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Influence of fly ash on the volumetric and physical properties of Stone Matrix Asphalt Concrete

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ABSTRACT

Stone Matrix Asphalt (SMA) is a gap-graded asphalt concrete hot blend combining high-quality coarse aggregate with a rich asphalt cement content. This blend generates a stable paving combination with a powerful stone-on-stone skeleton that offers excellent durability and routing strength. The objectives of this work are: Studying the durability performance of stone matrix asphalt (SMA) mixture in terms of moisture damage and temperature susceptibility and Discovering the effect of stabilized additive (Fly Ash) on the performance of stone matrix asphalt (SMA) mixture. In this investigation, the durability of stone matrix asphalt concrete was assessed in terms of temperature susceptibility, resistance to moisture damage, and sensitivity to the variation in asphalt content. Specimens of 63.5 mm height and 102 mm diameter were compacted using the Marshall method at 150 °C. The optimum asphalt content was determined. Additional specimens were prepared with (0.5) percent below and above the OAC requirement. Specimens were subjected to indirect tensile strength (ITS) determination at (25 and 40) °C, and double punch shear strength determination. Another group of specimens was subjected to Marshall properties determination and to moisture damage. It was observed that stone matrix asphalt exhibit lower sensitivity to the change in asphalt content from the resistance to moisture damage and temperature susceptibility points of view. However, the tensile and shear properties exhibit significant sensitivity to the variation in asphalt content.

Keywords: Stone Matrix, Asphalt concrete, moisture damage, temperature susceptibility, sensitivity, durability

تأثير الرماد المتطاير على الخصائص الحجمية والفيزيائية لخرسانة الهيكل الركامي الاسفلتي

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الخلاصة

(SMA) عبارة عن الخرسانة الإسفلتية ذات المزيج الساخن ذو الفجوة التي تجمع بين الركام الخشن عالي الجودة ونسبة غنية من الأسمنت الإسفلتي. ينتج هذا المزيج خليطًا ثابتًا من الرصف بهيكل عظمي قوي من الحجر على الحجر يوفر مقاومة فائقة للالتصاق

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ومتانة. في هذا البحث ، تم تقييم متانة خرسانة الأسفلت المصفوفة بالحجر من حيث درجة الحرارة ، ومقاومة تلف الرطوبة ، وحساسية التباين في محتوى الاسفلت.تم ضغط العينات التي يبلغ قطرها 102 ملم وارتفاعها 63.5 ملم باستخدام طريقة المارشال عند 150 درجة مئوية. تم تحديد محتوى الأسفلت الأمثل. تم تحضير عينات إضافية مع 0.5٪ من الإسفلت أعلى وتحت المتطلبات المثلى. تعرضت العينات لقوة الشد غير المباشرة لتقريرها عند درجة حرارة 25 و 40 درجة مئوية ، وتحديد قوة القص المزدوج. تعرضت مجموعة أخرى من العينات لتحديد قبل المشير قبل الأضرار وتلف الرطوبة. وقد لوحظ أن الأسفلت المصفوفة الحجرية تظهر حساسية أقل للتغير في محتوى الإسفلت من المقاومة لتلف الرطوبة ونقاط التعرض لدرجة الحرارة. ومع ذلك ، فإن خصائص الشد والقص تظهر حساسية كبيرة للاختلاف في محتوى الأسفلت.اهداف هذا العمل هي دراسة أداء المتانة لمزيج الأسفلت (SMA) من حيث تلف الرطوبة وقابلية التعرض لدرجة الحرارة واكتشاف تأثير المضاف المستقر (الرماد المتطاير) على أداء خليط الإسفلت المصنوع من الحجر (SMA).

الكلمات الرئيسية: المصفوفة الحجرية ، خرسانة الأسفلت ، أضرار الرطوبة ، القابلية لدرجات الحرارة ، الحساسية ، المتانة

1.INTRODUCTION

Stone Matrix Asphalt (SMA) was created in Germany in the early sixties as a warm blend asphalt. For more than two decades, SMA has been used in other European nations to provide greater rutting strength and studded tire wear (**Ahmadinia, et al., 2011**)**.** Because of its achievement in Europe, in cooperation with the Federal Highway Administration, in some states, the USA also initiated the development of S.M.A pavements **(Brown, et al. 1997)** and **(Asi, et al., 2006)**. S.M.A considered a gap graded aggregate-HMA with a high percent fraction of coarse aggregate. A stable stone on the stone skeleton provided by the Utilizing of S.M.A that is held collected by using AC, stabilizing additives, and filler **(NAPA, 1994)**. SMA has excellent properties, adequately designed, and produced. With its high inner friction, the stone skeleton provides outstanding shear strength. In fact, the aggregates have a high angularity that enhances the interlocking, packaging, and stone-on-stone contact between grains **(Dondi et al., 2012) and (Dondi et al., 2012).** Recent surveys have shown that MORE than twenty-eight countries in the United States use S.M.A due to its enhanced durability, more than 20%-30% compared with standard mixtures **(AI-Hadidy et al., 2009). (Tashmana and Pearson, 2012)** applied standard laboratory experiments and sophisticated imaging methods to test coarse aggregate voids (VCA). To form relations between (VCA) proportion, the mechanical reaction of (S.M.A), and microstructure parameters, five SMA were explored. The outcomes indicated that the (VCA) method reasonable to identify mixtures with a stone on a stone coarse aggregate structure. SMA is a tough, stable, rut resistant mixture that relies on stone-to-stone contact for its strength and a rich mortar binder for its durability **(Myers, 2007)**. The pavement strength is achieved through the interlocking of a high-quality gap-graded aggregate. **Fig. 1** exhibits that the gradation contains only a small percentage of aggregate particles in the mid-size range, which leaves more room for the mortar of fine aggregate and polymer modified binder.

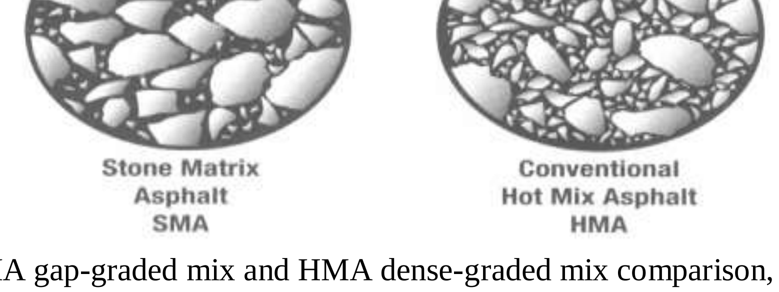


Figure 1. SMA gap-graded mix and HMA dense-graded mix comparison, **(Myers, 2007).**

SMA is an HMA containing a coarse aggregate skeleton and a high binder content mortar to resist researched tire wear and provide better resistance to rut, **(Scherocman JA, 1991).** The quality of the

SMA blend is superior; it includes high rut resistance, high durability, elevated skid resistance, enhanced reflective cracking strength, decreased pollution noise, and improved drainage **(Moghadas Nejad F et al, 2010)**. In Europe, Japan, Canada, the USA, Australia, and many other nations around the world, SMA has been commonly accepted as a wearing layer for high traffic highways. It has also been commonly used on expressway road surfaces in China Since SMA was first used on the capital airport highway in (1992), **(Shen JA, 1999)**. **(Qiu and Lum, 2006)** introduced a mix design procedure based on the Bailey technique to quantify stone-to-stone contact for blends of SMA objectively. A total of sixteen asphalt mixtures were studied with (6) different aggregate gradations and (3) different contents of asphalt binder. Volumetric analysis of specimens showed that the volume of coarse aggregate in the mixtures had a significant effect on the voids in the coarse aggregate and the voids in the mineral aggregate. It was concluded that the coarse aggregate stone-to-stone contact was developed in the range of 95–105 percent of the rodded unit weight when the volume of coarse aggregate was present. The content of the 5.5 percent asphalt binder was optimal for the expected general gradation of SMA blends. **(Bernard, 2017)** showed that SMA is a gap-graded HMA used to maximize resistance to rutting and durability in heavy traffic conditions. Stone Mastic Asphalt has a high content of coarse aggregate that interlocks into a stone skeleton and can withstand permanent deformation. In such pavements to which fibers are added, a relatively higher amount of bitumen is used to provide stability of bitumen and to prevent binder drainage. Typical structure of SMA comprises of (70-80) % coarse aggregates; (8-12) % filler; (6-7) % binder and (0.3) % fiber. Methods of mixing and paving are like HMA. In the study by **(Cao, et al., 2013),** the performance of (3) kinds of SMA blends with basalt and limestone aggregates was compared. The obtained results showed that the (SMA) with basalt aggregates indicated the best resistance to rutting, followed by (SMA) with limestone aggregates. However, in terms of low-temperature performance of cracking resistance and susceptibility to moisture, they have the opposite sequence. It was concluded that the aggregate kind has a major impact on the resistance of rutting. But no major difference in sensitivity to low- temperature cracking or sensitivity to moisture was found in blends of SMA. **(Asi, 2006)** compared the performance of SMA and HMA blends. Tests performance were compared that involved loss of Marshall stability; Marshall stability; split tensile strength; loss of split tensile strength, MR; rutting, and fatigue testing were implemented. The results of these tests showed that though the HMA has greater tensile and compressive strengths, the durability and resilience properties SMA mixtures is greater. Each mixtures samples were fabricated at their OAC that were (6.9 %) for SMA and (5.3) % for HMA mixtures.

2. METHODS AND MATERIALS

2.1. AC (40-50)

The properties are shown in **Table 1**. Asphalt cement was obtained from the Al-Doura refinery.

Table1. Properties of AC (40-50)

Test procedure as per ASTM [14]	Result	Unit	SCRB Specification [15]
Ductility (25 °C, 5cm/min), (ASTM D 113)	156	cm	≥ 100
Penetration (25°C, 100g, 5sec), (ASTM D 5)	44	0.1 mm	(40-50)
Softening point (ring & ball), (ASTM D 36)	48	°C	(50-60)
After Thin-Film Oven Test (ASTM D-1754)			
Ductility at 25 °C, 5cm/min, (cm), (ASTM D-113)	145	cm	More than 25
Retained penetration of original,(ASTM D 946)	32	0.1mm	Less than 55
Loss in weight (163°C, 50g,5h) (ASTM D-1754)	0.17	%	---

2.2. Coarse and Fine Aggregates

Table 2 shows the properties of coarse and fine aggregate. Coarse and fine aggregate was taken from the Al-Nibaee quarry.

Table 2. Properties of Al-Nibaee Aggregate.

Property as per ASTM [14]	(Coarse Aggregate)	(Fine Aggregate)
Apparent Specific Gravity, ASTM C 127 and C 128	2.64	2.68
Bulk Specific Gravity, ASTM C 127 and C 128	2.61	2.63
Percent Wear (Los-Angeles Abrasion), ASTM C 131	20.1	----
Percent Water Absorption, ASTM C 127 and C 128	0.42	0.54

2.3. Mineral Filler

The mineral filler passes sieve No.200 (0.075mm). In this work is limestone dust, the filler used and was obtained from the Karbala governorate. The properties of the filler are presented in **Table 3**.

Table 3. Physical Properties of Filler (Limestone dust).

Property	Value
% (Passing Sieve No.200)	94
(Bulk specific gravity)	2.617

2.4. Stabilizing Additive

Fly ash was used in this work. Fly ash was added at 1% by weight of aggregate. **Table 4** shows the physical properties of Fly ash based on (**Sarsam, 2013).**

Table 4. Properties of Fly ash based on **(Sarsam, 2013).**

Property	(Value)
(% Passing) Sieve No.200	98%
Specific Surface Area (m^2/ kg)	649
Sp.gr	2.1

2.5. Asphalt Concrete Combined Gradation Selection

The designated gradation submitted to the (AASHTO 2005) and by many researchers (**Qiu and Lum, 2006), (Rekha and Rao, 2017), (Asi, 2006)** and **(Engineering Road, 2016)**. **Fig.2** and **Table 5** demonstrate the gradation selected with 12.5 (mm) nominal maximum size of aggregates.

2.6. Preparation of Hot Mix Asphalt Concrete

The aggregate was dried at 110 °C to a constant weight. Aggregate sieved to different proportions and kept. To meet the specified gradation shown in **Fig.2**. Coarse and fine aggregates were combined with mineral filler.

Table 5. Selected Combined Gradations of Aggregates and Filler; (% passing by weight).

Sieve size (mm)	Selected Gradation	AASHTO Provisional Standards (2005) 12.5 mm
19	100	100
12.5	90.6	90-100
9.5	64	50-80
4.75	27.9	20-35
2.36	17.5	16-24
0.075	10.5	8-11

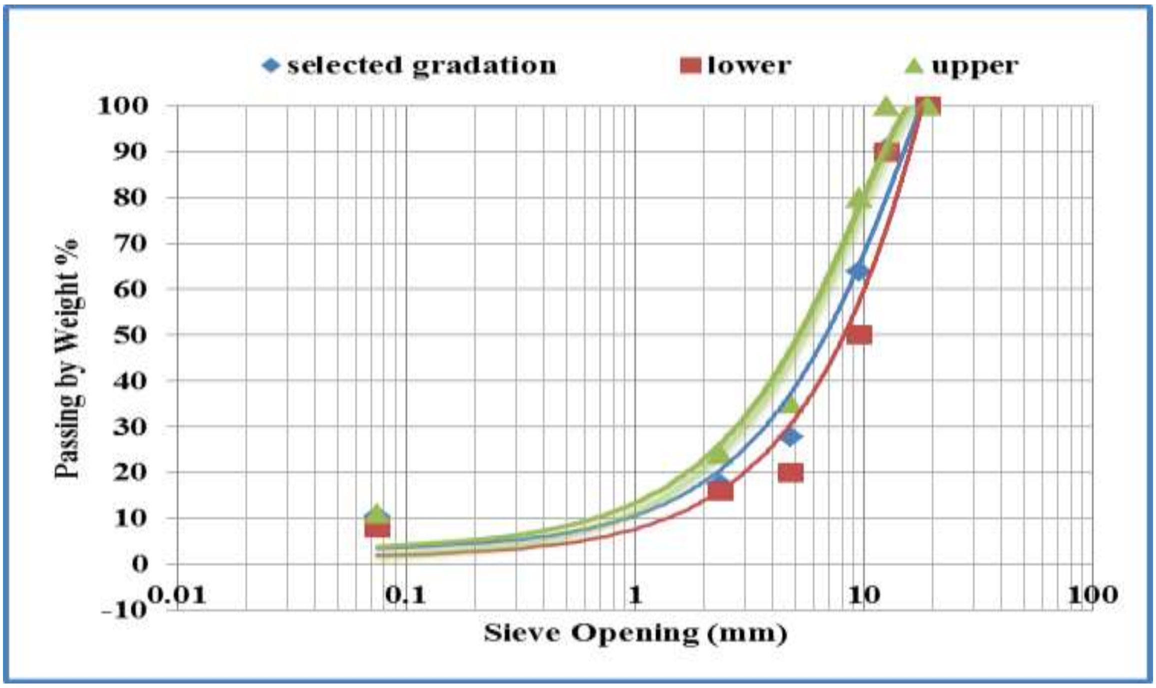


Figure 2. The SMA gap gradation implemented.

Before mixing with asphalt cement, the combined aggregate mixture was heated to 150 ºC, then added fly ash to the aggregate and mixed. The asphalt cement was heated to the same temperature of 150 ºC; it was then added to the heated aggregate to obtain the required quantity and carefully blended with a mechanical mixer and particles covered with asphalt cement. Marshall samples were implemented using 75 Marshall hammer blowing on each side of the specimen following (ASTM D1559, 2009). As per the above operation, the optimum asphalt content was 5.1%. The implemented Marshall size specimens separated into three groups. The first group was evaluated at (25 and 40) ºC for (ITS), while the second group was tested at 60 ºC for (punching shear strength). The third group was exposed to sensitivity for the moisture of the procedure by **(AASHTO, 2013)**. Additional samples of Asphalt Concrete implemented using AC(40-50) of (0.5%) below and above the OAC. Samples were tested in triplicate; finally, the mean value was considered.

2.7. Plastic Flow Resistance (Marshall Test)

This technique involves measuring the plastic flow of cylindrical asphalt paving combination loaded on the lateral surface employing the Marshall device and submitted to **(ASTM D 1559, 2009)**. For every combination, three samples were tested, and the mean results were reported. **Fig. 3** shows the Marshall test device.

Figure 3 Marshall Test Device.

2.8. Indirect Tensile Strength Test (ITS)

The indirect tensile strength test was conducted following the procedure of **(ASTM 2009)**. Marshall Size Samples were kept for thirty min. in the water bath at 25 ºC, and 40 ºC and every sample was centered on the vertically diametrical plane, between the (2) parallel loading strips of 12.7 mm width. **Fig. 4** indicates the ITS apparatus. The Versa tester machine applied vertical compression load at a speed of (2 in / min) until the reading of the dial gauge achieved the highest resistance of the load. The (ITS) was calculated using the following Eq. (1), **(ASTM, 2009)**.

$$ITS = 2000 * P/\pi * T * D \qquad (1)$$

Where:

P = maximum load resistance at failure, N
ITS = indirect Tensile Strength, kPa
T = thickness of specimen immediately before the test, mm
D = diameter of specimen, mm

The Temperature Susceptibility was calculated using **Eq. (2)**.

$$TS = \frac{(ITS)t1-(ITS)t2}{t2-t1} \qquad (2)$$

Where:

(ITS) t2 = Indirect tensile strength at t2 =40ºC
TS = Temperature susceptibility (kPa/˚C)
(ITS) t1= Indirect tensile strength at t1 =25ºC

Figure 4. The device of the ITS Test.

2.9. Testing for moisture damage

Asphalt concrete specimens with the (3) groups were exposed for sensitivity to moisture as per the procedure by **(AASHTO, 2009), (Sarsam and Husain, 2017)** and **(Sarsam S. and Husain H., 2017)**. The set of six specimens was divided into two groups; the first group of three specimens was denoted as unconditioned specimens (SI). They were stored in a water bath at 25°C for 30 minutes, then tested for ITS at 25°C and a mean value for these specimens of (ITS) was considered. The second group of three specimens of asphalt concrete was conditioned by placing (4000-ml) heavy wall glass filled with water at room temperature (25 ˚C) in a volumetric flask. Then applying a vacuum of twenty-eight mm/Hg for five to ten minutes to achieve a fifty-five to eighty percent saturation level. The specimens were then removed from the water chamber and stored at -18° C for sixteen hours in a deep freezer. Specimens were removed from the deep freezer and thawed in the air for 120 minutes, then transferred to a water bath and stored at sixty °C for 120 minutes. Specimens were denoted as conditioned specimens (SII) and kept at twenty-five °C for 120 minutes before testing for ITS. The Indirect Tensile Strength Ratio (TSR) test of mixtures was calculated to evaluate the sensitivity for moisture resistance. **Fig. 5** shows the conditioning process of specimens for the TSR test at the laboratory. The indirect tensile strength ratio could be calculated from equation (3), **(AASHTO, 2013)**.

$$TSR= \frac{SII}{SI} \qquad (3)$$

Where:

T.S.R = Indirect tensile strength ratio, %
S.I.I = Average (ITS) for conditioned specimens, kPa
S.I= Average (ITS) for unconditioned specimens, kPa

a-Vacuum process for specimens

b- controlling the heat of water path at 60 ºC

Figure 5. TSR test at Laboratory for specimens (Conditioning process)

2.10. Double Punching Shear Strength Test

This test procedure was reported and cited by many studies **(Sarsam and AL-Shujairy A., 2015).** It was used to measure the resistance of SMA to punching shear. Marshall Size Specimen was immersed in a bath filled with water at sixty ºC for thirty minutes. By using two cylindrical steel punches located on the bottom and top surface of the sample, this test was executed by centrally loading the cylindrical sample. The sample was centered between the two punches (1 in.) in diameter, perfectly aligned one over the other, then loaded at a speed of rate (1 in./min.) until the sample failure. The PSS test apparatus is shown in **Fig. 6**. The reading of dial gauge at the maximum load resistance was recorded as unconditioned PSS. The punching shear strength was computed using equation 4.

$$\sigma t = p \, / \, (1.2bh - a2) \qquad (4)$$

Where:

a= radius of punch, mm
σt = punching stress, Pa
h=height of the specimen, mm
b=radius of the specimen, mm
P= maximum load, N

Figure 6. Apparatus Test of (PSS)**.**

3. RESULTS AND DISCUSSION

Fig.7 and **Table 6** exhibit the volumetric properties of SMA. The results show the bulk density of SMA without fly ash was (+ 3.11 %) when using fly ash**.** The bulk density decreases with further increment in asphalt content. The results show the Marshall Stability of SMA without fly ash was (+ 17.64 %) when using fly ash. An increase in the stability may be due to the fly ash has a high surface area. Therefore, asphalt cement demand is quite high in the SMA which is rich asphalt cement content mixture, and that leads to high stability value and subsequent increase in mixture stiffness. The voids-asphalt content relationship further supported this finding. The results show the AV % of SMA without fly ash was (- 2.04 %) when using fly ash with aggregate gradation. The air voids decreased when added fly ash due to the filling property attributed by fly ash coating. The results show the voids filled with asphalt (VFA) % of SMA without fly ash was (- 5.4 %) when using fly ash, such behavior of materials comply with the findings of **(Tashmana and Pearson, 2012)**, and **(Myers, 2007)**.

Table 6. Marshall Properties of each Type of Mixtures at Optimum Asphalt Content.

Marshall Test Properties	SMA without fly ash	SMA with fly ash
OAC %	5.1	5.3
Stability (kN)	6.8	8.0
Flow(mm)	3.8	3.5
Bulk Density (gm/cm3)	2.250	2.320
AV (%)	4.9	4.8
VMA (%)	18.2	16.0
VFA (%)	74.0	70.0

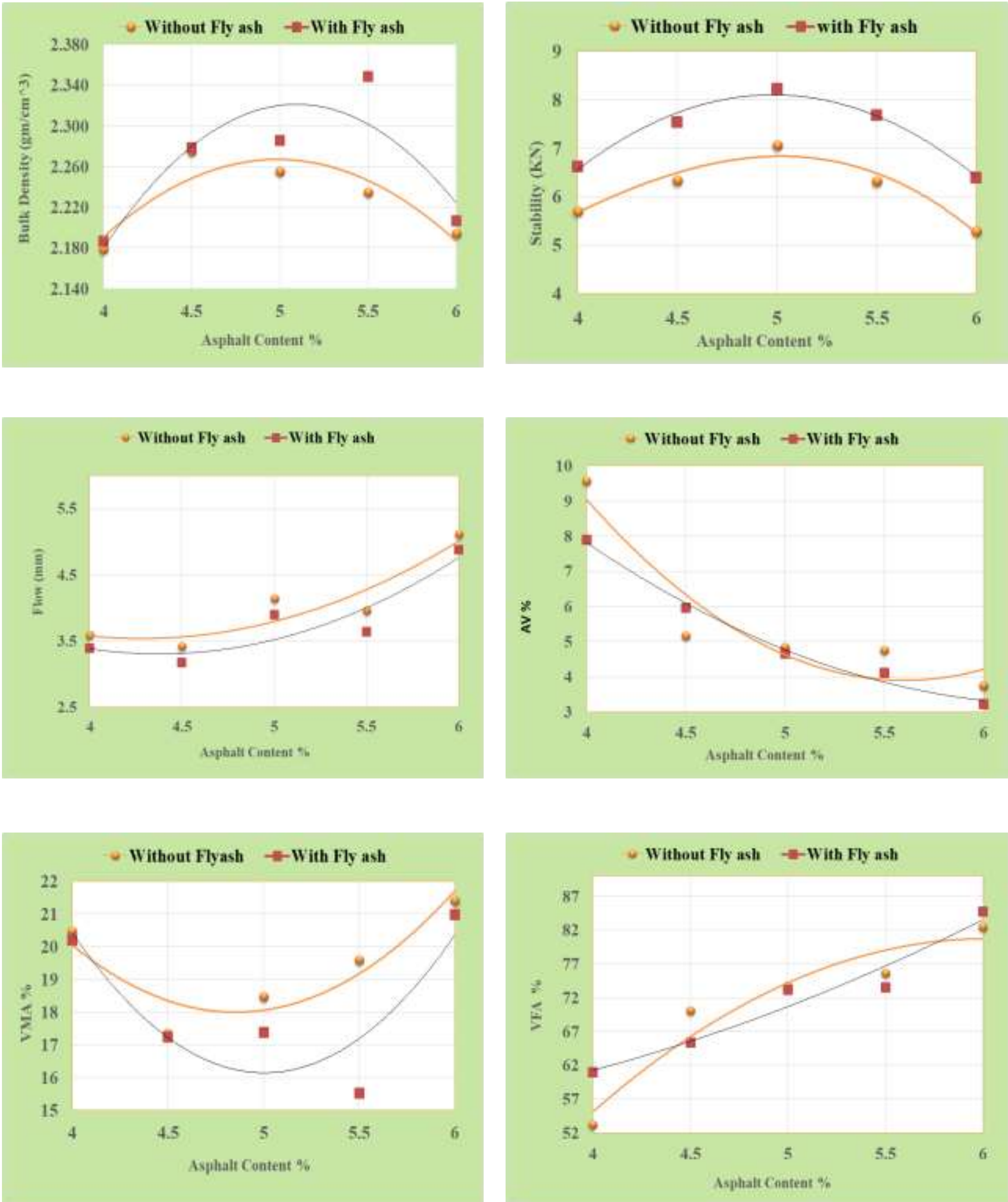


Figure 7. Effect of Fly ash on Marshall properties of SMA.

The sensitivity in punching shear strength of SMA with the variation in asphalt content could be observed in **Fig.8**. The results of the mixture without fly ash show that the PSS was (- 22.7 and + 29.8) % when OAC increased and decreased by (0.5) percent, respectively. The results of the mixture with fly ash show the PSS was (- 19.8 and + 28.71) % when OAC increased and decreased by (0.5) percent, respectively. This could be related to the fact that the shear strength is obtained from the cohesion between aggregates due to particle interlock, which will be disturbed with the change of asphalt film thickness surrounding the aggregated.

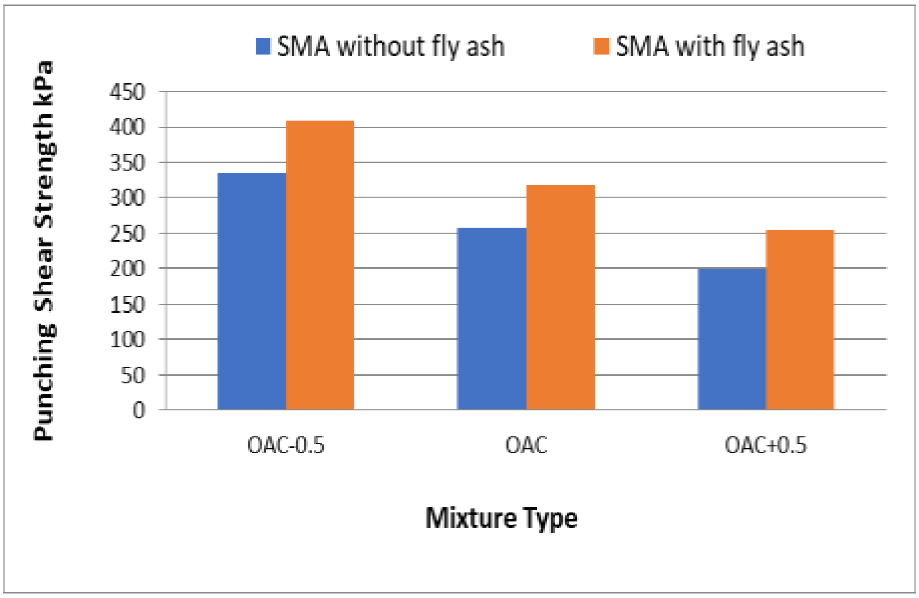


Figure 8. Punching shear strength of SMA.

Fig.9 demonstrates the variation of the indirect tensile strength (ITS) of SMA with testing temperature and variable asphalt content. It can be observed that ITS decreases as the testing temperature increases. The different percentages of asphalt content have been used. Namely, OAC ± 0.5 % to study the impact content of asphalt on the I.T.S value as presented in **Fig.5** at 25 ^{0}C. The results of SMA without fly ash show the ITS was (+ 17.53 and - 10.27) % when the asphalt content increased and decreased by 0.5 % from OAC, respectively. SMA with fly ash results shows that the ITS (+8.52)% and (-9.61) % when the content of asphalt increased and decreased by 0.5 % when compared with OAC, respectively. At 40 ^{0}C, results of SMA without fly ash show the ITS was (+ 23.93 and - 5.31) % when the content of asphalt increased and decreased by 0.5 % when compared with OAC consequently. The results of SMA with fly ash show the ITS was (+ 7.42 and - 8.25) % when the content of asphalt increased and decreased by 0.5 % when compared with OAC separately. ITS increases when asphalt content is increased by 0.5 % above the optimum. This increment may be attributed to the fact that tensile strength depends mainly on adhesion of the binder to aggregate and the binder film thickness increases with the increment of asphalt content.

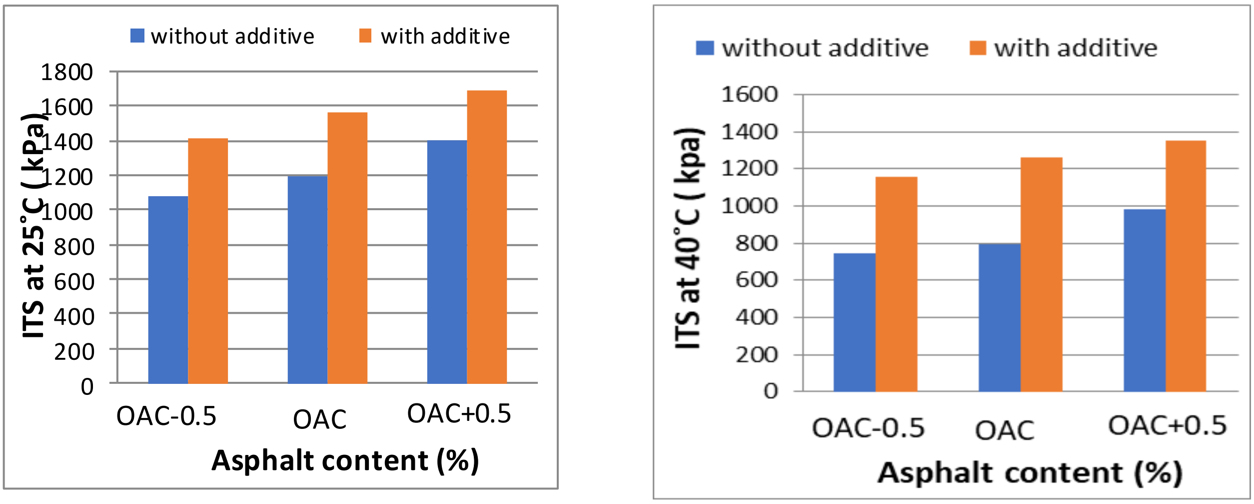
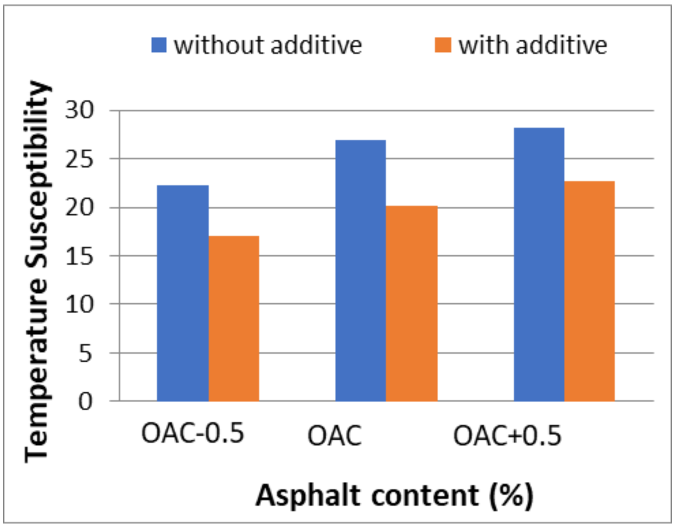


Figure 9. Variation of ITS with asphalt content and temperature of testing

Fig.10 exhibits the resistance to moisture damage in terms of tensile strength ratio (TSR) and the temperature susceptibility of SMA. The SMA exhibit lower sensitivity to the change in asphalt content from the resistance of sensitivity to a moisture point of view. TSR of SMA without fly ash changes by (3.36 and 0.76) % when the content of asphalt by (+0.5 and -0.5) percent from optimum asphalt content, and TSR of SMA with fly ash changes by (2.99 and 1.84) % when the content of asphalt +0.5 and – 0.5 from optimum asphalt content. The results showed the TSR increase with an increase of asphalt content. This increase in TSR may be attributed to the reduction of air voids content with an increase of asphalt content. The results showed the TSR increase when added fly ash; this behavior can be attributed to the role of fly ash in filling the available voids. Therefore SMA with fly ash was good resistance to water damage because the fly ash was sufficient to fill the voids, which fill with water that causing less stresses when it freezes with less possibility to stripping, which leads to increase TSR. **Fig.11** showed the temperature susceptibility (TS) results; the results showed the SMA without fly ash was more affected by temperature than SMA with fly ash. The results show the temperature susceptibility of SMA without fly ash was (+ 4.94 and -17.18%) when the content of asphalt +0.5 and – 0.5 from optimum asphalt content. The results show the temperature susceptibility of SMA with fly ash was (+ 13.12 and - 15.32%) when the content of asphalt +0.5 and – 0.5 from optimum asphalt content. This could be attributed to the fact that the high proportion of coarse aggregate interlocks to form a strong skeleton of aggregate, the void spaces that accommodate binders are within the stone skeleton, filler, and fine aggregate are mixed together to form a stiff mastic. A similar finding was reported by **(Rekha K. and Rao B. H., 2017).**



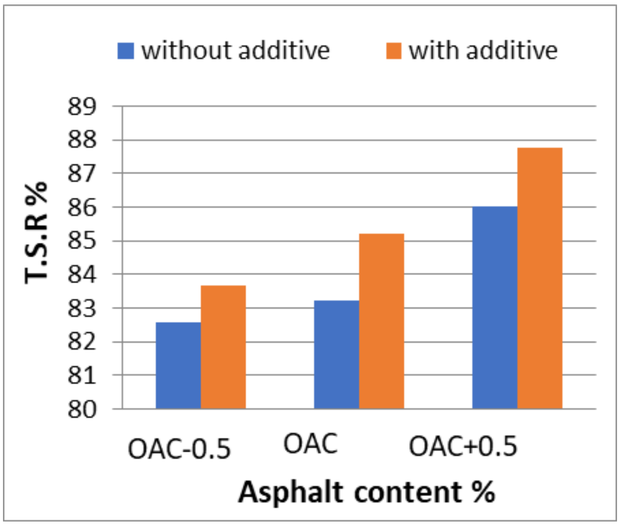


Figure 10. Variation of TSR and temperature susceptibility with asphalt content.

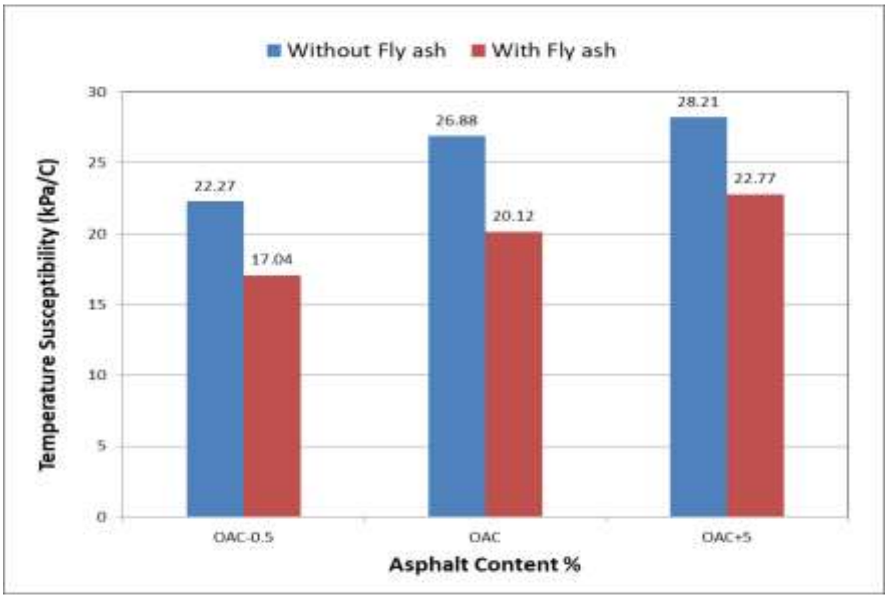


Figure 11. Effect of Asphalt Mixture and Content on the Temperature Susceptibility.

4. CONCLUSIONS

Based on the testing program, it can be concluded that:

1. The results show that Marshall Stability of SMA without fly ash was increased by 16.17 %. While the Marshall Flow of SMA without fly ash decreased by 5.26 % when using fly ash at OAC.
2. The results of mixture without fly ash show the PSS was (decreased by 22.7% and increased by 29.8 %) when the asphalt content increased and decreased by 0.5 % from OAC respectively, and mixture with fly ash show the PSS was (decreased by 19.8% and increased by 28.71%) when the asphalt content increased and decreased by 0.5 % from OAC respectively.

3. The results of SMA without fly ash at 25 ^{0}C show the indirect tensile strength ITS was (increased by 17.53% and decreased by 10.27 %) when the content of asphalt +0.5 and – 0.5 from optimum asphalt content consequently. The results of SMA with fly ash show the ITS was (increased by 8.52 and decreased by 9.61%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively. At 40 ^{0}C the results of SMA without fly ash show the ITS was (increased by 23.93 and decreased by 5.31%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively. The results of SMA with fly ash show the ITS was (increased by 7.42 and decreased by 8.25%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively.
4. TSR of SMA without fly ash changes by (3.36 and 0.76%) when the asphalt content increased and decreased by 0.5 % from OAC respectively, and TSR of SMA with fly ash changes by (2.99 and 1.84%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively.
5. The results show the temperature susceptibility of SMA without fly ash was (increased by 4.94 and decreased by 17.18%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively. The results show the temperature susceptibility of SMA with fly ash was (increased by 13.12 and decreased by 15.32%) when the asphalt content increased and decreased by 0.5 % from OAC, respectively.

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