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Impact of rest time on creep recovery of asphalt mixtures modified with calcined marl filler

Idorenyin Ndarake Usanga[1*], Fidelis Onyebuchi Okafor[2] and Chijioke Christopher Ikeagwuani[2]

Abstract

Recently, there has been a trend among pavement engineers and scientists to utilize natural mineral resources found in different parts of the world to develop and enhance sustainable infrastructure. One of such materials is calcined clay. However, the fatigue performance of asphalt mixtures made with these alternative materials needs to be properly studied. Due to its complex composition, asphalt concrete exhibits diverse non-linear characteristics when subjected to different conditions. As such, the impact of rest time, considering the effect of hardening relaxation and healing on the creep recovery of asphalt mixtures modified with calcined marl filler (CMF), has been evaluated in this present study. Thus, the locally sourced marl was pulverized and calcined to produce CMF. Different amounts of CMF were added to asphalt mixtures as a mineral filler, ranging from 0% to 100% by weight. Afterwards, the rheological properties of CMF mastic using a dynamic shear rheometer (DSR) were investigated. Notably, the outcomes of the experiments revealed compelling insights. Specifically, under the influence of 50% CMF modification, the asphalt mixtures exhibited a remarkable rutting resistance, with values reaching 12.7 kPa for unaged conditions and 16.1 kPa for aged conditions. Additionally, the results underscored an enhancement in the low-temperature characteristics of the bitumen mastic, which consequently contributed to heightened resistance against fatigue-induced damage. Furthermore, the statistical analysis, such as the student t-test, deployed to compare the creep recovery with and without rest time indicated that the creep recovery changes with the application of rest time. Hence, at long rest times, the hardening relaxation behavior reduces and the chances of healing increase, leading to a decrease in the amount of deformation in the samples.

Keywords Calcined marl filler, Creep recovery, Fatigue behavior, Rest time, Healing, Hardening relaxation

Introduction

Highway infrastructural development is considered as a key stimulus that drives the socio-economic growth of a nation [1]. This explains why most nations commit huge amount of resources to the construction and maintenance of highway facilities such as pavement. Regrettably, some pavement, despite the huge amount of resources they consume during their construction, usually show early signs of distresses that tend to undermine the safety of motorists or jeopardize the durability of the pavement itself leading to its deterioration [2]. The deterioration of pavement is a common sight in most developing countries [3], and it is caused by a plethora of factors ranging from increased traffic loads, poor selection of constituent materials, inadequate construction methods and so on. In Nigeria, for example, most flexible pavement develops surficial distress such as fatigue cracks which does not only widens over time but also permits the

*Correspondence:
Idorenyin Ndarake Usanga
idorenyinusanga@aksu.edu.ng
[1] Department of Civil Engineering, Akwa Ibom State University, Ikot Akpaden, Nigeria
[2] Department of Civil Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria

infiltration of moisture into its underlying layers leading to its deterioration. The fatigue cracks, which are accumulated tensile strains occasioned by repeated vehicular loads, usually develop at the bottom layer of an asphalt pavement thereby causing severe menace to the overlying layers [4]. Thus, it is therefore germane to utilize an effective approach for asphalt pavement construction so that it can withstand vehicular loads satisfactorily during its service life without developing fatigue crack failure. One of such approaches that can be used is the introduction of mineral filler in an asphalt mixtures design so that the mixtures strength can be enhanced.

Mineral filler is a material that passes through 0.075 mm test sieve in asphalt technology. It constitutes more than 6.5% of the volume of bituminous mixtures. Numerous studies implemented by different researchers and pavement engineers have demonstrated that mineral fillers have significant effect on the properties of hot mix asphalt (HMA) when blended with bituminous mixtures [5, 6]. Specifically, mineral fillers reduce void spaces, and improves the stiffness and density of a compacted asphalt mixtures leading to the prevention of failure in the service life of a pavement constructed with the asphalt mixture. Interestingly, several researchers as well as pavement engineers have advanced the course of the utilization of mineral fillers in asphalt mixtures design because of the huge benefit it offers particularly in the improvement of an asphalt pavement performance. Unfortunately, most mineral fillers used in practice, especially the conventional ones, are gradually being jettisoned by pavement engineers and technologists owing to their soaring cost. This has prompted researchers to resort to seeking alternative mineral fillers that can fulfill the twin action of pavement cost reduction and asphalt mixture properties improvement. Some of the commonly used alternative mineral fillers are industrial and agro-based materials such as rice husk ash [7], maize cob ash [8], sugar cane bagasse [9]; fly ash [10], cement kiln dust [11], marble dust [12]; ceramic tiles dust [13], steel slag [14], etc.

Recently, it has been established that pulverized and calcined clays, due to their pozzolanic properties, can be used as mineral fillers in asphalt mixture design. In fact, most calcined clays used by some researchers in literature have proven to be effective in the improvement of the properties of an asphalt mixture when blended with it. In a study conducted by Rondon-Quintana et al [15] on the improvement of the properties of asphalt mixture with a calcined expansive clay, bentonite, it was observed that the calcined bentonite significantly improved the properties of the asphalt mixtures. The calcined bentonite, which was used as partial replacement of a natural filler, was reported to maintain the optimum bitumen content of the asphalt mixtures. Similar study executed by Marin-Garcia et al. [16] also lent credence to the efficacy of calcined clay in the improvement of the properties of asphalt mixtures. In the study by Marin-Garcia et al. [16], calcined kaolin, which was also used as partial replacement of a mineral filler, was observed to enhance the resilience of an asphalt mixture and also decreases its moisture susceptibility. In a related study conducted by Zghair et al [17] to examine the influence of nano metakaolin filler on the rheological characteristics of an asphalt binder produced by blending the nano metakaolin with 1, 3 and 5% of 60/70 penetration grade, it was observed that the addition of 5% nano metakaolin filler was suitable for the enhancement of the rheological behavior of the binder.

Notably, most thermally treated clays are commonly utilized in civil engineering for building construction, owing to the presence of calcite that enhances their pozzolanic properties [18]. A typical example of such type of clay is Marl which occurs naturally as mudstone. It has varied clay and calcium carbonate content ranging from 35 to 65%, It is usually referred to as "poor clay" owning to its high lime content. It is neither suitable in its natural form for most standard clay applications nor for the construction of buildings. However, when treated thermally, it can be transformed into a very good pozzolan because of its high level of calcite [19, 20]. The utilization of calcined marl as a filler in asphalt mixtures is driven by its beneficial pozzolanic properties. Calcined marl, when incorporated into asphalt mixtures, can enhance various performance aspects due to its ability to contribute to the formation of stronger and more durable binder-aggregate bonds. Its pozzolanic nature allows it to react with the binder, creating a supplementary binding matrix that improves the cohesion and adhesion of the asphalt mixture components [21]. This transformation has motivated quite a few researchers to explore areas of its usefulness in the construction industries. In a recent study implemented by Danner et al [22] to evaluate the feasibility of utilizing calcined marl for the production of high strength mortar, it was submitted that calcined marl, which was added in varying percentages ranging from 0 to 60%, improved the strength of the mortar produced with it. The improvement was rightly adduced to the filler and pozzolanic effects offered by the calcined marl. As indicated in the foregoing few reviewed literature, it is evident that calcined marl, because of its filler and pozzolanic potential, can be used as a filler, as attempted in this study, for the improvement of the fatigue behavior of asphalt mixture.

The fatigue behavior of asphalt can be predominantly seen in the intermediate temperature zone that ranges between 0 and 45°C [23] At this specific temperature, when an asphalt mixture is subjected to repeated loading, the structure of the asphalt undergoes changes that are linked to considerable microdamage. The development of microdamage in asphalt mixtures, which is influenced by the viscoelastic properties of the mastic, results in the decline of mechanical properties such as stiffness and strength. As the process continues, this damage can eventually lead to complete failure of the material. While unloading and resting, the relaxation of stress concentration in asphalt concrete is directly related to its viscoelastic properties. At the same time, microdamage in the material is healed during this process [24]. Also, during this repeated loading, the asphalt mixture's initial response to deformation indicates a rearrangement of the mixture through densification and restructuring of its internal microstructure, resulting in an increase in its stiffness. However, when the load is removed and the mixture is allowed to rest, the structure of the asphalt begins to rearrange itself in response to the previously applied load. This rearrangement process leads to a reduction in stiffness and an increase in flexibility over time, even in the absence of any external load or stress. The entire process of loading and resting causes a phenomenon known as hardening relaxation.

Several studies [25–28] have demonstrated that when rest time is introduced between loading cycles, the asphalt specimen is more likely to deform than when subjected to continuous loading. During creep-recovery tests, the aggregate components in the specimen are compressed together while the bitumen is compressed between them, causing a shift in orientation and position (known as hardening). Subsequently, during the rest period, the compressed bitumen starts to release residual stress as the aggregates redistribute and shift in position and slope, leading to a partial recovery of the previous viscoplastic hardening energy, which is known as relaxation.

In contrast, numerous studies [24, 29–32] have indicated that incorporating rest periods between loading cycles can enhance asphalt material properties and result in a longer fatigue life compared to a continuous load application. Various studies have demonstrated that longer rest periods during beam fatigue tests consistently lead to a longer fatigue life [33, 34]. The term "self-healing" refers to the ability of materials to regulate themselves and reduce damage levels after the removal of factors that cause failure during unloading and rest intervals. In the case of asphalt concrete, a process known as healing competes with a process of deterioration [35].

In the light of the aforementioned literature, incorporating rest time in the repeated loading of asphalt mixtures appears to have both a beneficial and detrimental effect. Adversely, it can cause hardening relaxation and the potential for increased deformation. Positively, it can promote self-healing behavior that is consistent with the inherent properties of mastic, resulting in enhanced asphalt properties and fatigue life. The current literature on compressive repeated loading of asphalt mixtures has primarily focused on the incorporation of rest time in experiments using conventional materials as filler. However, there is a research gap regarding the investigation of the effect of rest time on hardening relaxation and healing using alternative materials as filler. This gap in knowledge is significant as the use of alternative materials as fillers is becoming increasingly popular in the construction industry due to their environmental and economic benefits. Therefore, there is a need for further research to explore the influence of rest time on the mechanical behavior of asphalt mixtures incorporating alternative materials as filler, specifically in terms of hardening relaxation and healing. Thus, this study investigates the impact of rest time on creep recovery of asphalt mixtures modified with calcined marl filler as filler and subjected to uniaxial repeated compressive loading.

Materials and methods

Materials

The study used 60/70 penetration grade bitumen binder sourced from Osmoserve Global Services Asphalt Batching Plant in Eket, Nigeria, which is commonly used in bituminous mixtures in Nigeria due to its suitability for various temperatures. Table 1 summarizes the physical properties of this binder. The coarse aggregate used in the study was obtained from a quarry industry in Akamkpa, Cross River State, Nigeria, and consisted of crushed granite stone with a maximum size of 19mm. The fine aggregate used was a natural river collected from a dredging site in Afaha Ikot Osom, Nigeria. The physical properties of the coarse and fine-grained aggregates used in the study are presented in Table 2. The study also employed granite stone filler (GSF) and calcined marl filler (CMF) as mineral fillers. GSF was obtained from a quarry in Akamkpa, Nigeria, while CMF was produced from marl stone collected from a natural deposit in New

Table 1 Physical properties of 60/70 bitumen

Test	Standard Adopted	60/70 Value
Penetration at 25 °C (0.1 mm)	ASTM D5 [38]	67
Softening point (°C)	ASTM D36 [39]	48.5
Brookfield rotational viscosity at 135^{0}C (MPa.s)	ASTM D4402 [40]	560
Flash Point (°C)	ASTM D92 [41]	250
Specific gravity (g/cm^3)	ASTM-D70 [42]	1.02

Table 2 Physical properties of coarse and fine aggregates

Test	Standard Adopted	Value
Coarse		
Angularity (%)	ASTM D5821 [43]	98/97
Elongated and flat particles (%)	ASTM D4791 [44]	6.94
Soundness (%)	ASTM C88 [45]	0.069
Specific gravity	ASTM C127 [46]	2.564
Los Angles abrasion (%)	ASTM C131 [47]	23.7
Water absorption (%)	ASTM C127 [46]	1.98
Fine		
Absorption	ASTM C131 [47]	1.77
Specific gravity	ASTM C128 [48]	2.60
Sand equivalent	ASTM D2419 [49]	77.01
Clay content (%)	ASTM C142 [50]	0.61
Angularity (%)	ASTM C1252 [51]	48.71

Netim, Cross River State, Nigeria. The marl stone was subjected to oven drying at 105°C for 6 hours, pulverized, and calcined at 600°C for 2 hours. The temperature for calcination was chosen based on previous research indicating that clay undergoes dehydroxylation and dehydration between 500°C and 700°C [36]. The calcined marl was then left to cool before being sieved through a 75 µm standard test sieve. The particles that passed through the sieve, referred to as CMF, were stored in a moisture-proof container until used. The physical properties of the GSF and CMF fillers are displayed in Table 3, while the chemical composition of CMF, as determined by X-ray fluorescence, is presented in Table 4. The sum of the percentages of silica (SiO2), alumina (Al2O3), and ferric oxide (Fe2O3) in CMF is 71.225%, which is above the 70% requirement for a class N pozzolan, according to ASTM C618 [37].

Method

Mixture gradation

The study utilized an asphalt mix that meets the midpoint gradation criteria specified in the Nigerian General Specification for Highways and Bridges (1997) for the wearing course layer. The maximum aggregate size used in the mix was 19mm, and Fig. 1 shows the gradation limit for the aggregate used in the wearing course asphalt.

Table 4 Chemical Composition of CMF

Chemical Composition	Content (%)
Silicon oxide (SiO_2)	49.60
Aluminum oxide (Al_2O_3)	13.234
Iron oxide (Fe_2O_3)	8.391
Calcium oxide (CaO)	14.21
Magnesium oxide (MgO)	1.599
Potassium (K_2O)	3.266
Sodium (Na_2O)	0.167
Titanium oxide (TiO_2)	0.881
Sulfur trioxide (SO_3)	2.354

Experimental design and specimen fabrication

At first, the optimum bitumen content (OBC) for each type of asphalt mix was determined using the Marshall mixing design technique. The mineral filler, GSF, was replaced with CMF at different weight percentages of 0%, 25%, 50%, 75%, and 100%, making up 6% of the aggregate weight. These mixtures were labeled as M0, M25, M50, M75, and M100. Each of these mixtures was prepared by gradually increasing the bitumen content from 4.5% to 6.5% in 0.5% increments. The OBC was determined to be 5.67 for M0; 5.72 for M25; 5.81 for M50; 5.96 for M75, and 6.10 for M100. To get the laboratory specimens ready for the uniaxial repeated compressive loading test, cylindrical asphalt specimens with a 100 mm diameter and a height of 150 mm were prepared using their respective OBC and compacted using a Marshall compactor at 75 blows on each side of the specimen to obtain 4% void in accordance to ASTM D1559 [55].

Rutting factor and fatigue resistance of mastic

Mastic is a composition of mineral filler and bitumen, mixed in specific proportions. Understanding the interaction between these two components can reveal the effect of the mineral filler on the rheological behavior of bitumen and its overall performance in Hot Mix Asphalt (HMA). To ensure that the asphalt flows correctly and that the fillers reach the blending temperature, the researchers heated GSF, CMF, and bitumen separately in an oven to a temperature of 150°C prior to conducting the study. The fillers and bitumen were

Table 3 Physical Properties of GSF and CMF fillers

Test	Standard adopted	GSF value	CMF value
Specific gravity (g/cm^3)	ASTM C854 [52]	2.58	2.95
Specific Surface area (m^2/kg)	ASTM C204 [53]	420	1620
Percentage passing sieve No. 200	ASTM D546 [54]	92	100

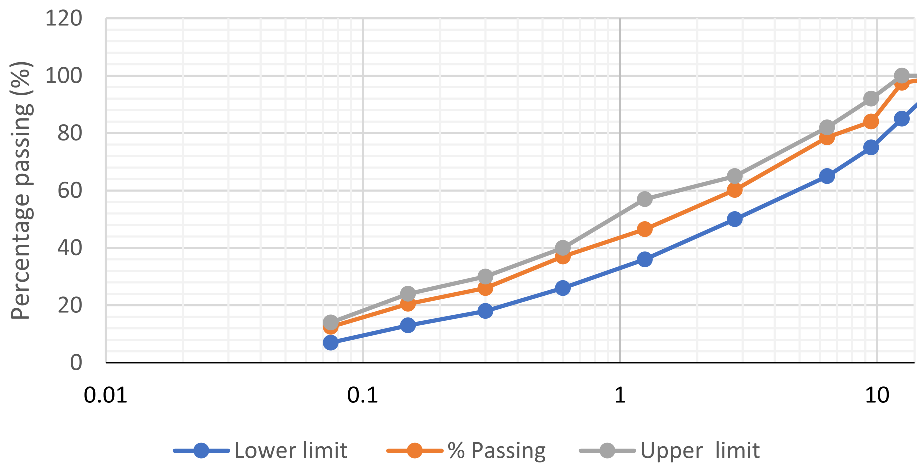

Fig. 1 Aggregate gradation curve

Table 5 Mastic proportioning and abbreviations

Asphalt Mastic	Abbreviation
Based bitumen (Pen 60/70)	Pen 60/70
Pen 60/70 + 6% GSF	100 GSF
Pen 60/70 + 4.5% GSF + 1.5% CMF	75/25 GSF – CMF
Pen 60/70 + 3% GSF + 3% CMF	50/50 GSF – CMF
Pen 60/70 + 1.5% GSF + 4.5% CMF	25/75 GSF – CMF
Pen 60/70 + 6% CMF	100 CMF

then mixed using a high-shear mixer at a speed of 4000 rpm for 40 minutes at 150°C, according to the proportions specified in Table 5, to guarantee the uniform dispersion of the fillers within the bitumen. To evaluate the rheological properties of the mastic, a Dynamic Shear Rheometer (DSR) was used in accordance with AASHTO T-315 [56]. The tests were performed at four different temperatures, namely 58°C, 64°C, 70°C, and 76°C, to replicate the temperature at the testing location. The upper and lower plates of the DSR were first heated to the required testing temperature. The specimens were then placed between the plates, and they were brought together to achieve the desired testing gap. The testing frequency was maintained at 10 rad/s, as specified in the test. Using eq. (1), the DSR software calculated the maximum applied stress (σ), maximum strain (τ), and complex shear modulus (G*). The phase angle (δ) was determined by the time difference between the occurrence of σ_max and τ_max.

$$G^* = \frac{\sigma_{\max}}{\tau_{\max}} \tag{1}$$

Where, σ_max is the maximum stress; τ_max is the maximum strain.

To assess the potential for rutting, the rutting factor (G*/Sin(δ)) of the binder was calculated. Binders with good resistance to rutting should have high elastic properties, which would result in a high rutting factor. Mastic was evaluated in three states: unaged, short-term aging using Rolling Thin Film Oven (RTFO aged), and long-term aging using Pressure Aging Vessel (PAV aged). The minimum value of G*/Sin(δ) for an unaged binder was 1.0 kPa, while for an RTFO-aged binder, it was 2.2 kPa. The RTFO mastic was tested at the maximum temperature on a 25 mm steel base plate with a 1000 mm gap.

Creep test of mastic using a bending beam rheometer (BBR)

The BBR test method was used to assess the low-temperature performance and vulnerability of bitumen mastic to thermal cracking. The test was performed using a BBR (Applied Test Systems) in accordance with AASHTO T313 [57]. The test was conducted at three different temperatures, namely 0°C, -6°C, and -12°C. Bitumen beams, which were 127 mm in length, 6.4 mm in thickness, and 12.7 mm in width, were submerged in a temperature-controlled bath for one hour. After preloading, a constant load of approximately 100 g was applied to the rectangular beam, which was supported on stainless steel half rounds on both ends. The deflection from the center was measured continuously, and the rate of creep (m) and stiffness of creep (S) were calculated at various loading times ranging from 8 to 240 seconds.

Loading cycles and rest periods

In this study, loading cycles and rest time was determined through trial continuous loading of specimens. The specimen was mounted in a Hydraulic Compression Testing Machine, which can apply controlled loads and measure displacements. The initial dimensions of the specimen (gauge length and cross-sectional area) are precisely measured before applying a constant load of 400 kPa which induces deformation in the specimen. As the load is applied, the testing machine simultaneously measures the corresponding deformation (strain) in the specimen at various time intervals according to ASTM C39 [58]. The loading cycle and rest time were selected after the initial elastic deformation, where the specimen remained undamaged. During the initial stage of the deformation, the specimen experiences elastic deformation, meaning that it can fully recover its shape when the load is removed, and no permanent damage occurs. As the loading continue, the asphalt specimen moves into the next stage, where microdamage starts to occur. Microdamage refers to small, subtle changes in the material's structure and properties due to repeated loading. Therefore, the loading cycle and rest period were chosen to be twice the value at the end of the initial stage of deformation. The reason for choosing twice the value of the initial deformation as the rest time is likely to ensure that the specimen has sufficient time to heal between loading cycles. By having a longer rest time, the microdamage is given more time for healing, which can provide valuable insights into the material's viscoelastic properties and to consider the effect of both hardening relaxation and healing.

Creep recovery test of asphalt concrete specimen

Creep-recovery tests in this study was conducted using Hydraulic Compression Testing Machine (ISO VG 32 + 68) model with linear variable differential transformer (LVDT) to evaluate the creep and recovery behavior of asphalt mix samples. The test samples were prepared following ASTM D1074 [59] standards, with each dimension of specimen 100 mm diameter and 150 mm height. The air void content of the test samples was maintained at 4% to ensure consistency. For each experimental condition, three (3) replicates specimens were prepared to ensure statistical reliability and accuracy of the results. When considering the creep recovery of asphalt mixtures with rest time, it means that the material is subjected to a load, and then the load is removed, allowing the mixture to rest or recover for a certain period before measuring its deformation recovery. This phenomenon is useful in understanding hardening relaxation and healing behavior of the asphalt material under cyclic loading conditions. On the other hand, creep recovery test without rest time, the asphalt mixture is loaded for a certain period, and then the load is quickly removed, followed by an immediate measurement of the material's deformation recovery. This phenomenon only evaluates hardening relaxation and not consider the effect of healing behavior of the asphalt material. In the testing arrangement, repeated compressive loading was applied for each loading cycle with and without rest. The axial strain of the samples was determined by measuring it using two LVDTs placed on the sample. To study the effect of hardening relaxation and healing in creep recovery, it is pertinent to consider intermediate temperature and a long resting period, as previously reported by Moghadas et al [23]. This is because at intermediate temperature, the specimen represents the typical pavement temperature of many regions, minimizes the thermal gradient, and reduces the risk of thermal cracking. Most importantly, at intermediate temperatures, there is a balance between the fluidity and stiffness of the asphalt, which can lead to optimal healing behavior due to the diffusion of healing agents and the rearrangement of molecules within the asphalt. Consequently, the tests were conducted at a temperature of 25°C. The number of cycles and rest period were selected based on continuous loading. The time in seconds that the specimens show significant strain (response to deformation) is considered the loading cycle, and twice the loading cycles were considered to evaluate the impact of the rest time of each mixture. The choice of this rest period allows for the consideration of both hardening relaxation and healing, which can improve the accuracy and representativeness of the test results. Prior to commencing the tests, the specimens were placed in the environmental chamber of the UTM equipment for a minimum of one hour to allow for thermal stabilization of the specimens. Figure 2 shows the experimental setup and the creep recovery measured using eq. (2).

$$\mathrm{R} = \frac{\varepsilon_r}{\varepsilon_c}\, x\ 100\% \tag{2}$$

Where, R is the creep recovery (%); ε_r is the creep strain measured during the recovery phase of the test;

Fig. 2 Experimental setup

ε_c is the total strain measured during the loading phase of the test.

To evaluate the significance level within the data sets for creep recovery results of asphalt mixtures with and without rest time, confirmatory tests such as the student t-test were performed.

Result and discussion

Rutting factor and fatigue resistance

The study investigated the rheological behavior of bitumen and mastic by using the rutting factor to determine their stiffness properties. The results of the rutting factor for unaged bitumen-mastic at different test temperatures are presented in Fig. 3, which shows that adding CMF to conventional filler improves the rutting resistance of the mastic. At 50% CMF modification, the rutting factor increased by 43% compared to 100% GSF mastic. However, at 100% CMF, the rutting factor was reduced beyond that of conventional mastic, suggesting that CMF can enhance the rutting resistance of asphalt concrete when partially replaced. The addition of CMF helps to prevent rutting by acting as an anti-rutting additive due to the presence of CaO. The study also found that 100% CMF mastic may become deformed due to the absorption of bitumen by CMF, reducing the stiffness properties of the mixture.

Figure 4 shows that RTFOT-aged bitumen mastic with 50% CMF has a higher value of G*/Sin δ compared to 100% GSF mastic, indicating that the addition of CMF can withstand the higher temperature and oxidation rate

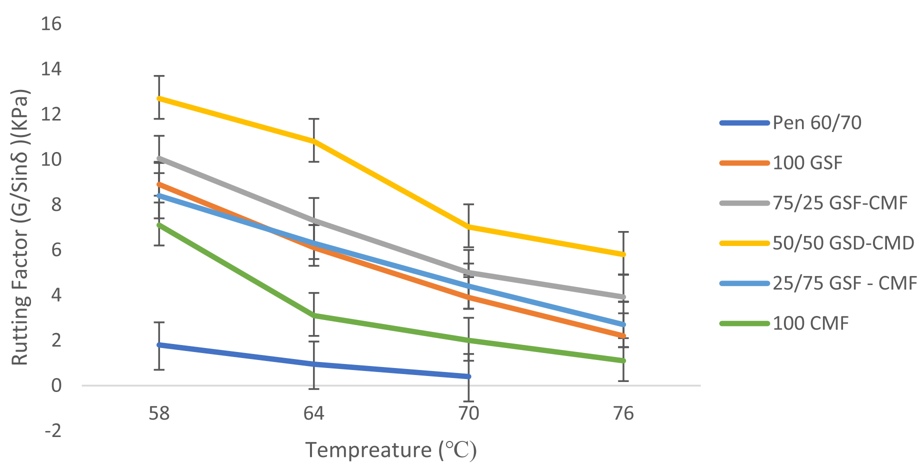

Fig. 3 Rutting factor of mastic at unaged condition

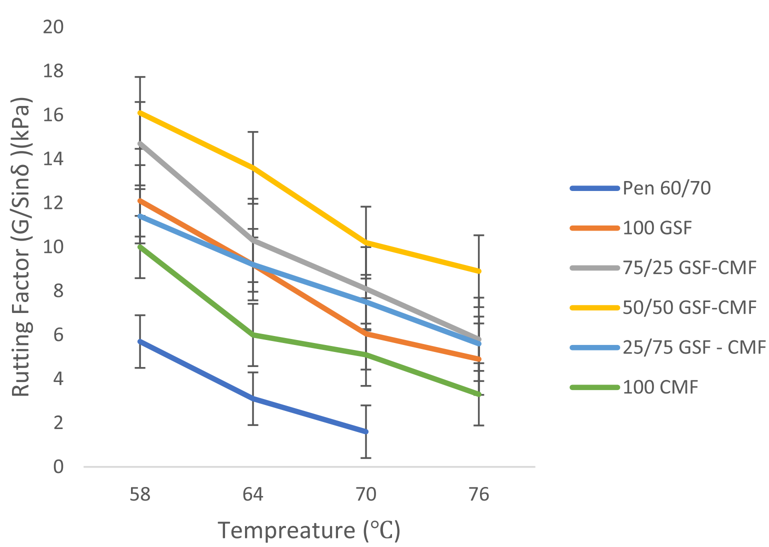

Fig. 4 Rutting factor of mastic at RTFOT-aged condition

associated with asphalt concrete production, transportation, and compaction. The long-term aging test using PAV showed different values of fatigue resistance of bitumen mastic at different temperatures, as shown in Fig. 5. The study found that the fatigue resistance of 50% modified conventional filler with CMF was higher than 100% GSF, which is consistent with previous studies [60]. However, at 100% CMF in the bitumen, the fatigue resistance decreased below that of conventional filler mastic. This suggests that adding CMF to conventional GSF improves the stiffness properties of mastic due to the pozzolanic content in CMF. However, completely replacing conventional filler with CMF makes the mastic excessively dense, difficult to compact, and prone to crack initiation and growth.

Creep rate and stiffness

Figures 6 and 7 depict the stiffness (S) and creep rate (m) of PAV-aged bitumen mastic. A low value of S and a high value of m indicate that the bitumen mastic is less prone to cracking at low temperatures and has a lower level of stress relaxation performance. According to AASHTO M320 [61], the S value should be less than 300 MPa, and the m value should be more than 0.3. Figure 6 demonstrates that adding filler to bitumen increases its stiffness at low temperatures, and a mixture of 50% CMF and 50% GSF produces a lower stiffness value in mastic than 100% GSF mastic. However, fully replacing GSF with CMF results in a highly cohesive mix due to the large specific surface area of CMF. Figure 7, which illustrates the creep rate, shows an inverse trend in the creep stiffness,

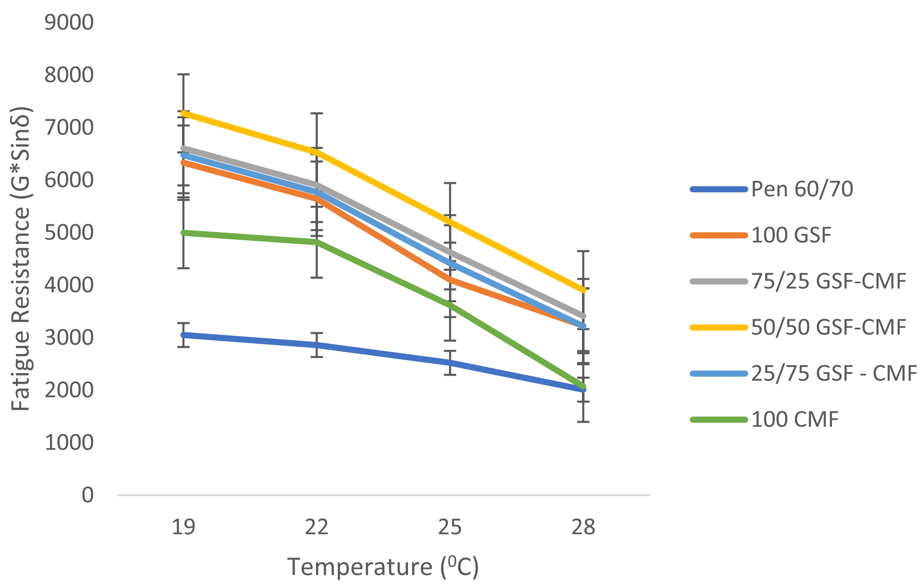

Fig. 5 Fatigue resistance of RTFOT-PAV aged bitumen mastic

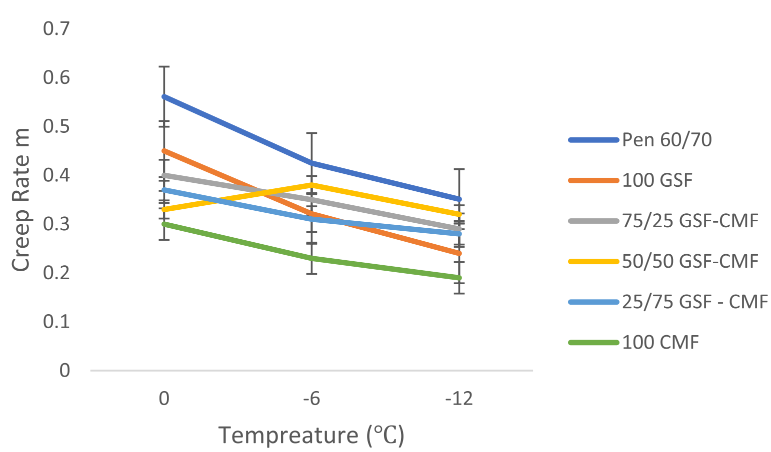

Fig. 6 Creep rate m- temperature relationship of mastic

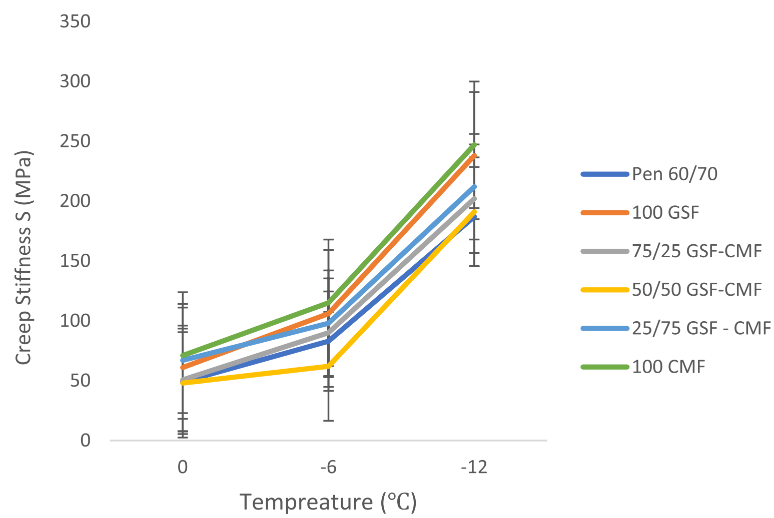

Fig.7 Creep stiffness S-temperature of mastic

indicating that adding a moderate volume of CMF can improve the relaxation behavior of asphalt concrete at low temperatures.

Loading cycles and rest periods

The loading cycles and rest time for each mixture were loaded continuously, and the response is shown in Fig. 8. It can be observed in Fig. 8 that at around 9,000–12,600 seconds (or 90,000–120,600 cycles), the mixture specimens go through the next phase of deformation. During the initial stage of deformation, the sample sustains no damage, but micro-damage can only occur once the sample enters its second stage of deformation. Table 6 presents the loading cycles and rest time for each mixture. It can see that the initial elastic deformation is different for each mixture. This suggests that the mixtures have different levels of initial elasticity, and they behave differently under initial loading conditions. The loading cycle represents the time taken for each mixture to undergo initial elastic deformation. Double

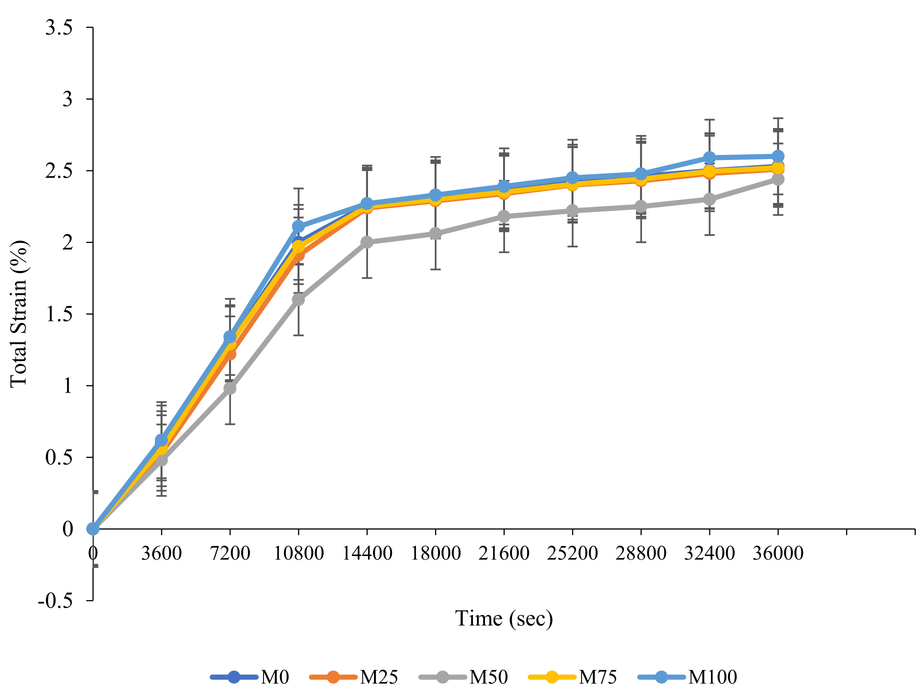

Fig. 8 Response of continuous loading of specimens

Table 6 Loading cycles and rest time

Mixture	Loading cycle/rest time
MO	18,000
M25	18,700
M50	21,600
M75	18,500
M100	17,300

Table 7 Response of asphalt mixtures to creep recovery

Asphalt Mixture		Creep Recovery	
		Without rest time	With rest time
M0	Mean value	48	54
	Standard deviation	3.12	3.3
	CV (%)	6.5	6.1
M25	Mean value	49.2	55.8
	Standard deviation	2.95	3.1
	CV (%)	5.9	5.6
M50	Mean value	53.1	59.3
	Standard deviation	3.4	3.3
	CV (%)	6.4	5.6
M75	Mean value	50.7	56
	Standard deviation	3.2	3.06
	CV (%)	6.3	5.4
M100	Mean value	43	46
	Standard deviation	2.99	3.18
	CV (%)	5.9	6.9

the value of the time interval was reported as loading cycle and rest time in Table 6.

Creep recovery of asphalt concrete specimens

The response of asphalt mixtures to creep recovery is presented in Table 7, and the loading pattern for experimental data of creep and recovery is shown in Fig. 9. The percentage recovery of the specimens with and without rest time is shown in Fig. 10. As illustrated in Fig. 10, creep recovery increases with the addition of CMF, indicating resistance to permanent deformation and thus greater resilience to fatigue damage. However, beyond a 50% concentration of CMF in the mixture, the value decreases and recorded the lowest recovery when the mixture was completely replaced with CMF, showing that the mixture is susceptible to deformation and crack development. The trend in the results can be attributed to the high contents of silica in GSF and alumina in CMF as presented in Table 4. These compositions can influence the rheological properties of the bitumen leading to improved viscosity and elasticity of the bitumen-filler blend, which in turn can enhance the material's resistance to deformation [62] and promote better recovery. However, at high dosages or full replacement of CMF, the larger surface area and the presence of CaO in CMF make the mixture excessively dense and stiffer, which can actually increase the creep recovery of the asphalt mixtures. Moreover, it can be observed in both Table 7 and Fig. 9 that all the mixtures improve the creep recovery when rest time is applied. In fact, it is suggested that by applying rest time, the impact of hardening relaxation on the deformation potential is minimized due to a more significant healing effect [23]. At 50% modification of asphalt mixture with CMF filler, the mixture tends to develop a higher resistance to deformation and fatigue damage, indicating the existence of strong adhesive bonding

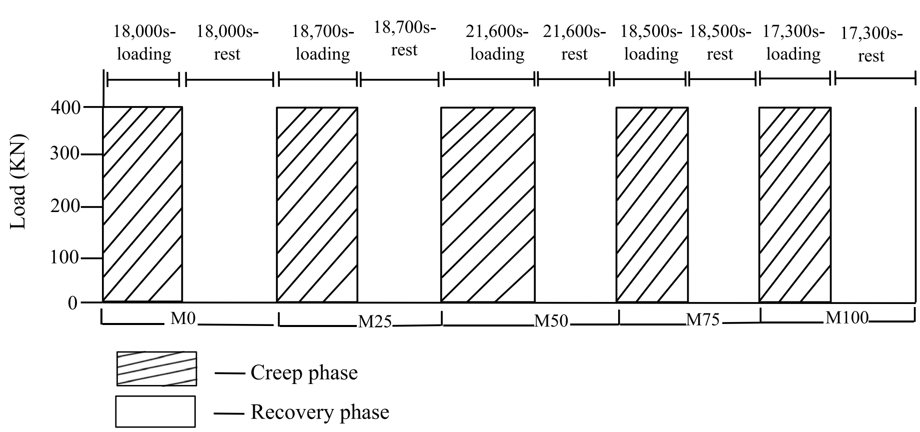

Fig. 9 Experimental data of creep and recovery phase

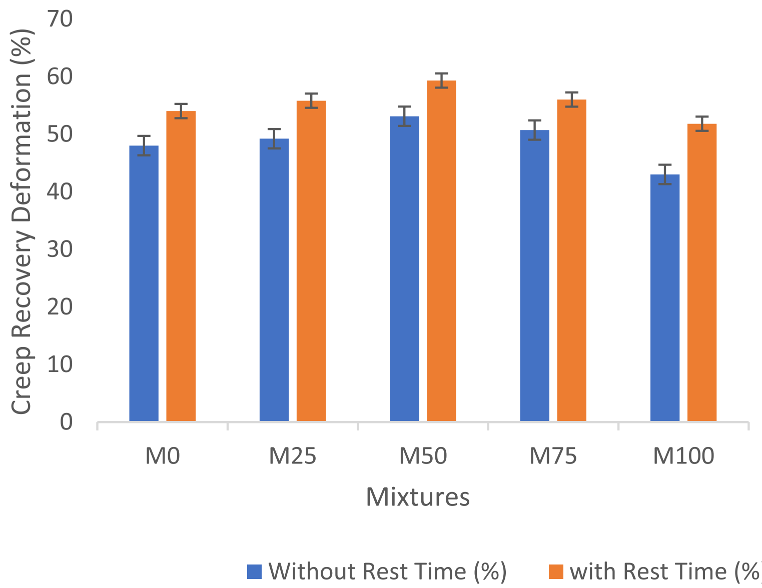

Fig. 10 Creep recovery of specimens

resulting from the larger surface area of CMF and the silica content of GSF. Hence, for viscoplastic deformation to take place, the repeated loading must overcome the bonding strength; otherwise, the material has the tendency to recover from the initial strain.

Testing and validation of results

The statistical significance of the obtained results from the t-test analysis holds paramount importance in determining the validity of our research findings. The benchmarks for accepting or rejecting the null hypothesis, established through the significance level (α) of 0.05, play a pivotal role in this evaluation. In the context of our t-test analysis, the null hypothesis posits that there is no significant difference between the means of the two compared groups, while the alternative hypothesis suggests that a significant difference indeed exists. The *p*-value generated by the t-test serves as a crucial indicator in making this determination. When the *p*-value is less than the predetermined significance level (α), which in our case is 0.05, it signifies that the observed difference between the means is statistically significant. Consequently, we reject the null hypothesis and accept the alternative hypothesis, implying that the observed disparity between the two groups' means is not due to chance variations but rather a genuine distinction. From Table 8, which summarizes the outcome of our t-test analysis, it can be observed that the calculated *p*-value (two-tailed) is indeed less than the designated significance level (α) of 0.05. This alignment between the *p*-value and the significance level reinforces our earlier explanation: the difference in means between the two groups is not merely due to chance but holds statistical significance.

Conclusion

The creep recovery and fatigue behaviors in asphalt mixtures depend on the viscoelastic properties of the mastic. The viscoelastic behavior of asphalt mixtures is typically characterized by measuring their creep and recovery responses under repeated loading. When rest time is incorporated into the creep recovery analysis, it allows for the measurement of the time-dependent recovery behavior of the asphalt mixture after a certain period of rest following the application of a repeated load. As such, an alternative material in the form of CMF can be used to modify the viscoelastic behavior of asphalt mixtures. This study evaluated the combined impact of hardening relaxation, and healing on asphalt

Table 8 Statistical validation of results

Description	Mean	Variance	t-stand	P(T<=t)	T critical one tail	P(T<=t) two tail	T critical two tail
Without rest time	48.8	14.135	-3.15747	0.006784	1.859	0.013588	2.306
With rest time	55.38	7.662					

mixtures modified with CMF, by the application of long rest period at an intermediate temperature. Based on the results of the analysis and test conducted, the following observation can be drawn;

- According to X-ray fluorescence analysis, the chemical composition of the calcined marl filler indicates that it is a pozzolan and meets the criteria for a class N pozzolan specified by ASTM 618.
- The use of 50% calcined marl filler in asphalt concrete resulted in 12.7 kPa and 16.1 kPa for unaged and aged values for rutting factor. Furthermore, this modification showed a notable enhancement in fatigue resistance compared to the conventional mastic.
- According to the results of the BBR test, incorporating CMF-modified asphalt into the mixture improves relaxation behavior in low-temperature conditions and increases resistance to cracking.
- At 50% modification of asphalt mixture with CMF filler, the mixture tends to develop a higher resistance to deformation and fatigue damage when compared to GSF filler.
- All the mixtures improve the creep recovery when rest time is applied. However, mixtures modified with 50% CMF recovered more from deformation indicating 59.3%.
- According to the statistical analysis using a student t-test, there is a significant difference between the means of the two groups. This indicates that the application of rest time minimizes the impact of hardening relaxation on the deformation potential, leading to a more pronounced healing effect.

Authors' contributions
All authors contributed immensely to the study in the aspect of conceptualization, methodology, analysis, validation and manuscript writing. Formal analysis of laboratory outcome was jointly carried out by all the authors [Idorenyin Ndarake Usanga], [Fidelis Onyebuchi Okafor], [Chijioke Christopher Ikeagwuani]. Conceptualization of the work, laboratory investigations, results analysis and writing of the first draft of the manuscript was performed by Idorenyin Ndarake Usanga. Laboratory investigation, data analysis and substantial technical contribution in reviewing and editing the work was performed by Chijioke Christopher Ikeagwuani. Laboratory investigation, data analysis and vetting of the draft manuscript was performed by Fidelis Onyebuchi Okafor. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated and analyze during the study are included in the published article.

Declarations

Ethics approval and consent to participate
Ethical approval not applicable.

Competing interests
The authors declare no competing interests.

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References
1. Ng C, Law T, Mohd J, Subramaniam K (2019) Road infrastructure development and economic growth. IOP Conf Series 512:012045
2. Edigbe J (2005) Influence of Pvement Distress on Capacity Loss and Their Implications for PCE, A Ph.D Thesis Submitted to the Department of Civil Engineering. University of Strathclyde, Glasgow
3. I. Usanga, C. Ikeagwuani, R. Etim and I. Attah, "Predictive Modelling of Modified Asphalt Mixture Rutting Potentials: Machine Learning Approach," Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2023 https://doi.org/10.1007/s40996-023-01192-w
4. Ruge J, Rondon-Quintana H, Bastidas-Martinez J (2022) Assessment of the asphalt mixtures properties subjected to a flexural strength. J Physics 2153:012001
5. Y. Chen, S. Xu, G. Tebaldi and E. Romeo, "The Role of Mineral Filler in Asphalt Mixtures," Road Materials and Pavement Design, https://doi.org/10.1080/14680629.2020.1826351, 2020
6. Faleh (2020) The Impact of Utilizing Silica Fume as Filler on Asphalt Concrete Mixes. Key Eng 31:22. https://doi.org/10.4028/www.scientific.net/KEM857
7. Sargin S, Saltan M, Morova N, Serin S, Terzi S (2013) Evaluation of rice husk ash as filler in hot mix asphalt concrete. Constr Build Mater 48:390–397. https://doi.org/10.1016/j.conbuildmat.2013.06.029
8. D. Kifile, N. Getu, A. Mesfin, W. Yifru and A. Sewunet, "Evaluation Maize Cob Ash as Filler in Hot-Mix Asphalt Concrete," Int J Pavement Res Technol 2022 https://doi.org/10.1007/s42947-021-00150-x
9. Zainudin M, Khairuddin F, Ng C, Che Osmi S, Misnon N, Murniati S (2016) Effect of Sugarcane Bagasse Ash as Filler in Hot Mix Asphalt. Mater Sci Forum 846:683–689. https://doi.org/10.4028/www.scientific.net/MSF.846.683
10. Woszuk A, Bandura L, Franus W (2019) Fly ash as low cost and environmentally friendly filler and its effect on the properties mix asphalt. J Clean Prod 235:493–582
11. Al-Asi A, Asi I (2021) Using Cement Kiln Dust in Ashalt Concrete Mixes in Jordan. J Mater Civil Eng 33(3):04021010
12. Mahto S, Sinha (2022) Application of Marble dust and ground granulated blast-furnance slag in emulsified asphalt warm mixtures. J Clean Prod 370:133532. https://doi.org/10.1016/j.jclepro.2022.133532
13. Huang B, Dong Q, Burdette E (2009) Laboratory Evaluation of Incoporating Waste Ceramic Materials into Portland Cement and Asphaltic Concrete. Constr Build Mater 23(12):3451–3456
14. Hasita S, Suddeepong A, Horpibulsuk S, Samingthong W, Arulrajah A, Chinkulkijniwat A (2020) Properties of Asphalt Concrete Using Aggregates Composed of Limestone and Steel Slag Blends. J Mater Civil Eng 32(7):1–7
15. H. Rondon-Quintana, J. Ruge, Y. Velandia-Castelblanco, M. Fraias, J. Bastidas-Martinez, "Use of Thermally Treated Bentonite as Filler in Hot Mix Asphalt," J Mater Civil Eng, 2020; 32, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003127
16. B. Marin-Garcia, O. Jimenez-Jimenez, H. Rondon-Quintana, "Behavior of thermally treated Kaolin filler in an asphalt concrete mixture," Revista Logos, Ciencia Tecnologia, 2019;11(3), https://doi.org/10.22335/rlct.v11i3.861
17. H. Zghair, H. Joni and A. Mohammed, "Assessment of the Influence of Nano Metakaolin filler on Asphalt Binder Rheological Properties," in 3rd International Conference on Engineering Science, Kerbala, 2019.

18. R. Rahkhimov, N. Rahkhimov, A. Gaifullin, V. Morozov, "Properties of Portland cement pastes enriched with addition of calcined marl," J Build Eng. 2017; 11. https://doi.org/10.1016/j.jobe.2017.03.007
19. A. Bahhou, Y. Taha, Y. El Khessaimi, R. Hakkou, A. Tagnit-Hamou , M. Benzaazoua, "Using Calcined Marls as Non-Common Supplementary Cementitious Materials," Materials. 2021; 11(5): https://doi.org/10.3390/min//050517
20. Bahhou A, Yassine T, Elkhessaimi Y, Hakkou R, Tagnit-Hamou A, Benzaazoua M (2021) Using Calcined Marls as Non- Common Supplementary Cementitious Materials. Materials 11(5):512–539
21. I. Usanga, F. Okafor and C. Ikeagwuani, "Investigation of the Performance of Hot Mix Asphalt Enhanced with Calcined Marl Dust Used as Fillers," Int J Pavement Res Technol. 2023; https://doi.org/10.1007/s42947-023-00323-w
22. T. Danner, H. Justness, G. Nordon and T. Ostnor, "Feasibilty of Calcined Marl as an Alternative Pozzolanic Material," in 1st International Conference on Calcined Clays for Sustainable Concrete, Lausanne, 2016
23. F. Moghadas Nejad, H. Sorkhabi, M. Karimi, "Experimental Investigation of Rest Time Effect on Permanent Deformation of Asphalt Concrete," Journal of Materials in Civil Engineering. 2015; 28: https://doi.org/10.1061/(ASCE)MT.1943-5533.0001498
24. Kim B, Roque R (2006) Evaluation of Healing Property of Asphalt Mixtures. Transp Res Rec 1970:84–91
25. Masoud KD, Eyad RKAAM, Dallas NL (2013) Constitutive Modeling of Fatique Damage Response of Asphalt Concrete Materials with Consideration of Micro-Damage Healing. Int J Solids Struct. 50(19):2901–2913
26. Masoud KD, Eyad RKAAM, Dallas NL (2012) A thermodynamic framework for constitutive modelling of time- and rate-dependent materials. Part II: Numerical aspects and application to asphalt concrete. Int J Plast 35:67–99
27. Subramanian V, Guddati MN, Richard K (2013) A Viscoplastic model for rate-dependent handering for asphalt concrete in compression. Mech Mater 59:142–157
28. Taeyoung Y, Richard K (2011) Experimental Investigation of Rate-Dependent Hardening -Softening Behavior of Hot Mix Asphalt in Compression. Road Mater Pavement Des 12(1):99–114
29. Rashid K, Masoud K, Dallas N, Eyad M (2010) A mico-damage healing model that improves prediction of fatigue life in asphalt. Int J Eng Sci 48(11):966–990
30. Kim Y, Little D, Lytton R, D'Angelo J, Davis R, Reinke G, Marasteanu M, Masad E, Roque R, Tashman L (2002) Use of dynamic mechanical analysis (DMA) to evaluate the fatigue and healing potential of asphalt binders in sand asphalt mixtures. Asphalt Paving Technol 71:176–206
31. D. William, D. Little, R. Lytton, Y. Kim, Y. Kim, "Microdamage healing in asphalt and asphalt concrete, Volume 2: laboratory and field testing to assess and evaluate microdamage and microdamage healing," FHWA-RD-98-142, Washington, 2001
32. Masoud K, Rashid K, Dallas N (2012) A continuum damage mechanics framework for modelling micro-damage healing. Int J Solids Struct 49(3):492–513
33. Mansourkhaki A, Samdzadeh A, Jebalbarezi M (2015) Study of loading waveform, loading duration, rest period and stress level on fatigue life of asphalt mixtures. Eng Solid Mech 3:93–102
34. Hsu T, Tseng K (1996) Effect of Rest Periods on Fatigue Response of Asphalt Concrete Mixtures. J Transp Eng 122(4):316–322
35. Qiu J (2012) Self- healing of asphalt mixtures :, Ph.D dissertation, Department of Civil Engineering. Delft University of Technology, Netherlands
36. Drits VA, Besson G, Muller F (1995) An improved model for structural transformations of heat-treated aluminous dioctahedral 2:1 layer silicates. Clays Clay Miner 43(6):718–731
37. ASTM C618, American standard testing method for coal fly ash and raw or calcined natural pozzolan for use in concrete, Pennyslvania, 2022.
38. ASTM D5, American Society for Testing and Materials, Standard test methods for penetration of bituminous materials, Pennsylvania, 2006.
39. ASTM D36, American Society for Testing and Materials, Standard test methods for softening point of bitumen (Fing and ball apparatus), Pennsylvania, 2006.
40. ASTM D4402, American society for testing and materials, Standard test method for viscosity determination of asphalt at elevated temperatures using rotational viscometer, Pennsylvania, 2022.
41. ASTM D92, American society for testing and materials, Standard test method for determination of flash point using a Prensky-martens closed-up apparatus, Pennsylvania, 2020.
42. ASTM D70, American society for testing and materials, Standard test method for density of semi solid bituminous materials (Pycnometer method), Pennsylvania, 2003.
43. ASTM D5821, American society for testing and materials, Standard test method for determing the percentage of fractured particles in coarse aggregate. Pennsylvania; 2017.
44. ASTM D4791, American society for testing and materials, Standard test method for flat particles, elongated particles. Pennsylvania; 2010.
45. ASTM C88, American society for testing and materials, Standard test method for soundness of aggregates. Pennsylvania; 2018.
46. ASTM C127, American society for testing and materials, Standard test method for relative density and absorption of coarse aggregate. Pennsylvania; 2016.
47. ASTM C131, American society for testing and materials, Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine. Pennsylvania; 2010.
48. ASTM C128, Americn society for testing and materials, Standard test method for density, relative density and absorption of fine aggregate. Pennsylvania; 2016.
49. ASTM D2419, American society for testing and materials, Standard test method for equivalent value soil and fine aggregates. Pennsylvania; 2022.
50. ASTM C142, American society for testing and materials, Standard test method for clay lumps and friable particles. Pennsylvania; 2017.
51. ASTM C1252, American society for testing and materials, Standard test method for uncompacted void content of fine aggregate. Pennsylvania; 2017.
52. ASTM C854, American society for testing and materials, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. Pennsylvania; 2002.
53. ASTM C204, American society for testing and materials, Standard test method for fineness of hydraulic cement by air permeability apparartus. Pennsylvania; 2004.
54. ASTM D546, American society for testing and materials, Standard test method for sieve analysis of mineral filler for asphalt paving mixtures. Pennyslvania; 2017.
55. ASTM D1559, American society for testing and materials, standard test method for Marshall test. Pennsylvania; 2002.
56. AASHTO T 315, Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). Washington DC: AASHTO; 2010.
57. AASHTO T 313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder using the Bending Beam Rheometer (BBR), Washington DC: AASHTO; 2022.
58. American Society for Testing and Materials ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Pennsylvania: ASTM; 2016.
59. ASTM D1074, American society for testing and materials, Standard test for compressive strength of asphalt mixtures. Pennsylvannia: ASTM; 2017.
60. Mana M, Ghohomali S, Muhammed A (2021) "Evaluation of Fatigue and rutting properties of asphalt binder and mastic modified by synthesized polyurethane," J Traffic Transp Engineering (English Edition) 8(2095):1036–1045.
61. AASHTO M 320, Standard Specification for Performance-graded Asphalt Binder. Washington DC; AASHTO. 2010.
62. Alhamali D, Wu J, Liu Q, Hassan N, Md Yusoff N, Ali S (2015) "Physical and Rheological Characteristics of Polymer Modified Bitumen with Nanosilica Particles," Arab J Sci Eng 41(4). https://doi.org/10.1007/s13369-015-1964-7.

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