa)	-6	137.0	300 mPa, max.

Table 2. Aggregate mixing ratio for wearing course**.**

Sieve size, mm (inch)	Percent passing								
	The gradation of aggregate samples							Final gradation	SCRB Specification requirements
	Coarse agg.	Mid size agg.	Crusher Sand	Natural Sand	Filer				
					Lime-stone	Portland cement	Hydrated lime		
19(3/4)	100	100	100	100	100	100	100	100	100
12.5(1/2)	81	100	100	100	100	100	100	95	90-100
9.5(3/8)	39	98	100	100	100	100	100	84	76-90
4.75(No.4)	0	3	99	100	100	100	100	55	44-74
2.36(No.8)	0	0	48	79	100	100	100	32	28-58
0.30(No.50)	0	0	11	32	100	100	100	13	5-21
0.075(No.200)	0	0	1	3	95	98	99	6	4-10
Mixing Ratio	25%	20%	40%	10%	5%				

Table 3. Physical properties of aggregates.

Property	ASTM designation	Test results	SCRB specification
Coarse aggregate			
1. Bulk specific gravity	C-127	2.623	……
2. Apparent specific gravity		2.692	……
3. Water absorption,%		0.433	……
4. Percent wear by Los Angeles abrasion ,%	C-131	18.0	30 Max
5. Soundness loss by sodium sulfate solution,%	C-88	4.3	12 Max
6. Fractured pieces, %	D5821	97	90 Min
Fine aggregate			
1. Bulk specific gravity	C-127	2.667	……
2. Apparent specific gravity		2.694	……
3. Water absorption,%		0.809	……
4. Sand equivalent,%	D-2419	59	45 Min.
5. Clay lumps and friable particles,%	C142	1.2	3 Max.

Table 4. Properties of fillers.

Filler type	Chemical Composition ,%							Physical Properties		
	Cao	Sio_2	$Al_2 0_3$	Mgo	$Fe_2 o_3$	So_3	L.O.I	Specific gravity	Surface area* (m^2/kg)	% Passing sieve No. 200(0.075)
Limestone	29	10	6	16	1	0.12	37	.284	247	95
Portland cement	54	20	6	2	1	0	17	3.14	290	98
Hydrated Lime	69	1	-	2	-	.150	27	2.43	395	99

***** Blain air permeability method (ASTM C204)

Table 5. Physical and chemical properties of wma additive, Aspha-min.

Property	Result
Ingredients	Na2O.Al2O3.2SiO2 (Sodium aluminosilicate)
SiO_2	32.8 percent
Al_2O_3	29.1 percent
Na2O	16.1 percent
L.O.I	21.2 percent
Physical state	Granular powder
Color	White
Odor	Odorless
Specific gravity	2.03
Bulk Density	568 kg/m3
Ph value	11.6
Solubility in water	Insoluble

Table 6. Composition of the extracted asphalt concrete mixture.

Sieve size, mm (inch)	Aggregate Gradation – Percent passing							
	Warm L	Hot L	Warm P	Hot P	Warm HL	Hot HL	Job Mix	
19(3/4)	100	100	100	100	100	100	100	
12.5(1/2)	94	95	95	96	94	94	95	
9.5(3/8)	86	85	85	84	85	86	84	
4.75(No.4)	54	56	54	55	54	54	55	
2.36(No.8)	32.6	31.7	32.2	31.9	32.1	31.8	32	
0.30(No.50)	13.4	12.8	13.3	13.5	13.2	12.7	13	
0.075(No.200)	5.8	5.9	5.8	6.1	5.9	5.8	6	
Asphalt Content,%	4.72	4.74	5.05	5.06	5.37	5.39	L mix	4.80
							P mix	5.10
							HL mix	5.40

Table 7. Marshall properties of mixes at optimum asphalt content**.**

Mix type		Warm L	Hot L	Warm P	Hot P	Warm HL	Hot H L	SCRB specification
Marshall Properties	Stability, kN	8.7	10.4	10.3	11.6	11.9	12.5	Min. 8
	Flow, mm	3.5	3.4	3.5	3.2	3.7	3.1	2-4
	Density, gm/cm^3	2.328	2.333	2.320	2.331	2.311	2.328	…..
	Air Voids, %	4.18	4.11	4.16	4.03	4.28	4.07	3-5
	VMA , %	14.4	14.2	14.9	14.6	15.8	15.3	Min. 14

Table 8. The results of moisture susceptibility.

Mix Type	ITS, kPa (psi)		TSR, %
	Unconditioned	Conditioned	
Wma L	876 (127)	587(85)	67
Hot L	1042(151)	854(124)	82
Warm P	1090(158)	850(123)	78
Hot P	1180(171)	1027(149)	87
Warm HL	1125(163)	967(140)	86
Hot HL	1256(182)	1193(173)	95

Table 9. Resilient modulus test results**.**

Mix Type	Warm L	Hot L	Warm P	Hot P	Warm HL	Hot H L
Resilient Modulus, kPa (psi)	18130 (125097)	24500 (169050)	20457 (141150)	24947 (172134)	22164 (152929)	25772 (177825)

Table 10. Permanent deformation parameters.

Mix Type	Warm L	Hot L	Warm P	Hot P	Warm HL	Hot H L
Intercept	108	113	102	95	80	70
Slope	0.372	0.366	0.355	0.341	0.324	0.312

Table 11. Fatigue test results.

Mix Type	Warm L	Hot L	Warm P	Hot P	Warm HL	Hot H L
k_1	6.30E-07	6.3189E-07	2.9625E-06	9.5653E-06	4.8536E-06	5.5173E-7
k_2	2.65	2.92	3.32	3.15	3.38	3.55

Figure 1. Photograph for asphalt cement PG test

Figure 2. Selected aggregate gradation and specification limit

Aspha-min

Aspha-min addition

Aspha-min mixing with aggregate

Pouring the asphalt cement

Figure 3. Aspha-min, addition and mixing method.

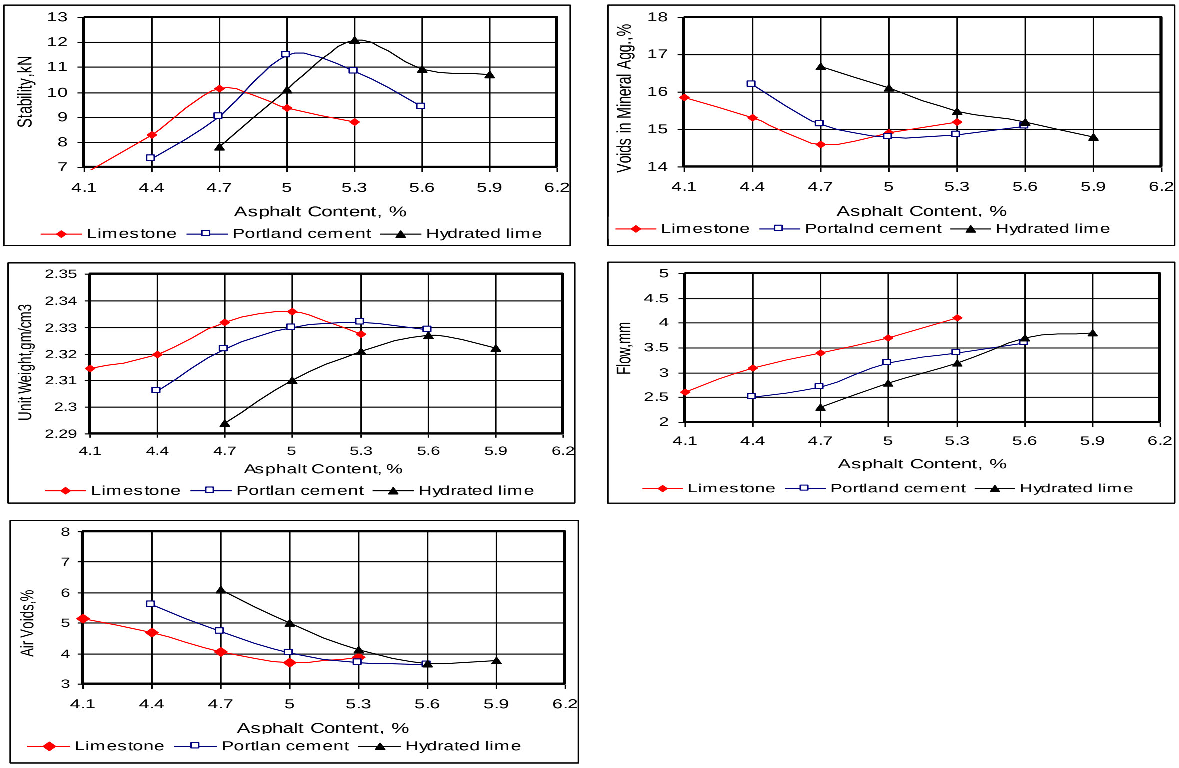

Figure 4. Marshall properties plots.

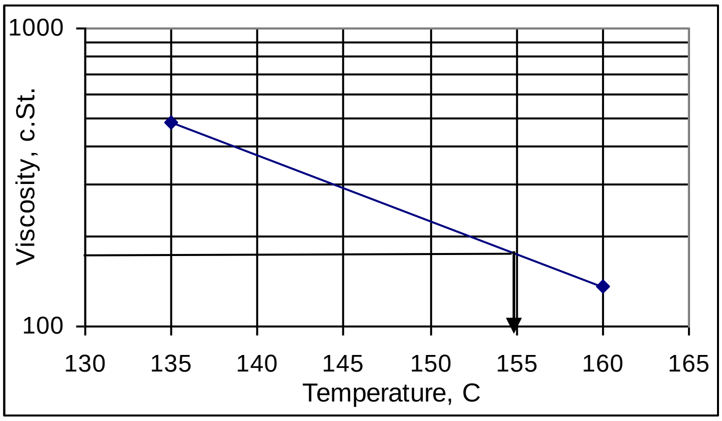

Figure 5. Viscosity – Temperature chart of PG 64-16.

WMA delivery

HMA delivery

WMA temperature measurement

Mix sampling

Figure 6. Asphalt concrete production and sampling.

Figure 7. Marshall Specimens in immersion.

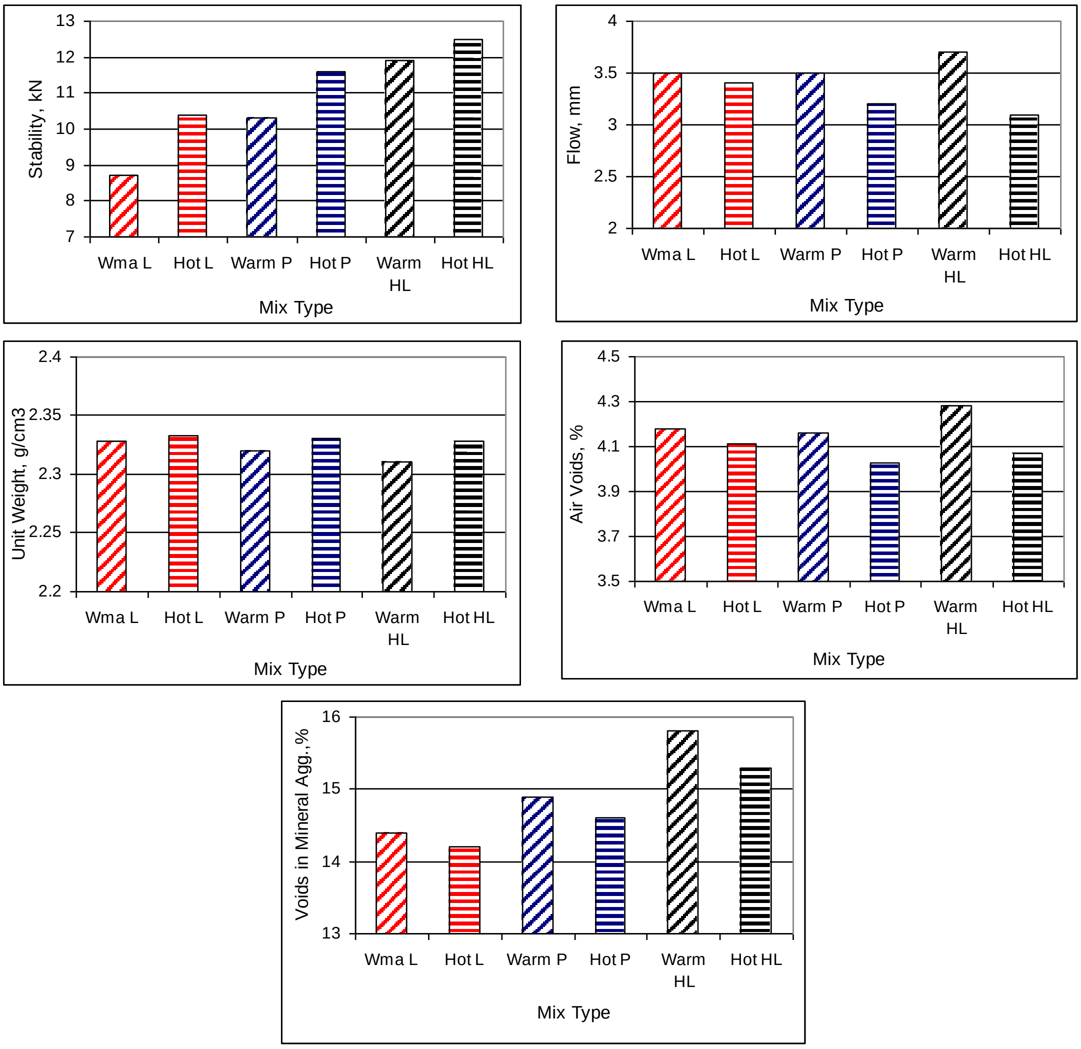

Figure 8. Effect of mix types on Marshall properties.

Figure 9. Indirect tension test for WMA specimen.

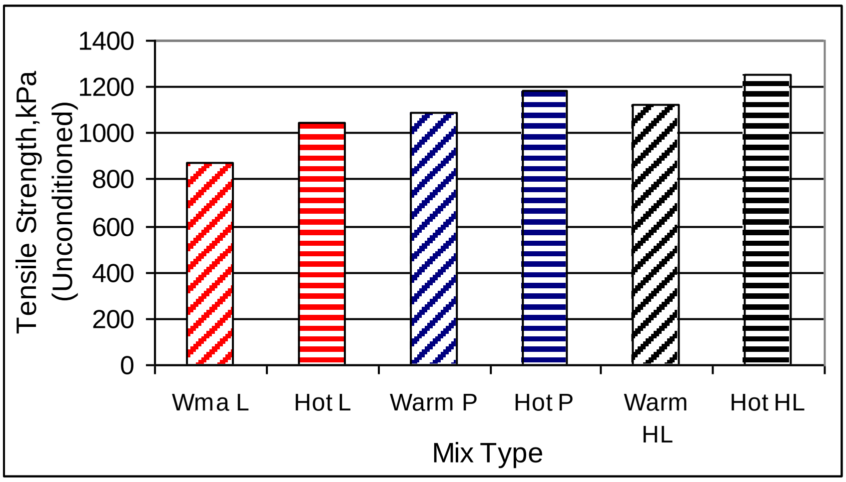

Figure 10. Unconditioned Indirect tension test results specimen.

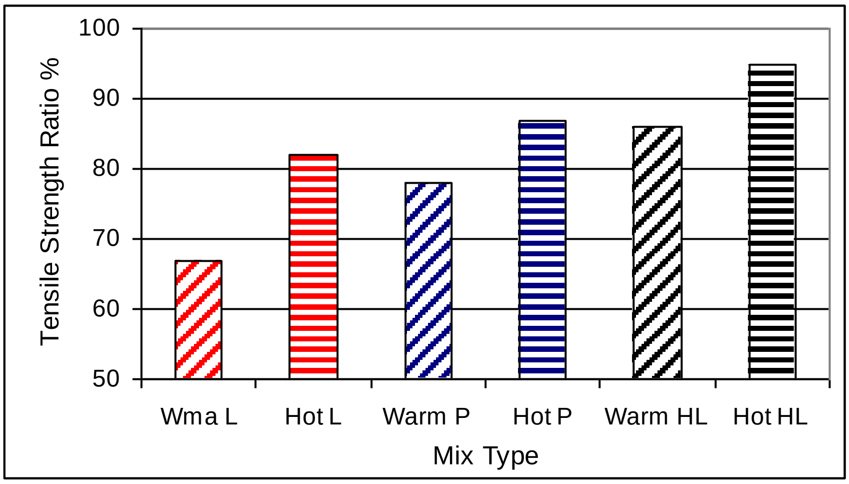

Figure 11.Tensile strength ratio results.

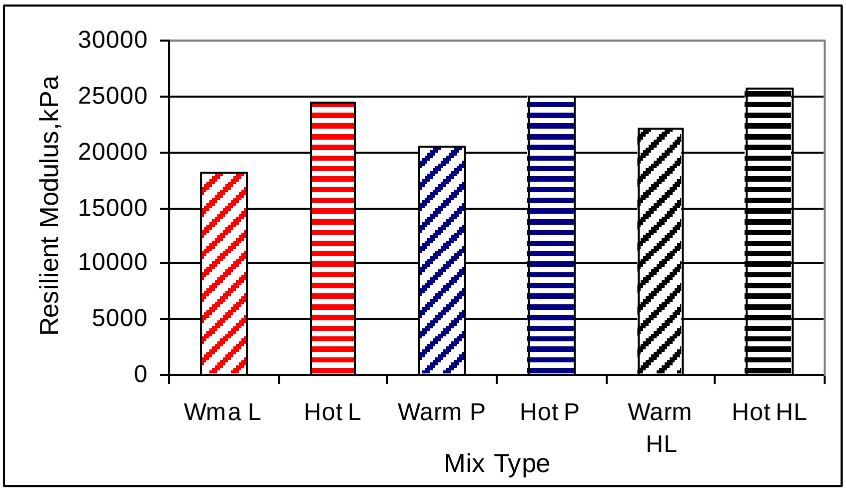

Figure 12. Results of resilient modulus.

Figure 13. Test set up and permanent deformation readings.

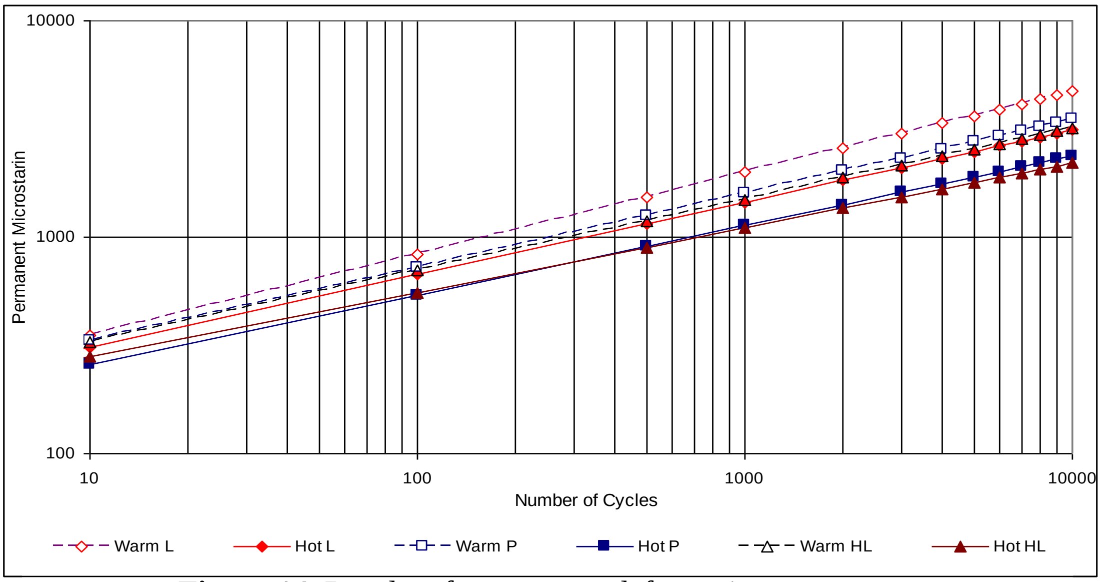

Figure 14. Results of permanent deformation test.

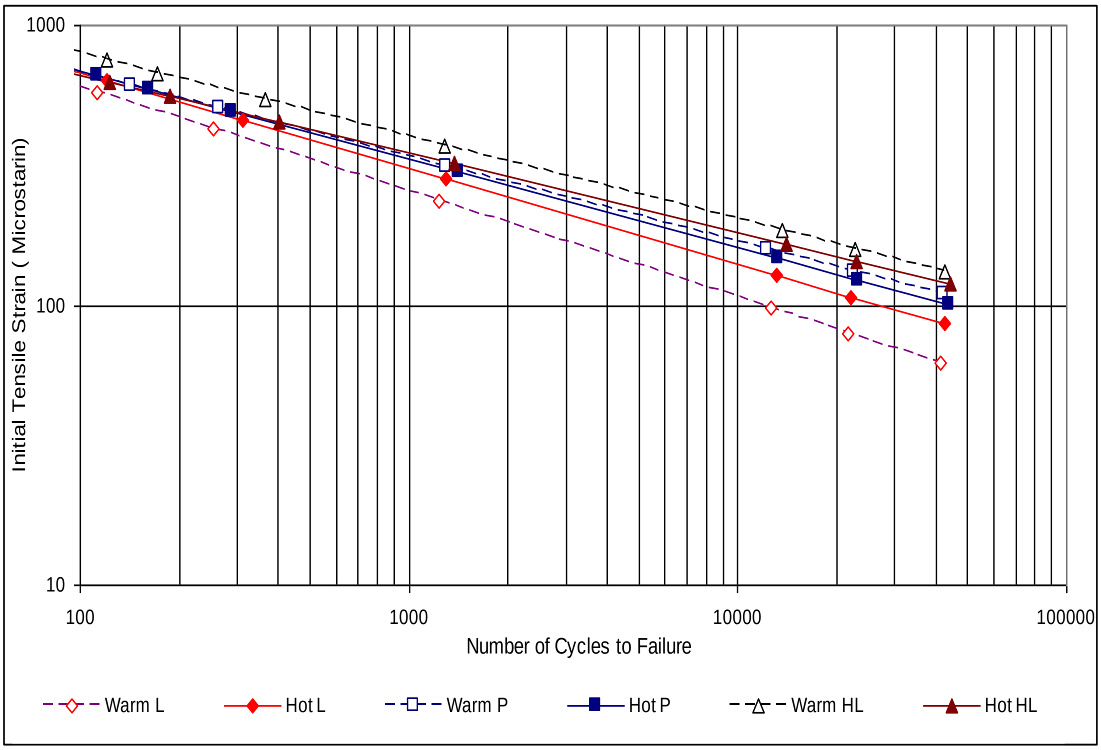

Figure 15. Effect of mix type on fatigue performance.