Resilient behavior of stone matrix asphalt concrete (SMAC) under repeated shear stresses

Saad Issa Sarsam✉, **Shahed Mahmood**

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

✉**Correspondence author**
Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad,
Iraq
Email: saadisasarsam@coeng.uobaghdad.edu.iq

ABSTRACT

The accumulation of traffic load repetitions on the flexible pavement usually exhibit rutting and shear failure of pavement layers at hot climatic condition. Stone matrix asphalt concrete SMAC is implemented to resist such type of distress as well as supporting the durability of the pavement layer. In this investigation, an attempt has been made to assess the resilient behavior of SMAC in terms of resilient modulus Mr and deformation under repeated shear stresses. The ability of SMAC mixture for micro crack healing is also assessed in terms of the change in resilient modulus Mr and deformation after healing. Specimens of 102 mm diameter and 63.5 mm height were prepared using coal fly ash as a stabilizing additive at optimum asphalt content OAC. Additional specimens were prepared with 0.5 % asphalt above and below the optimum requirement and without using the stabilizing additive for comparison. Specimens were subjected to repeated punching shear stresses for 1200 load cycles at 25 °C using the pnumatic repeated load system PRLS.Then the specimens were allowed to heal by external heating for 120 minutes at 60 °C. Specimens were subjected to

another loading cycles. The deformation was monitored and the resilient modulus was calculated before and after healing. It was concluded that SMAC is sensative to the variation in asphalt content. The Mr increases by 40% and the permanent deformation decreased by 15% when coal fly ash was implemented as stabilizing agent as compared with control mixtures. After healing, the Mr increased by 15 % and the permanent deformation decreased by 11 % at optimum asphalt content.

Keywords: Punching shear, Repeated load, Resilient modulus, Deformation, Healing, Stone matrix asphalt

1. INTRODUCTION
Stone matrix asphalt concrete (SMA) is a tough, stable and rut resistant mixture that relies on stone-to-stone contact for its strength and a rich mortar binder for its durability, [1]. Bernard, [2] stated that SMA is a gap graded hot mix asphalt (HMA) used to maximize rutting resistance and durability in heavy traffic conditions. It has a high coarse aggregate content that interlocks to form a stone skeleton which resists permanent deformation. Relatively higher amount of bitumen is used in such pavements to which stabilizing additives are added to provide stability of bitumen and to prevent the drain down of binder. Typical SMA composition consists of 70-80% coarse aggregates, 8-12% filler, 6-7% binder and 0.3% fiber. Mixing and paving methods are like HMA. Rekha and Rao, [3] reported that SMA's distinctive feature is its potential to slow down the occurrence of reflective cracking. SMA asphalt mix has its durability nature by the result of higher binder content and thicker binder coating. The high proportion of coarse aggregate, interlocks to form a strong skeleton of aggregate. The proportion of filler in SMA is about 10%, and it is important that SMA has a higher binder content to coat the large surface area of the high proportion of fine material in the mastic. This mastic is what provides SMA with improved fatigue resistance. Nejad, et al. [4] investigated the fatigue behavior of SMA and HMA mixtures. It was stated that Fatigue crack is a main form of structural damage in flexible pavements. Under the action of repeated vehicular loading, deterioration of the asphalt concrete materials in pavements caused by the accumulation and growth of the micro and macro cracks gradually takes place. Asi, [5] compared the performance of HMA and SMA mixtures. Samples from both mixtures were prepared at their optimum asphalt contents for HMA and SMA mixtures. Tests that included Marshall stability, loss of Marshall stability, split tensile strength, loss of split tensile strength, resilient modulus, fatigue, and rutting testing were performed on both mixtures. Test results showed that although the HMA have higher compressive and tensile strengths, SMA mixtures have higher durability and resilience properties. The Stone Matrix Asphalt mixtures (SMA) were investigated by Bindu and Beena, [6] using triaxial shear strength testing to investigate the effect of additives, waste plastics and polypropylene on strength properties. The test was conducted at 0, 50, 75 and 100 kPa confinements. Analysis using Mohr-Coulomb failure theory shows that the stabilized SMA had highest cohesion and shear strength as compared to control mixture (SMA without additive). Ghasemia and Marandi, [7] assessed Asphalt mixture performance tests including Marshall Stability, indirect tensile strength and resilient modulus were performed on the modified and control asphalt samples. The results of the evaluation showed that SMA mixtures modified by 3.5% recycled glass powder (RGP) and 1.5% styrene butadiene styrene (SBS) presented the best results in the experiments conducted and considerably increased mechanical and physical properties of asphalt and bitumen.

The aim of this investigation is assessing the influence of implementing coal fly ash as stabilizing additive on the resilient behavior of SMAC in terms of resilient modulus Mr and permanent deformation under repeated punching shear stress. The influence of micro crack healing on Mr and deformation will also be assessed.

2. MATERIALS AND METHODS
Asphalt Cement
Asphalt cement was obtained from Dora refinery; the physical properties are shown in Table 1.

Table1 Physical Properties of Asphalt Cement

Test procedure as per ASTM [8]	Result	Unit	SCRB Specification [9]
Penetration (25°C, 100g, 5sec) ASTM D 5	43	1/10mm	40-50
Ductility (25°C, 5cm/min). ASTM D 113	156	Cm	≥ 100
Softening point (ring & ball). ASTM D 36	49	°C	50-60
After Thin-Film Oven Test ASTM D-1754			
Retained penetration of original, % ASTM D 946	31	1/10mm	< 55

Ductility at 25 °C, 5cm/min, (cm) ASTM D-113	147	Cm	> 25
Loss in weight (163°C, 50g,5h) % ASTM D-1754	0.175	%	-

Coarse and Fine Aggregates

Coarse and fine aggregates were obtained from Al-Nibaee quarry, Table 2 exhibits the physical properties of coarse and fine aggregates.

Table 2 Physical Properties of Al-Nibaee Coarse and fine Aggregates

Property as per ASTM [8]	Course Aggregate	Fine Aggregate
Bulk Specific Gravity (ASTM C 127 and C 128)	2.610	2.631
Apparent Specific Gravity (ASTM C 127 and C 128)	2.641	2.6802
Percent Water Absorption (ASTM C 127 and C 128)	0.423	0.542
Percent Wear (Los-Angeles Abrasion) (ASTM C 131)	20.10	-

Mineral Filler

The mineral filler used in this work is limestone dust and was obtained from Karbala governorate. The physical properties of the filler are presented in Table 3.

Table 3 Physical Properties of Filler (Limestone dust).

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

Stabilizing Additives

Coal Fly ash was used in this work as stabilizing additive. Fly ash was added at 1% by weight of aggregate, the physical properties for fly ash were listed in Table 4. Table 5 shows the chemical composition of Fly ash.

Table 4 Physical Properties of Fly ash

Property	Value
specific gravity	2.0
Passing Sieve No.200%	99%
Specific surface area (m²/ kg)	650

Table 5 Chemical Composition of Fly Ash

Chemical composition	Percent	Specification of class F fly ash
SiO_3	54.70	SiO_3+ Al_2O_3+ $Fe_2O_3 \geq 70\%$
Al_2O_3	31.91	
Fe_2O_3	8.79	
SO_3	0.06	$\leq 5\%$
CaO	1.50	----

Selection of Asphalt Concrete Combined Gradation

The selected gradation in this work follows the Gap gradation suggested by many researchers, Rekha and Rao,[3], Asi,[5], and Engineering Road Note, [10]. Figure 1 demonstrates the gradation adopted with 12.5 (mm) nominal maximum size of aggregates.

Preparation of Hot Mix Asphalt Concrete

The aggregate was dried to a constant weight at 110 °C, then sieved to different sizes, and stored. Coarse and fine aggregates were combined with mineral filler to meet the specified gradation shown in Figure 1.
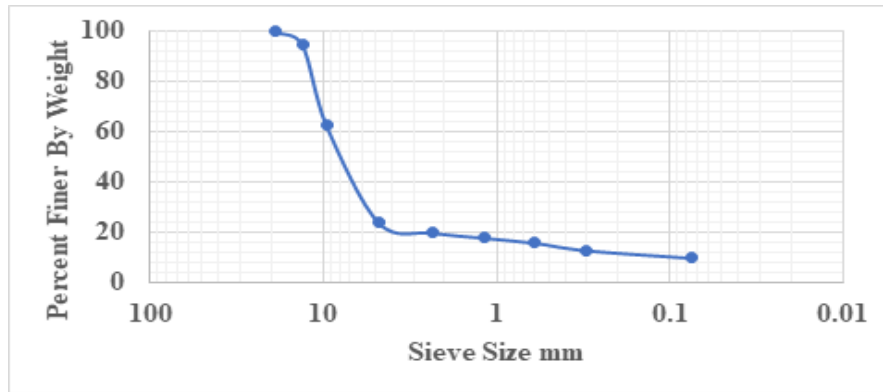
Figure 1 The SMA gap gradation implemented

The combined aggregate mixture was heated to a temperature of 150 °C before mixing with asphalt cement. The asphalt cement was heated to the same temperature of 150 °C, then it was added to the heated aggregate to achieve the desired amount and mixed thoroughly using mechanical mixer for two minutes until all aggregate particles were coated with thin film of asphalt cement. Marshall Size specimens were prepared in accordance with ASTM D1559, [8] by applying 75 blows of Marshall hammer on each face of the specimen. The optimum asphalt content was determined as per the procedure above to be 5.0 and 5.1% by weight of aggregates for control and fly ash stabilized mixtures respectively. The prepared Marshall Size Specimens were subjected to the repeated punching shear test at 25°C. Additional asphalt concrete specimens have been prepared using asphalt cement of 0.5% above and below the optimum asphalt content and without using the stabilizing additive for comparison. Specimens have been tested in triplicate, and the average value was considered for analysis.

Repeated Double Punching Shear Strength Test
This test is used to evaluate the shear resistance of the mixture. This test was implemented through many studies, Sarsam and AL-Zubaidi [11], Sarsam and Saleem, [12]. In this test, the prepared Marshall specimens were used; after it was conditioned at 25°C for two hours in the PRLS chamber. The test was implemented by centrally loading of the cylindrical specimen, by means of two cylindrical steel punches seated on the top and bottom of the specimen, the specimen was fixed between the two punchers (2.54cm in diameter), perfectly allied one above the other, and then subjected to repeated punching shear stress. Such load assembly applies shear stress on the specimen in the form of rectangular wave with constant loading frequency of (60) cycles per minutes with a stress level of 0.138 MPa. A heavier sine pulse of (0.1) sec load duration and (0.9) sec rest period was applied over the test duration. A digital video camera was fixed on the top surface of the (PRLS) to capture dial gage reading. The test was continued for 1200 load repetitions, upon completion of test, the recording was terminated. Specimens were withdrawn from the PRLS and stored in an oven for 120 minutes at 60°C to allow the micro crack healing process by external heating. Specimens were returned to the PRLS chamber and subjected to another 1200 load repetitions; the deformation was monitored by digital camera throughout the test. The average of two specimens was calculated and considered for analysis. Figure 2 shows the PRLS and the test setup and the specimens after testing for the repeated double punch shear. Specimens were tested for punching shear strength before and after the healing process.

Figure 2 Repeated double punching shear test

3. RESULTS AND DISCUSSION

Influence of Stabilizing Agent (Coal Fly Ash) on Resilient Modulus Mr of SMAC

The effect of fly ash on the Mr under repeated PSS is presents in Figure 3. The resilient modulus increases after implementation of fly ash by (36, 40, and 46) % for SMAC mixtures at optimum asphalt content and for 0.5 % above and below OAC. This may be attributed to the high specific surface area added to the mixture by the addition of fly ash. Fly ash was able to control the drain down of binder and fill more voids which increase the stiffness of SMAC. Such finding agrees with the work reported by Ghasemia and Marandi, [7].

Influence of Asphalt Content and Stabilizing Agent (Coal Fly Ash) on Resilient Modulus Mr of SMAC

As demonstrated in Figure 3; the lower asphalt content is generally preferable to resist the traffic loading and limit the vertical deformation. However, the higher asphalt content is required to resistance the tensile stress and increase the durability of the mixture. The limitation for such case is OAC to resist the flow under environmental conditions and load. The SMAC without fly ash show that the Mr decreased by (26.83 and 14.29) % when the asphalt content increased and decreased by 0.5 % from OAC respectively. On the other hand, SMAC with fly ash exhibit that the Mr decreased by (21.43 and 12) % when the asphalt content increased and decreased by 0.5 % from OAC respectively.

Impact of Coal Fly Ash on Permanent Deformation under Repeated Shear Stresses

Figure 3 exhibit the variation in permanent deformation when fly ash was implemented. The deformation after implementation of fly ash decreases by (13.6, 10.2, and 12.1) % for SMAC mixtures at optimum asphalt content and for 0.5 % above and below OAC. This could be attributed to the stiffer mixture and lower voids attained after implementation of fly ash.
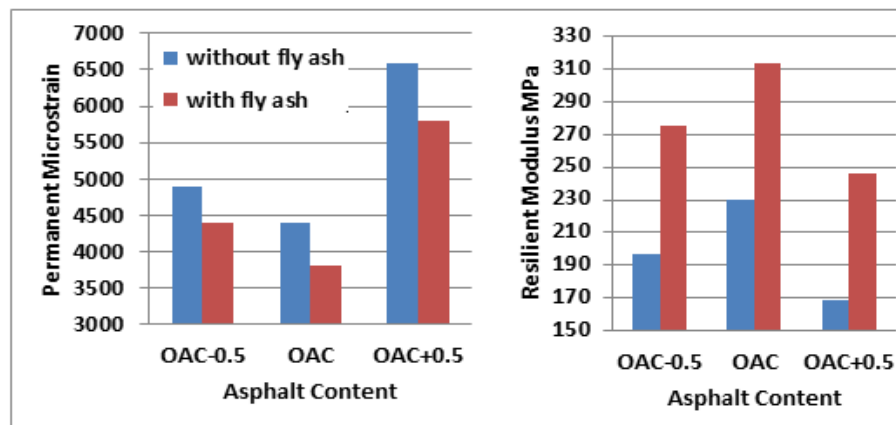

Figure 3 Influence of Fly Ash on Resilient Modulus and Deformation of SMAC

Influence of Asphalt Content and Coal Fly Ash on Permanent Deformation of SMAC

Figure 4 exhibit the axial micro strain-number of load repetitions relationship. It can be noted that OAC exhibit the lowest permanent deformation as compared to other asphalt percentages. Based on the results, the asphalt contents have a great influence on the plastic response of the material. The percentage increases in permanent deformation under repeated punching shear stress (0.138) MPa at 25 °C as shown in Figure 4 indicated that SMAC without fly ash exhibit that the permanent deformation increased by (50 and 11.36) % when the asphalt content increased and decreased by 0.5 % from OAC respectively. On the other hand, SMAC with fly ash show that the permanent deformation increased by (52.63 and 15.78) % when the asphalt content increased and decreased by 0.5 % from OAC respectively. That might be attributed to the high viscosity for the mixture SMAC with fly ash.

The high permanent deformation is associated with the increase in asphalt content as shown in Table 6. Permanent deformation parameters of SMAC under 0.138 MPa of repeated shear stress as demonstrated in the table shows that the permanent strain at N=1 is represented by the intercept (a), where N is the load cycles number. The higher the value of intercept, the larger the strain and hence the larger the potential for permanent deformation. While, the slope (b) represents the rate of change in the permanent strain as a function of the change in loading cycles N in the log-log scale, high slope values for a mix indicate an increase in the material deformation rate hence less resistance against rutting, GUL, [13]. To calculate the permanent deformation, the three selected parameters were considered (intercept, slope and deformation measured at 1200 cycles).
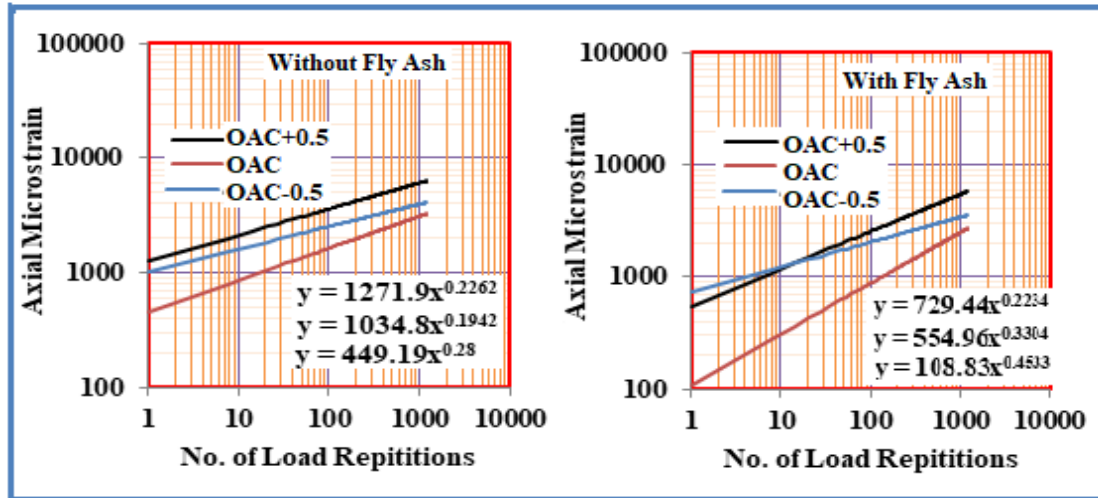
Figure 4 Axial micro strain-number of load repetitions relationship of SMAC

Table 6 Permanent deformation parameters of SMAC under 0.138 MPa of repeated shear stress

Without additive				With additive			
Mixture Type	Intercept Microstrain	Slope	Permanent Microstrain @1200cycle	Mixture Type	Intercept Microstrain	Slope	Permanent Microstrain @1200cycle
OAC+0.5	1034.8	0.194	4900	OAC+0.5	729.44	0.223	4400
OAC	449.19	0.28	4400	OAC	108.83	0.453	3800
OAC-0.5	1271.9	0.226	6600	OAC-0.5	554.96	0.330	5800

Effect of Crack Healing on Permanent Deformation under Repeated Punching Shear Stresses

Table 7 exhibit the impact of healing cycle on SMAC behavior under repeated punching shear stress of (0.138) MPa at (25 °C) on Permanent deformation. It can be noted that the Permanent deformation for mixtures without fly ash after the healing process decreased by (11.3, 8.16, and 7.57) % for mixes with optimum asphalt content and and for the mixtures when the asphalt content increased and decreased by 0.5 % from OAC respectively. On the other hand, the permanent deformation of SMAC mixtures with fly ash decreased by (5.26, 13.63, and 12.06) %for mixes with optimum asphalt content and for the mixtures when the asphalt content increased and decreased by 0.5 % from OAC respectively. This may be attributed to the more viscosity added for the specimen after healing cycle due to evaporation of volatiles from the binder during the long heating period. Figure 5 demonstrate the variation of permanent deformation after healing at various asphalt percentages. Similar finding was reported by Sarsam and Mahdi, [14].

Table 7 Permanent deformation parameters of SMAC before and after micro crack healing

Mixture Type without fly ash	Before healing			After healing		
	Intercept Microstrain	Slope	Permanent Microstrain @1000cycle	Intercept Microstrain	Slope	Permanent Microstrain @1000cycle
Mixtures without fly ash						
OAC+0.5	1034.8	0.1942	4900	739.38	0.2372	4500
OAC	449.19	0.28	4400	322.65	0.3242	3900
OAC-0.5	1271.9	0.2262	6600	991.49	0.2521	6100
Mixtures with fly ash						
OAC+0.5	729.44	0.2234	4400	301	0.3236	3800
OAC	108.83	0.4533	3800	133.41	0.4107	3600

OAC-0.5	554.96	0.3304	5800	238.99	0.4334	5100

It can be observed that SMAC with the optimum asphalt content OAC possesses the lowest permanent deformation before and after the micro crack healing process regardless of implication of fly ash. On the other hand, mixtures with fly ash exhibit lower permanent deformation as compared to the mixtures without fly ash regardless of exposure to healing cycle. This may be attributed to the lower voids, higher viscosity, and increased stiffness of SMAC after implication of fly ash.

Impact of micro crack Healing on Resilient Modulus under repeated punching shear stress
Figure 5 exhibit the influence of healing cycle process on resilient modulus of SMAC under repeated punching shear stress of 0.138 MPa at (25 °C) on resilient modulus (Mr). It can be noted that the (Mr) after the healing cycle increased regardless of implication of fly ash in the mixtures. The SMAC without fly ash show that the Resilient Modulus was increased by (20, 12.90, and 2.50) % formixtures with optimum asphalt content and for the mixtures when the asphalt content increased and decreased by 0.5 % from OAC respectively. On the other hand, The SMA with fly ash show that the Resilient Modulus was increased by (15.78, 19.04, and 16.67) % formixtures with optimum asphalt content and for the mixtures when the asphalt content increased and decreased by 0.5 % from OAC respectively. This couldbe attributed to the more stiffness added for the specimens after healing cycle. Such findings agree with Sarsam and Mahdi, [15].
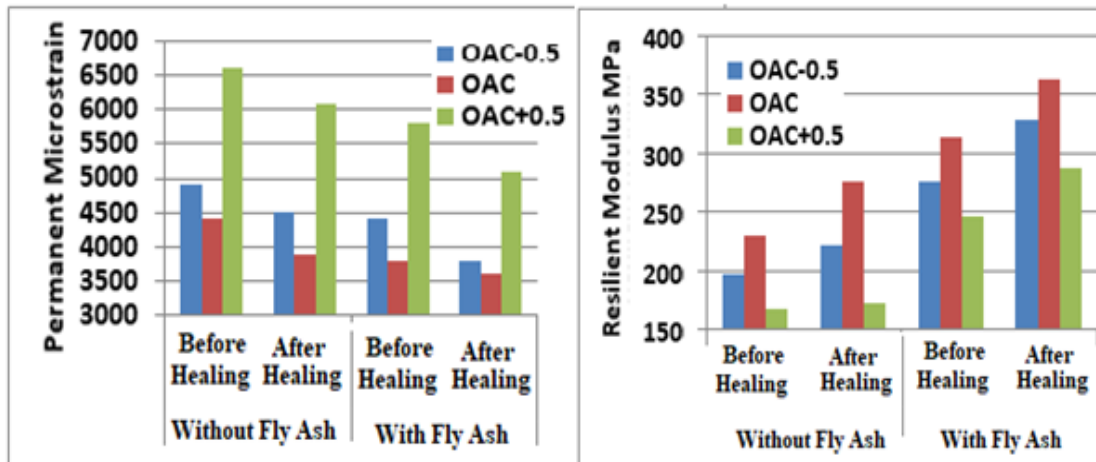

Figure 5 Impact of micro crack Healing on Mr and Deformation of SMAC

4. CONCLUSION
Based on the limited testing program, the following conclusions can be drawn.
1. The resilient modulus increases after implementation of fly ash by (36, 40, and 46) % for SMAC mixtures at optimum asphalt content and for 0.5 % above and below OAC.
2. The permanent deformation after implementation of fly ash decreases by (13.6, 10.2, and 12.1) % for SMAC mixtures at optimum asphalt content and for 0.5 % above and below OAC.
3. The permanent deformation of SMAC increased by (50 and 11.36) % and (52.63 and 15.78) % when the asphalt content increased and decreased by 0.5 % from OAC respectively before and after implication of fly ash respectively.
4. Permanent deformation after the healing process decreased by (11.3, 8.16, and 7.57) % and (5.26, 13.63, and 12.06) % for mixes with optimum asphalt content and when the asphalt content increased and decreased by 0.5 % from OAC before and after implication of fly ash respectively.
5. Resilient modulus of SMAC after healing increased by (20, 12.90, and 2.50) % and (15.78, 19.04, and 16.67) %for mixtures with optimum asphalt content and when the asphalt content increased and decreased by 0.5 % from OAC before and after implication of fly ash respectively.

Conflicts of Interest: The authors declare no conflict of interest.

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