INDIAN JOURNAL OF
ENGINEERING

18(50), 2021

Comparative Evaluation of Moisture Susceptibility for Porous and Stone Matrix Asphalt Concrete

Saad Issa Sarsam

To Cite:
Sarsam SI. Comparative Evaluation of Moisture Susceptibility for Porous and Stone Matrix Asphalt Concrete. *Indian Journal of Engineering*, 2021, 18(50), 424-432

Author Affiliation:
Professor, Sarsam and Associates Consult Bureau (SACB), Iraq
Email: saadisasarsam@coeng.uobaghdad.edu.iq

Peer-Review History
Received: 12 October 2021
Reviewed & Revised: 14/October/2021 to 18/November/2021
Accepted: 20 November 2021
Published: November 2021

Peer-Review Model
External peer-review was done through double-blind method.

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ABSTRACT

Stone Matrix Asphalt Concrete (SMA) is a mixture with a gap-graded aggregate, while porous asphalt concrete is the pavement with high voids content that allows water to infiltrate through its surface. Both mixtures are implemented for heavy traffic and harsh environmental condition especially heavy rainfall. The present investigation assesses the moisture susceptibility of both mixtures. Asphalt concrete specimens were prepared and tested for the indirect tensile strength under dry and moisture conditioned status. The resistance of the mixtures to binder stripping was investigated with the aid of Tensile Strength Ratio (TSR) % and the change of resilient modulus. It was noted that the control SMA mixture exhibits higher TSR % by 25.7 % than that of the control porous mixture, while the fly ash modified SMA exhibits lower TSR % by 7.6 % when compared with carbon fibers modified porous asphalt concrete. For porous asphalt concrete mixture, the resilient modulus declines by (13.2, and 16) % for control and carbon fibers modified mixture respectively after practicing moisture damage process. However, the stone matrix asphalt mixture exhibits decline in the resilient modulus by (30.8, and 31.1) % for control and fly ash modified mixture respectively after practicing moisture damage process. It was revealed that the modified porous asphalt concrete exhibit higher TSR %, while it shows lower resilient modulus after moisture damage as compared with modified SMA.

Keywords: Porous Asphalt concrete, SMA, Moisture Susceptibility, Tensile stress, TSR, Resilient modulus

1. INTRODUCTION

Moisture susceptibility was defined by Masri et al., (2019) as the decline of durability, strength, and stiffness of asphalt concrete due to the existence of moisture, this will cause adhesive loss of binder and aggregate. It was revealed that the tensile strength ratio (TSR) value should be equal or more than 80% to resist moisture induced damage. However, for porous asphalt concrete, TSR value of 70% is consider acceptable due to porous nature of that permit water to flow inside the mix. Both Porous and stone matrix asphalt concrete have high voids content and used for surface course layer of the pavement. Putman and Kline, (2012) stated that the design of porous asphalt concrete pavement mixture is based on an open graded aggregate gradation so that the number of fully permeable air voids is increased. This will allow water to traverse through the voids in a proper drainage process of removing the water from the surface of a roadway much faster than traditional dense-graded pavement. The mixture of porous pavement surface layer may have a high voids index ranging between (16 to 22) %, to allow for proper drainage as revealed by WAPA, (2015). Qin, (2019) stated that porous friction course can of enhance the quality of riding and reduces the noise effectiveness. However, it was revealed that because of the large voids content in the pavement layer, this could give rise to the asphalt binder to be more vulnerable to the sun, the air, and other negative factors. This can cause rapid declines of the asphalt binder properties and cause distresses and early damage such as loosening of materials and stripping. Gupta et al., (2019) summarizes the best practices performed on porous asphalt mixtures. It was revealed that particular emphasis is placed on the strength and resilience of the mixture by incorporating additives like crumb rubber, Nano silica, fibers (such as steel, synthetic fibers, cellulose, and glass), and some eco-friendly materials. It was found that various additives seem to have different influence on the overall properties of the porous asphalt concrete mixture. Kanitpong et al., (2003) quantified the influence of air void content, aggregate shape, specimen thickness, and aggregate gradation on the permeability of porous asphalt concrete. It was revealed that the air void content is the predominant factor controlling hydraulic conductivity; however, aggregate gradation and shape also have a statistically significant influence. Yu et al., (2017) stated that permeable pavement systems are one of the most complete sustainable urban drainage systems and they attracted attention in previous decades due to their ability to withstand sufficient vehicular loads. The advantages of porous pavement as reported by Cetin, (2013) include reduction in the noise generated by tire, skidding, water splashing, and soil erosion. They also reduce the damage to pavement caused by stagnant water, mitigate the urban heat island effect, and facilitating high infiltration capacity. The constant environmental exposure of the porous asphalt pavement accelerates the ageing process through the increase in the asphaltene content, which makes bitumen stiffer and brittle, leading to cracking and raveling as reported by Kumbargeri and Biligiri, (2016). Ma et al., (2018) evaluated the possibilities of implementing additives to improve the durability and strength of the porous asphalt concrete. It was noticed that fiber can enhance its durability and anti-cracking performance at low temperature, however, hydrated lime can improve its moisture stability while weakening its durability. The effects of fibers of basalt on the properties of stone matrix asphalt concrete (SMA) mixtures were investigated by Cetin et al., (2021) as a replacement to cellulosic fiber admixtures to prevent the infiltration of asphalt binder during the carriage of mixture due to high bitumen content. Norhidayah et al., (2019) reported that the incorporation of carbon fibers into the asphalt concrete mixture can significantly upgrade the performance of asphalt pavement, improve its mechanical properties, and prolong the fatigue life of a pavement structure. Qin et al. (2018) assessed the influence of changing the basalt fiber lengths and fiber content. It was observed that basalt fiber of 6.0 mm length had much better asphalt binder adsorption and strength behavior according to the largest interaction area in the matrix. Shukla et al., (2014) revealed that the fiber modified asphalt concrete mixtures exhibits increased resistance to permanent deformation and stiffness. However, Fatigue characteristics of the mixtures were also improved. Afonsoet al., (2017) evaluated the properties of porous asphalt concrete mixtures with the cellulosic fiber's addition. It was reported that such fibers are known for their adherence capacity between the aggregates and the binder and can help to prevent the binder loss by drainage, which is considered as a porous asphalt concrete major problem. Fibers can also improve the behavior of the porous asphalt pavement to permanent deformation. Sarsam and Khalil, (2019) assessed the behavior of stone matrix asphalt under repeated tensile stresses. It was revealed that the Resilient modulus of SMA mixture treated with coal flyash as a stabilizing agent is higher than that of mixture prepared without implementing flyash by 30% in general. However, Mr reduces by 50% after practicing the moisture damage. Cooley and Brown, (2003) revealed that stone matrix asphalt (SMA) has been used and have had either a (12.5 or 19.0) mm nominal maximum aggregate size (NMAS). Fine SMA mixes were rut resistant and thus are more durable. Permanent deformation test on SMA was conducted by Awanti, (2013) using the wheel tracking with immersion technique test. It was concluded that SMA shows higher rutting resistance by 42 % when compared with the control mixture. Nguyen et al., (2019) investigated the dynamic modulus values of porous asphalt materials with air void content of (9.0 and 20.5) % at dry condition and after moisture conditioning. It was observed that porous asphalt mixture with lower air void content of 9 % exhibited higher values of dynamic modulus by one to three folds when compared with that of porous asphalt with air void content of 20.5%.

The present investigation aim is to comparatively assess the moisture susceptibility and resilient modulus under repeated tensile stresses of porous asphalt and stone matrix asphalt concrete.

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2. MATERIALS, PROPERTIES AND TESTING METHODS

Asphalt Cement

The implemented asphalt cement binder in the present investigation was obtained from Dorah refinery. Table 1demonstrates the physical properties of the binder.

Table 1. Physical Properties of Asphalt Cement

Test procedure as per ASTM, 2016	Result	Unit	SCRB, 2003 Specification
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	%	-

Fine and Coarse Aggregates

Fine and Coarse aggregates were obtained from Al-Nibaee quarry; Table 2 shows the physical properties of aggregates.

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

Property as per ASTM, 2016	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 passes sieve No.200 (0.075mm). The implemented mineral filler in the present work is the Karbala limestone dust. The physical properties of the mineral filler (limestone dust) are shown in Table 3.

Table 3. ThePhysical Properties of the Mineral Filler

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

Stabilizing Additive

Coal Fly ash was used for SMA in this work. Fly ash was added at 1% by weight of combined aggregate, the physical properties for fly ash are listed in Table 4.

Table 4. Physical Properties of Fly ash

Property	Value
specific gravity	2.0
Passing Sieve No.200%	99%
Specific surface area (m^2/ kg)	650

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Carbon Fibers

Carbon Fibers were added to porous asphalt concrete at a rate of 0.3% by weight of mixture. The length of the fibers is (2 cm). These fibers were obtained by using a paper shredder machine. The physical properties are shown in Table 5.

Table 5. Physical characteristics of carbon fibers

Test Properties	Typical Value
Nominal thickness (mm)	0.167
Fiber Length (mm)	Can be produce any length
Color	Black
Density gm/cm3	1.82
Tensile Strength (N/mm^2)	40000
Elongation-at-Break, %	1.7
Tensile Modulus of elasticity (KN/mm^2)	225
Base	Polyacrylonitrile
Temperature of Carbonization	1400 °C

Selection of Asphalt Concrete Combined Gradation

The selected gradation for SMA follows the Gap gradation suggested by many researchers, Myers, 2007; Nejad et al., 2010; and Bernard, 2017. Figure 1 demonstrates the gradation adopted with 12.5 (mm) nominal maximum size of aggregates. However, the selected gradation for porous pavement follows ASTM D-7064, 2016 specification, the nominal maximum size of aggregate is 12.5 mm for wearing course. Many trial aggregate gradations were selected and tried. The final adopted gradation is demonstrated in Figure 1.

Preparation of Porous Asphalt Concrete Mixture

The aggregates were dried by oven to a constant weight at 110˚C in the oven, and then separated by sieving to different sizes. Fine and Coarse aggregates were recombined with the required amount of the filler to meet the selected gradation. The combined aggregates mixture (coarse, fine and filler) was then heated to (150˚C) in an oven. The asphalt binder was heated to (150˚C). Then the desired amount of asphalt binder was incorporated into the heated aggregate, and thoroughly mixed by hand for two minutes using a spatula until all the aggregate particles were covered with thin film of binder. In the case of specimens that contain carbon fibers, the carbon fibers are cut to the prescribed length of 2 cm and implemented by 0.3% of the total asphalt concrete mixture weight. The fibers were added to the aggregate before heating and mixed thoroughly. Details of mixture design can be found in Sarsam and Majeed, (2020) & Sarsam and Mahmood, (2019).

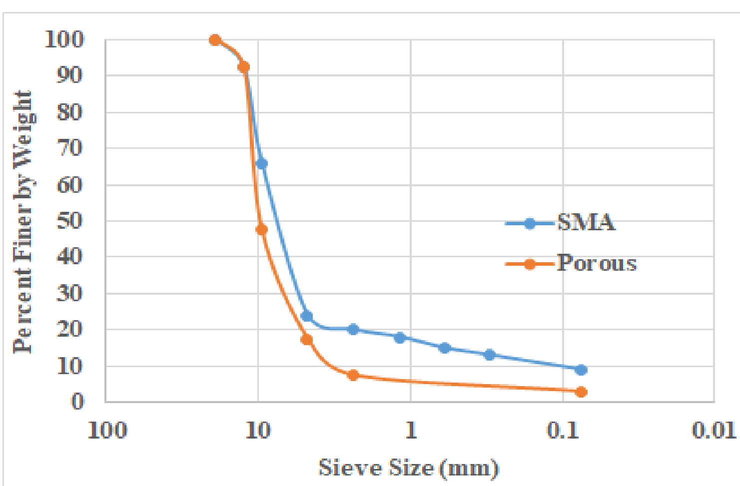

Figure.1 Grain Size Distribution OF Asphalt Concrete

Preparation of SMA Mixture

The aggregates were dried at 110 ºC to achieve a constant weight, then separated to different sizes by sieving, and stored. Mineral filler was combined with fine and Coarse aggregates to meet the selected gradation. The combined aggregates mixture was subjected to heating at 150 ºC before getting mixed with asphalt binder. However, the fly ash was added to the aggregate. The asphalt binder was heated to 150 ºC, then it was implicated in the heated aggregates to achieve the desired percentage and mixed thoroughly with the aid of a mechanical mixer for two minutes. All the aggregate particles were covered with a thin film of asphalt binder.

Preparation of Porous Asphalt Concrete and SMA Specimens

Asphalt concrete specimens of two types were prepared, the first type was specimens of 63.5 mm in height and 102 mm in diameter were prepared using the traditional Marshall Procedure. Mold and spatula were subjected to oven heating to a temperature of (150˚C) on a hot plate. Apiece of non-absorbent paper was cut to the mold size and was placed in the mold bottom prior to the introduction of the mixture. The hot asphalt concrete mixture was poured into the preheated steel mold and then vigorously spaded 15 times around the perimeter and 10 times around the inside with a heated spatula. The compaction temperature of mixture was monitored to be within (150 ±1 ˚C). Each specimen was subjected to Marshall Hammer compaction. The specimens were left overnight into the mold to cool overnight at the room temperature and then it was extracted from the mold with the aid of mechanical jack. The optimum asphalt binder content was 5.2 % by weight of aggregates. The optimum asphalt content was determined as per Marshall method. Details of obtaining the optimum asphalt binder content for each mixture could be foundat Sarsam and Majeed, (2020) for porous pavement, and Khalil and Sarsam, (2020) for SMA. The second type of the prepared specimens was specimens of 102 mm in height and 102 mm in diameter. Such specimens were compacted to their target densities using static compaction. Similar compaction condition was adopted regarding the compaction temperature of (150 ±1˚C). Such asphalt concrete specimens were implemented for determination of the resilient modulusunder repeated compressive stresses.Table 6 exhibit the Marshall properties of the tested specimens.

Table 6. The Marshall Properties of Tested Mixtures

Asphalt concrete property	Control SMA mixture	Modified SMA mixture	Control porous mixture	Modified porous mixture
Optimum binder %	5.1	5.3	5.2	5.2
Marshall stability kN	6.8	8.0	4.3	6.4
Marshall flow mm	3.8	3.5	9.3	5.2
Bulk Density gm/cm^3	2.250	2.320	2.018	2.150
Total voids %	4.9	4.8	18	17.5
VMA %	18.2	16.0	27	22
VFA %	74.0	70.0	32	20

It can be detected that significant variation in the strength and voids properties could be noted between SMA and porous asphalt concrete. It can be related to the variation in gradation of both mixtures. However, implementation of additives exhibits a positive influence on the strength and voids properties of the mixtures.

Testing for Moisture Damage

The set of six specimens of each mixture type was separated into two sets; the first set of three specimens was denoted as unconditioned specimens. They were stored in a water bath at 25°C for 30 minutes, then tested for ITS at 25°C and the average value for these specimens of (ITS) was considered. Thesecond set of three specimens of asphalt concrete was conditioned by placing the specimens in the heavywall glass volumetric flask filled with tap water at the room temperature of (25 ˚C). The specimens had practiced saturation by applying avacuum of twenty-eight mm/Hg for ten minutes to achieve eighty percentsaturation level. The specimens were then removed from the water flask and stored at -18° C forsixteen hours in a deep freezer. Specimens were then extracted from the deep freezer and thawed in the airfor 120 minutes.Thespecimens were transferred to the water bath and immersed at sixty °C for 120 minutes. Specimenswere denoted as conditioned specimens and kept at 25 °C for 120 minutes beforetesting for ITS. Tensile Strength Ratio (TSR) of each mixture was calculated to evaluatethe sensitivity for moisture resistance. The test was conducted considering ASTM, (2016) procedure.

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Testing for Resilient Modulus

Specimens were conditioned in the PRLS (Pneumatic Repeated Load System) chamber presented in Figure 2 at laboratory temperature of 20±1°C for 30 minutes, then the asphalt concrete specimens were centered on the horizontal diametrical plane between two identical steel plates. Repeated Uniaxial compressive loading was applied. The load excitation function is a rectangular wave with steady frequency equal to one cycle of 10 Hz per second. A maximum load pulse time is (0.1) second and (0.9) second is the rest period used throughout the interval of test. Before starting test, the pressure actuator was regulated to the specific pressure level of (55.16 kPa). LVDT was used to monitor the deformation every second (every cycle) till the test is completed. The specimen was subjected to repeated uniaxial compressive stresses. The average of three specimens for each mixture type was considered for the calculation of resilient modulus. Similar testing procedure was reported by Sarsam, (2020).

Figure 2. Resilient Modulus Testing at PRLS

3. RESULTS AND DISCUSSION

Influence on Mixture Type on the Resistance against Moisture Damage

Figure 3 demonstrates the variation in moisture susceptibility in terms of TSR % between porous and SMA mixtures using control and modified mixes. Higher TSR % indicates lower moisture susceptibility. It can be detected that implementation of carbon fibers in the porous asphalt concrete exhibits significant improvement in the TSR %. The resistance exhibited by the porous asphalt concrete mixture against moisture damage increases by 39.3 % after implementation of carbon fibers. This may be related to the impact of the carbon fibers as a stabilizing agent in reinforcing the mixture and blocking voids. On the other hand, (SMA) control mixture exhibits higher TSR % as compared with the control porous asphalt. However, when the fly ash was incorporated in the SMA mixture, the TSR % increases by 2.4 %.This may be related to the higher fines content after incorporating fly ash and the ability of such fines to block more voids in the mixture. It can be revealed that the control SMA mixture exhibits higher TSR % by 25.7 % than that of the control porous mixture, while the fly ash modified SMA exhibits lower TSR % by 7.6 % when compared with carbon fibers modified porous asphalt concrete. Test results agree with Qiu and Lum, (2006).

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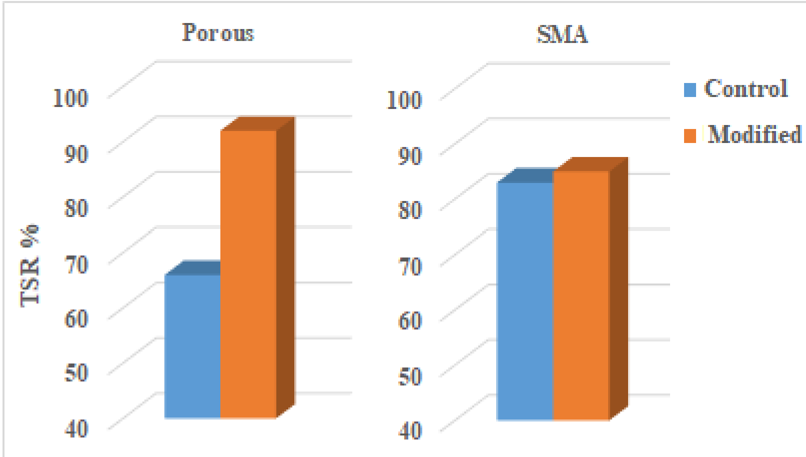

Figure 3. (TSR) Tensile Strength Ratio for Asphalt Concrete

Influence of Mixture Type on Resilient Modulus

Figure 4 exhibits the variation in the resilient modulus between porous and SMA mixtures using control and modified mixes. Higher resilient modulus in the range 0f (1000 to 20000) MPa is preferred for heavy duty asphalt concrete pavement.

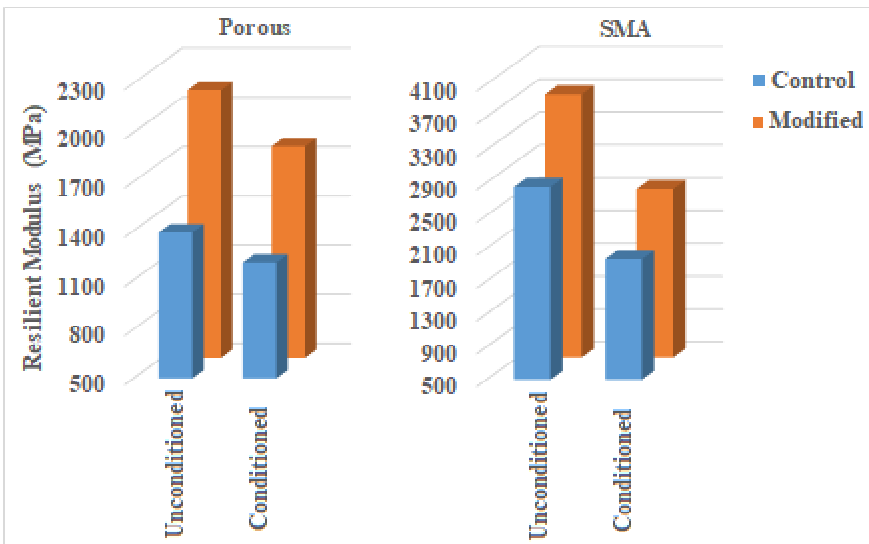

Figure 4. Resilient Modulus (Mr) for Asphalt Concrete

It was detected that the conditioned mixtures (practiced moisture damage process) exhibited lower resilient modulus when compared with the unconditioned mixtures (before practicing moisture damage) regardless of the mixture type. However, for porous asphalt concrete mixture, the resilient modulus declines by (13.2, and 16) % for control and carbon fibers modified mixture respectively after practicing moisture damage process. On the other hand, the stone matrix asphalt mixture exhibits decline in the resilient modulus by (30.8, and 31.1) % for control and fly ash modified mixture respectively after practicing moisture damage process. The Mr for the porous asphalt concrete control mixture increases by (53.3, and 48.4) % after implication of carbon fibers for unconditioned and conditioned mixtures respectively. Such behavior may be related to the reinforcing action provided by the carbon fibers which improves the tensile property of the modified mixture. However, The Mr for the stone matrix asphalt concrete control mixture increases by (30, and 29.6) % after implication of fly ash for unconditioned and conditioned mixtures respectively. This may be related to the higher density of the modified mixture created after implication of fly ash and its role in blocking more voids. It can be revealed that SMA exhibits higher Mr values as compared with porous asphalt concrete regardless of the modification process or the moisture damage process. Patil et al., (2018) and Mashaan et al., (2013) reported similar behavior.

4. CONCLUSION

Considering the limitation of materials and testing methods adopted, the following conclusions may be addressed.

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1- The control SMA mixture exhibits higher TSR % by 25.7 % than that of the control porous mixture, while the fly ash modified SMA exhibits lower TSR % by 7.6 % when compared with carbon fibers modified porous asphalt concrete.

2- The porous asphalt concrete mixture resistance to moisture damage increases by 39.3 % after implementation of carbon fibers. While, when the fly ash was incorporated in the SMA mixture, the TSR % increases by 2.4 %.

3- The resilient modulus of porous asphalt concrete mixture declines by (13.2, and 16) % for control and carbon fibers modified mixture respectively after practicing moisture damage process.

4- The resilient modulus of stone matrix asphalt mixture declines by (30.8, and 31.1) for control and fly ash modified mixture respectively after practicing moisture damage process.

5- The Mr for the porous asphalt concrete control mixture increases by (53.3, and 48.4) % after implication of carbon fibers for unconditioned and conditioned mixtures respectively. However, The Mr for the stone matrix asphalt concrete control mixture increases by (30, and 29.6) % after implication of fly ash for unconditioned and conditioned mixtures respectively.

6- Modified porous asphalt concrete exhibit higher TSR %, while it shows lower resilient modulus after moisture damage as compared with modified SMA.

Funding

This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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