




Comparative Assessment of Environment and Moisture Damage (MD) Impacts on Flow Number (FN) of Asphalt Concrete (AC) Under Dynamic Indirect Tensile Stresses (DITS)

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Keywords

*Dynamic,
Recycling,
Microstrain,
Carbon black (CB),
Flow number (FN),
Asphalt concrete (AC),
Moisture Damage (MD),
Indirect Tensile Stress (DITS).*

Abstract

Recycling of aged AC mixture is a sustainable process used to prolong the useful life of the AC pavement. In the present work, Reclaimed Asphalt Pavement (RAP) was obtained from the in-service field pavement and recycled with a mixture of binder and carbon black (CB). Laboratory specimens of Marshall size were prepared from both RAP and recycled mixtures. Part of AC specimens were subjected to (MD) process, then practiced the DITS at (25 and 40) °C environment at constant stress level of 138 kPa in the pneumatic repeated load system (PRLS) with constant loading frequency of 60 cycles per minute. The dynamic loading sequence for each cycle is 0.1 seconds of load duration and 0.9 seconds of rest period. The permanent microstrain (PM) and FN were recorded before and after the MD. At 25° C environment, the MD process exhibited a decline of FN by (80, and 72.5) % for RAP and recycled mixtures respectively. However, in the 40° C environment, the MD process exhibited a decline of FN by (75, and 33) % for RAP and recycled mixtures respectively. Before the MD process, the increment of testing temperature from (25 to 40) °C exhibited decline in FN of AC mixtures by (40, and 62.5) % for RAP and recycled AC mixtures respectively. The recycling index after practicing MD is higher than before MD for FN and PM. Recycling index increases at higher testing temperature of 40 °C as compared to that at 25 °C for PM regardless of testing condition.

1. Introduction

Recycling of aged AC mixture is a sustainable process used to prolong the useful life of the AC pavement. It consists of rejuvenating the aged and oxidized asphalt binder by adding recycling agents to control the viscosity and enhance the physical properties. Sun et al., 2026, [1] assessed a dense-graded AC mixture prepared with high RAP content, recycled with bio-oil rejuvenator and subjected to successive recycling cycles using dynamic modulus testing under the moisture-induced stress tester. The results showed that recycling progressively weakened interfacial aggregate-binder adhesion and causes loss of stiffness under dynamic conditioning. It was concluded that the high-RAP mixtures were able to maintain moisture resistance for up to two recycling cycles, while durability degraded sharply beyond this limit. The influence of MD and ageing of AC mixture on the FN was evaluated by Sarsam, 2026, [2]. The resistance to fatigue of AC under dynamic flexural stresses was evaluated before and after practicing the MD at 20° C environment. It was observed that the FN declined after practicing MD by 178 % as compared with the control mixtures. The permanent deformation (PD) of AC mixture increased after practicing the MD process by 11%. Njogu et al., 2026, [3] evaluated the potential of carbon black as a partial substitute of filler to enhance the mechanical performance of AC mixtures.

Mechanical performance was assessed through resilient modulus, ITS, and Four-Point Bending Beam fatigue tests under both control and aged conditions. It was revealed that carbon black extends fatigue life and improves resistance to ageing and stiffening and extended pavement durability. Eftekhari et al., 2025, [4] investigated the influence of oil-based rejuvenators on sensitivity of RAP mixture of AC to MD, along with three types of rejuvenators (sunflower oil, vacuum bottoms, and cyclogen.). Moisture-related tests such as Rheological Aging Index, Viscosity Aging Index, and Chemical Aging Index were conducted. Results showed that rejuvenator variations can significantly influence the resistance to MD of recycled RAP mixture. Liu et al., 2025, [5] established a method for calculation of the FN without dependence on the termination strain of AC mixture. It was concluded that there is a relationship between FN and the rate of strain during the failure stage, which is independent of AC type, level of stress, and testing environment. Yu et al., 2025, [6] assessed the changes in the physical property of recycled AC using microscopic and macroscopic approaches through laboratory tests. The test results exhibited that after recycling, the solubility of the implemented rejuvenator in old AC declines exponentially with further number of recycling cycles. It was revealed that the high stability temperature of recycled AC mixtures increases gradually with the number of recycling cycles, while the volumetric properties of Marshall test of the recycled AC mixtures meet the required regulatory. However, the cracking resistance of recycled AC mixture at low temperature rapidly deteriorates. Xu et al., 2025, [7] conducted a comparative analysis between Multi-Sequenced Repeated Loading (MSRL) test which can enhance confinement, sequences of loading, and control of temperature for better simulation of service conditions and uniaxial FN test. Field cores of AC pavement were collected for validation in China. It was revealed that MSRL was more sensitive than FN to the factors which affect the rutting resistance, and exhibits stronger correlation with growth of rutting, and superior applicability for assessment of the AC rutting resistance. Preethi and Ravichandran, 2025, [8] prepared recycled AC mixtures using nanomaterials modified binder and RAP. Waste cooking oil was implemented as a rejuvenator. It was concluded that nanomaterials have improved the strength properties of AC mixtures. The test result indicated that recycled AC mixtures exhibited higher resistance to rutting, high indirect tensile strength, and higher resistance to dynamic stability as compared with control mixes. Nada et al., 2025, [9] investigated the potential use of CB obtained from tire as a sustainable waste binder in AC mixtures and assessed the feasibility of incorporating resin tire CB into AC mixture as a full replacement for conventional

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binders. The performance, rheological, and mechanical properties of AC mixtures containing varying proportions of CB, ranging from 2% to 10% by weight of the binder. Marshall specimens were prepared and tested to evaluate its resistance to deformation of the modified AC mixtures. Specimens prepared with 6% CB showed the highest stability and lower flow values among all other samples. Shylaja and Ravichandran, 2024, [10] assessed the rutting behavior and physical properties of recycled AC developed with Nano silica and Nano clay. The test results showed that modification of asphalt binder with such nanomaterials can reduce the possibility of moisture damage, shows better performance in terms of strength and durability, enhance the rutting potential of the recycled AC mixtures, and provide higher tensile strength ratio. Costa et al., 2023, [11] analyzed the moisture resistance and fracture performance of AC mixtures prepared with high RAP content and residual engine oil as a recycling agent. The AC mixtures were subjected to mechanical tests. The results showed that recycling agents showed a lower slope of the post-peak curve. Conditioning cycle methods increase the susceptibility of AC mixtures to the deleterious effect of water. Statistical analysis indicated that the RAP content and recycling agent presented adequate significance for the conducted tests. Zarroodi et al., 2023, [12] investigated the influence of CB additive on MD resistance of AC using surface free energy methods, test results were compared with the Tensile Strength Ratio (TSR) test. The carbone black Modified binder samples were tested and compared with control sample. The sensitivity to MD was assessed using surface free energy components of the raw materials and testing the TSR. It was noticed that implementation of carbon black into the AC mixture had improved its resistance to MD as compared with pure asphalt binder. Sun et al., 2023, [13] assessed the behavior of CB-modified binder using the conventional tests. The evaluation of the best reaction temperature for CB involved studing ash content, productivity, iodine absorption value, and oil absorption value with the aid of scanning electron microscopy. The modification of the binder was conducted by involving hydroxymethylation and nitric acid oxidation. Dynamic shear rheometer was implemented to assess the ageing resistance of the CB modified binder. It was concluded that modification of asphalt binder with CB can significantly enhanced its viscosity, and temperature sensitivity and improve anti-ageing behavior in the AC. Pires et al., 2022, [14] assessed the PM for various AC mixtures [styrene butadiene styrene polymer (SBS), and rubber modified], and asphalt binders, verifying the performance relationship between them and correlating the properties. The modified AC mixtures exhibited higher FN which can suggest better behavior in the field. Ishaq et al., 2022, [15] studied the relation between susceptibility of asphalt binder to rutting with that of the AC using the FN of AC mixtures using dynamic uniaxial load tests at various testing environments. The test results were analyzed to evaluate the statistical fit between tests on asphalt binder and on AC mixes. Faccin et al., 2022, [16] assessed the rutting potential of various AC mixtures with the aid of uniaxial dynamic load tests in a criteria proposal for the parameter FN depending on traffic. The results exhibited that the modification of the asphalt binder was the most influential characteristics in monitoring the rutting initiation of AC. A new criterion was suggested. Jafari et al., 2022, [17] investigated the sensitivity to stress of modified asphalt binders in the creep and multiple stress recovery test and its relationship with resistance to rutting of the AC mixtures. Variable stress levels have been tried, and the FN was evaluated through dynamic creep performance and dynamic modulus tests. It was revealed that the FN test was established to cope for numerous sources of variations in AC mixture like testing loads, aggregate sizes, and sample preparation for laboratory tests. Zhang et al., 2022, [18] suggested calculation method for verifying the transition points of the stages of failure of AC which are independent of human factors. It was revealed that the differences of transition points of existing methods and the slopes between the proposed double-tangent method are assessed and a double-tangent method was recommended. Islam et al., 2019, [19] reported that the FN is implemented to determine the ability of AC mixture to resist PM and investigated the sensitivity of FN to the binder contents, and volumetric properties. The test results showed that FN increase with the increase in the effective binder content. Jitsangiam et al., 2019, [20] evaluated the MD potential of AC under cyclic loading using dynamic creep testing. Such test provides the FN, representing the number of loading cycles at the failure point of the AC mixture. It was revealed that the test provided reasonable evaluation of MD potential than any other conventional method. However, high uncertainty in the test results were observed. It was concluded that such test may be used for stripping potential in AC. Sarsam and Mahdi, 2019, [21] studied the effect of recycling of RAP mixture with carbon black and SBR. AC specimens were prepared and tested for DITS and dynamic compressive stress. The influence of recycling was identified in terms of the variations in Resilient Modulus and PM for each recycling agent. Recycled AC mixtures were prepared in the laboratory by Sarsam and AL-Zubaidi, 2015, [22] from aged AC using recycling agent (soft asphalt cement blended with silica fumes). Recycled and aged specimens were subjected to MD. It was revealed that the improvement in the resistance to MD of aged AC mixture after recycling was 76.17% as compared with the corresponding aged mixture before recycling. It was concluded that ITS of recycled mixture before MD declined by 67 % as compared with the control mixture. Apeagyei, 2014, [23] stated that the FN test is usually conducted to evaluate the performance of AC in its rutting resistance and may be used for quality assurance and quality control of AC. Walubita et al., 2013, [24] stated that the FN represents the actual initiation point of failure due to shear of AC mixture and indicates the points of inflection of the fitted load-deformation cycles relationship. It was revealed that FN can distinguish between various types of AC mixtures.

The aim of the present work is to assess the influence of MD and testing environments on the suitability of using FN in the evaluation of the efficiency of recycling process and suitability of (asphalt binder + carbon black) rejuvenator for enhancing the quality of RAP and controlling the deformation. RAP and recycled AC specimens are prepared and subjected to DITS at (25 and 40) °C in the PRLS testing chamber before and after practicing MD process. The variations in the FN and PM are evaluated among the testing conditions.

2. Materials and Methods

2.1. Rap material

The RAP mixture was obtained from the demolished AC from binder course layer of highway section at Karbala province. Table 1 exhibits its properties as per ASTM, 2015, [25] requirements. Figure 1 shows the gradation of aggregates. It can be noticed that gradation of RAP mixture is still within the required specification limits of AC binder course according to SCRB, 2003, [26] requirements. No sign of degradation is noticed.

Table 1. Properties of RAP mixture

Material	Property according to ASTM, 2015, [25]	Test results
Asphalt binder	Binder content %	3.84
	Bulk specific gravity	2.620
Coarse aggregate	Apparent specific gravity	2.760
	Water absorption (%)	0.83
	Percent of Fractured faces (%)	93
Fine aggregate	Bulk specific gravity	2.670
	Apparent specific gravity	2.810
	Water absorption (%)	1.52
Mineral filler	Percent passing sieve No. 200 (%)	97
	Specific gravity	3.10

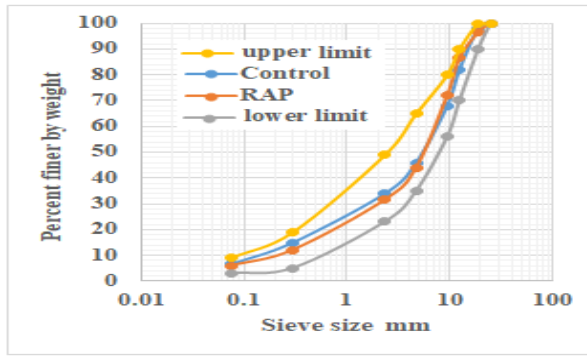


Figure 1. Gradation of aggregates for binder course as per SCRB, 2003, [26]

Figure 2 exhibits the variation in the physical properties between its control stage during construction and after being RAP after 20 years. It can be noticed that after the long service life, the binder content and Marshall flow declined by (18.3, and 15.4) % respectively while the Marshall stability and voids content increased by (62, and 45.7) % respectively. Stiffer AC was generated after the long service life of the pavement layer with lower flexibility and high susceptibility to cracking at low temperature and binder stripping due to higher voids content.

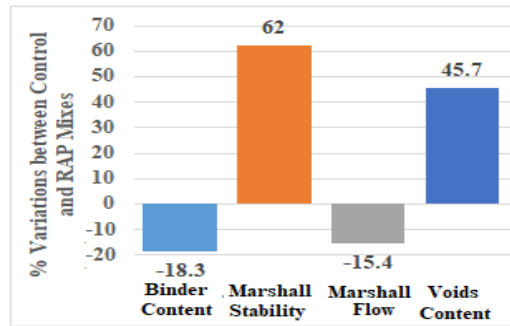


Figure 2. Variations in the physical properties between Control and RAP mixes

2.2. Carbon black

Table 2 presents the properties of carbon black powder as supplied by the manufacturer. It was obtained from local market.

Table 2. Properties of Carbon Black as provided by the Supplier

Property	ASTM, 2015, [25]	Test result
Residue on Sieve No. 35	D-1514	10
Pour density gm/liter	D-1513	352.4
Particle diameter (Nanometers)	-	300
Ash content %	D-1506	0.75
PH	D-1512	7.5-9
Specific Surface Area (m ² /gm)	D-6556	36
Oil absorption number	D-2414	122

2.3. Asphalt cement

Asphalt cement was obtained from Al-Durah oil refinery with penetration grade of (40-50). It was implemented for preparation of the rejuvenator. Table 3 exhibits its rheological properties. The physical properties of the binder are shown in Table 4.

2.4. Preparation of rejuvenator

The recycling rejuvenator was prepared in the laboratory; various percentages of carbon black were tried (0.5 to 3) % with 0.5 % increments. Asphalt cement was heated to 150 °C, and the carbon black was added gradually to the asphalt cement and mixed thoroughly until homogenous blend was obtained. Mixtures were tested for consistency, and the obtained optimum carbon black content was 1.5 % by weight of the binder. More details of the preparation process could be found in Sarsam and Mahdi, 2019, [27]. Table 3 presents the rheological properties of the rejuvenator. Table 4 exhibits the physical properties of the Rejuvenator.

Table 3. Rheological properties of asphalt cement and the prepared Rejuvenator

Property Value	AC (40-50)	Rejuvenator (binder + 1.5 % Carbon black)
Penetration Index (PI)	- 2.54	- 1.77
Temperature of Equivalent Stiffness (TES), (°C)	- 6	- 9
Viscosity Temperature Susceptibility (VTS), (centipoises/kelvin)	0.1494	0.1024
Penetration Viscosity Number (PVN),	- 1.0862	- 1.095
Stiffness modulus (N/m ²)	1.5 * 10 ⁹	1.2 * 10 ⁹

Table 4. Physical Properties of Asphalt Cement and Rejuvenator

Property Value	Test Conditions	ASTM, 205 [22] Designation No.	Asphalt cement	Rejuvenator (binder+1.5 % Carbon black)
Penetration	25°C, 100gm, 5sec	D5-06	43	38
Softening Point	-	D36-95	46	50
Ductility	25°C, 5cm/min	D113-99	140	132
Flash Point	Cleave land open cup	D92-05	269	218
Retained Penetration of Residue (%)	25°C, 100gm, 5sec	D5-06	57	51
Ductility of Residue	25°C, 5cm/min	D113-99	73	62
Loss on Weight	163° C, 50 gm, 5 hours	-	0.23	0.27

2.5. Preparation of AC specimens

The RAP was heated to 160° C, and various doses of the rejuvenator were tried (1 to 4) % with 1% increment. The optimum dose of the rejuvenator was 2 % by weight of the existing binder in the RAP based on testing of trial Marshall specimens for Volumetric properties and Marshall Stability and flow. More details on such trials and preparation of specimens may be referred to Mahdi and Sarsam, 2020, [28]. Table 5 exhibits the Marshall properties of RAP and Rejuvenated AC mixtures. A total of 24 Marshall specimens were prepared for the dynamic testing process of DITS using 75 blows of Marshall hammer on each face of the specimen. It can be noticed that more flexible mixture was obtained after implementation of rejuvenator. Specimens were tested in triplicate, and their average value was considered for further analysis. Such limited sample size may be used to preliminary prediction of FN and PM within the material ranges investigated and the testing conditions. The accepted standard deviation between the maximum and minimum values was 5 % and the average value of a minimum triplicate specimens was considered for the analysis for each testing temperature.

Table 5. Marshall and Volumetric properties of RAP and Rejuvenated AC mixtures

Properties	RAP	RAP + 2 % Rejuvenator
Asphalt content (%)	3.84	3.92
Stability (kN)	17.5	9.6
flow (mm)	2.9	3.08
Bulk density	2.320	2.324
Air voids (%)	5.1	4.4

Figure 3 presents the variations in the physical properties between RAP and Recycled mixes. It can be observed that the Marshall stability and voids content declined by (45.1, and 13.7) % after recycling with (asphalt binder + carbon black) and the binder content and Marshall flow increased by (2, and 4) % which indicates higher flexibility and lower stiffness.

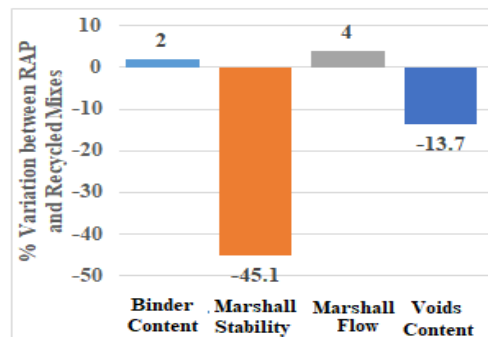


Figure 3. Variations in the physical properties between RAP and Recycled mixes

2.6. MD process

Part of the prepared AC Marshall specimens (RAP and recycled) was subjected to laboratory MD by immersion in a water bath for 120 minutes at 25° C. A vacuum of 3.74 kPa was applied for evacuation of the air in the voids of the AC specimens for 10 minutes so that 80 % saturation of the specimens could be obtained. The AC Specimens were placed in a freezer for a minimum of 16 hours at -18° C ± 1° C, then removed from the freezer and placed into water bath at 60± 1° C for 24 hours. AC specimens were removed from the water bath and were placed in another water bath at 25 ± 0.5 ° C for about 2 hours, and then they were tested in the PRLS at 25° C environment for DITS according to AASHTO T-283, 2014, [29].

2.7. Testing for DITS

Part of the prepared AC specimens (RAP and recycled) were subjected to DITS at 25° C environment with the aid of the PRLS. Another part of the prepared specimens was tested at 40° C environment using similar conditioning process of the specimens after practicing the MD. AC specimens were removed from the water bath and were placed in another water bath at 40 ± 0.5 ° C for about 2 hours, and then they were tested in the PRLS at 40° C environment for DITS. The Specimens were tested at constant stress level of 138 kPa. The constant loading frequency was 60 cycles per minute. The dynamic loading sequence for each cycle is 0.1 seconds of stress duration and 0.9 seconds of rest period. Figure 4 demonstrates the dynamic testing setup in the PRLS testing chamber. The accepted standard deviation between the maximum and minimum values was 5 % and the average value of a minimum triplicate specimens was considered for the analysis for each testing temperature. Specimens were tested

in triplicate, and their average value was considered for further analysis. The accepted standard deviation between the maximum and minimum values was 5 % and the average value of a minimum triplicate specimens was considered for the analysis for each testing temperature. Specimens were tested in triplicate, and their average value was considered for further analysis.



Figure 4. DITS test setup in the PRLS chamber

3. Results and Discussion

3.1. Variation in Marshall stiffness

Figure 5 exhibits the variations in Marshall Stiffness among the testing conditions; Marshall stiffness was calculated by dividing the Marshall stability by the Marshall flow. It can be observed that the stiffness of the control AC mixture during construction of the roadway was 3.08 kN/mm and it increased by 91.8 % after its service life of 20 years due to loss of volatiles which causes ageing. However, after recycling the AC mixture with the rejuvenator (binder + carbon black), the stiffness declined by 47.3 %. It can be revealed that the recycling process exhibits a positive influence on the quality of the AC mixture from the stiffness point of view.

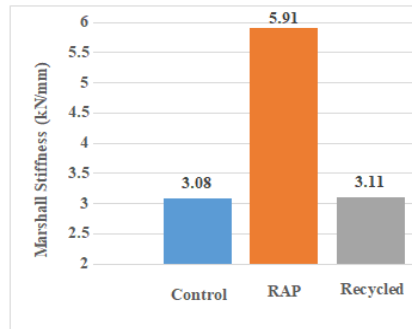


Figure 5. Variation in Marshall Stiffness among testing conditions

3.2. Influence of MD on FN and PM of RAP and recycled mixtures at 25°C

As demonstrated in Figure 6, the power mathematical relationships were presented in graph form between the PM and dynamic tensile strain cycles. The moisture damaged (conditioned) AC mixtures exhibit an increment in the PM and decline in FN as compared with the case before the MD process (unconditioned) regardless of the mixture type at 25° C testing environment. The impact of recycling of RAP before conditioning shows higher PM after the first load cycle by six folds than the RAP mixture while the variation was not significant at failure. The PM increases gently at initial stages of loading then rises sharply after the 10th repetition. However, after practicing the MD, similar trend of increment in PM could be noticed and the PM of recycled mixture is higher than that of RAP after the first cycle and at failure by (27, and 14) % respectively. On the other hand, the MD process exhibited an increase in the PM of (4.5, and one) folds for RAP and recycled mixes respectively after the first cycle of loading as compared with that before MD process. At failure, the PM of AC mixtures increased by (1.6, and 2.2) folds after MD for RAP and recycled mixtures respectively. As far as the FN of AC mixtures is concerned, recycling process exhibited decline in FN of 1.5 folds before conditioning and a decline of 45 % after conditioning. However, the MD process exhibited a decline of FN by (80, and 72.5) % for RAP and recycled mixtures respectively. Such performance of RAP agrees with the reported work by Zhang et al., 2013, [30]; Preethi and Ravichandran, 2025, [8]; and Sarsam, 2026, [2].

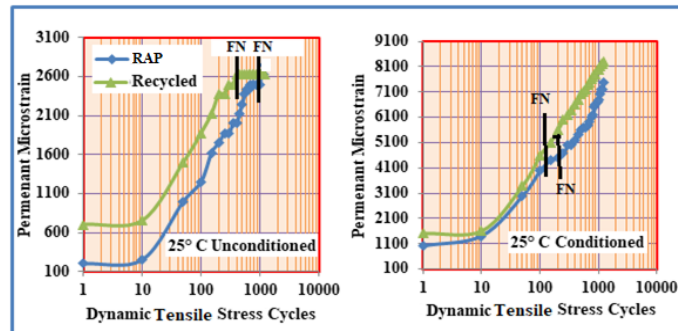


Figure 6. Influence of MD at 25° C environment

3.3. Influence of MD on FN and PM at 40°C

Figure 7 exhibits that the moisture damaged AC mixtures show an increment in the PM and decline in FN as compared with the case before the MD process (unconditioned) regardless of the mixture type at 40° C testing environment. The impact of recycling of RAP before conditioning shows higher PM after the first load cycle by ten folds than the RAP mixture while the variation was 1.25 folds at failure. The PM increases gently at initial stages of loading then rises sharply after 400 repetitions. However, after practicing the MD, similar trend of increment in PM could be noticed and the PM of recycled mixture is higher than that of RAP after the first cycle and at failure by (100, and 12) % respectively. On the other hand, the MD process exhibited variations in the PM between RAP and recycled mixes.

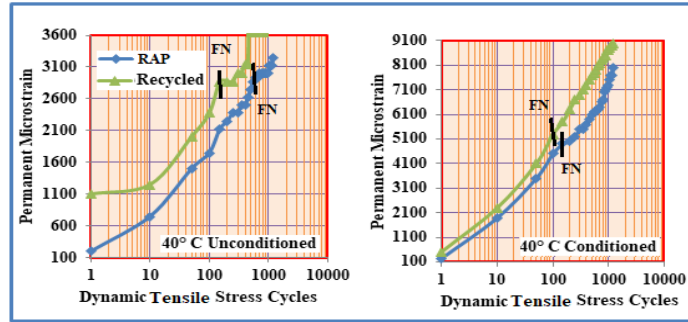


Figure 7. Influence of MD at 40° C environment

At failure, the PM after MD is higher than that before MD by (1.53, and 1.52) folds for RAP and recycled AC mixtures respectively. Recycling exhibited decline in FN of three folds before conditioning and a decline of 33.3 % after conditioning. However, the MD process exhibited a decline of FN by (75, and 33) % for RAP and recycled mixtures respectively. Similar findings were presented by Sarsam, 2023, [31]; Amirthalingam et al., 2013, [32]. The statistical analysis of data had provided power mathematical regression models which correlates the PM of AC mixtures with the dynamic tensile stress cycles for both testing environments before and after practicing MD process. Such obtained mathematical power regression models with high coefficients of determination (R²) and reasonable standard error of estimate (SEE) may be implemented for fast and preliminary prediction of the expected PM within the investigated material ranges and testing conditions. Due to the limited number of tested specimens, high R² exhibits empirical nature and limited domain. Table 6 exhibits the obtained mathematical power regression models. The intercept is presenting the PM and the slope represents the rate of change in the PM through the dynamic tensile stress cycles.

Table 6. Mathematical models of the PM-Dynamic tensile stress cycles relationship

Mixture type	Testing condition	Intercept	Slope	Mathematical model	Coefficient of determination (R ²)	Standard error of estimate (SEE)
RAP	Before MD @ 25 °C	180	0.3976	Y = 180 X ^(0.3976)	0.9434	0.103
	After MD @ 25 °C	926.5	0.2898	Y = 926.5 X ^(0.2829)	0.984	0.090
	Before MD @ 40 °C	295.6	0.3534	Y = 295.6 X ^(0.3534)	0.939	0.100
	After MD @ 40 °C	499	0.4030	Y = 499 X ^(0.4030)	0.945	0.103
Recycled RAP	Before MD @ 25 °C	663.5	0.2105	Y = 663.5 X ^(0.2105)	0.865	0.210
	After MD @ 25 °C	1239.6	0.2737	Y = 1239.6 X ^(0.2737)	0.982	0.095
	Before MD @ 40 °C	679.1	0.3156	Y = 679.1 X ^(0.3156)	0.849	0.270
	After MD @ 40 °C	804.6	0.3591	Y = 804.6 x ^(0.3591)	0.943	0.102

Where: Y= PM; X= dynamic tensile stress cycles

3.4. Influence of testing environment on FN and PM

For unconditioned state of AC mixtures, the increment of testing temperature from (25 to 40) °C exhibited decline in FN of AC mixtures by (40, and 62.5) % for RAP and recycled AC mixtures respectively. However, after practicing the MD, the FN declined by (25, and 16.6) % for RAP and recycled AC mixtures respectively. Such behavior may be related to the decline in the viscosity of the binder and increment in the flexibility in the structure of AC when the testing temperature rises. Similar results were found by Sarsam, 2022, [33]. Table 7 summarizes the variations in FN and PM among the various testing conditions.

Table 7. Summary of PM and FN among various testing conditions

Testing temperature	25 °C				40 °C			
	Unconditioned		Conditioned		Unconditioned		Conditioned	
Testing condition	RAP	Recycled	RAP	Recycled	RAP	Recycled	RAP	Recycled
AC Mixture type								
PM	2500	2600	7600	8200	3300	3600	8100	9100
FN	1000	400	200	120	700	150	150	100

3.5. Recycling index

The recycling index of RAP mixtures is a quantitative measure used to enhance the quality and evaluate the efficiency of rejuvenator material and its ability to self-repair the initiated microcracks and recover its mechanical properties after sustaining damage. It is typically expressed as a ratio or percentage of the material property after recycling to its original property of the RAP. It was determined for the various AC mixtures before and after MD based on the mathematical equation (1) and presented in Table 8. It can be noticed that the recycling index after practicing MD is higher than that before MD regardless of the testing temperature for FN and PM. However, the recycling index increases at higher testing temperature of 40 °C as compared to that at 25 °C regardless of the testing condition.

Recycling index for FN (%) = [FN after recycling / FN before recycling] x 100 % -----(1)

Recycling index for PM (%) = [PM after recycling / PM before recycling] x 100 % -----(2)

Table 8. Recycling index

Recycling index	Indices of DITS (%)
for FN before MD @ 25 °C	40
for FN after MD @ 25 °C	60
for FN before MD @ 40 °C	25
for FN after MD @ 40 °C	66
for PM before MD (at failure) under 25°C	104
for PM after MD (at failure) under 25°C	109
for PM before MD (at failure) under 40°C	109
for PM after MD (at failure) under 40°C	112

4. Conclusions

Based on the research findings, testing program, limited sample size, laboratory-scale applicability, and the material properties, the following conclusions may be introduced. At 25 °C testing temperature, the MD process exhibited a decline of FN by (80, and 72.5) % for RAP and recycled mixtures respectively. However, in the 40° C environment, the MD process exhibited a decline of FN by (75, and 33) % for RAP and recycled mixtures respectively. At failure, the PM of AC mixtures increased by (1.6, and 2.2) folds after MD for RAP and recycled mixtures respectively at 25 °C, while the PM after MD is higher than that before MD by (1.53, and 1.52) folds for RAP and recycled AC mixtures respectively at 40 °C. Before the MD process, the increment of testing temperature from (25 to 40) °C exhibited decline in FN of AC mixtures by (40, and 62.5) % for RAP and recycled AC mixtures respectively. However, after practicing the MD, the FN declined by (25, and 16.6) % for RAP and recycled AC mixtures respectively. The recycling index after practicing MD is higher than before MD regardless of the testing temperature for FN and PM. However, the recycling index increases at higher testing temperature of 40 °C as compared with that at 25 °C for PM regardless of testing condition. The stiffness of the control AC mixture during construction of the roadway increased by 91.8 % after its service life of 20 years the stiffness declined by 47.3 % after recycling.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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