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The Effect of Nano-Hydrated Lime on the Durability of Warm Mix Asphalt

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ABSTRACT

Premature failure in asphalt concrete pavement has been the main concern for pavement construction companies and engineers in recent years because of the large rise in traffic volume and loads and the temperature extremes in the summer and winter. The use of modifiers in asphalt concrete mixtures has attracted much attention to increase the performance and lifespan of pavements. As nanotechnology developed, several researchers concentrated on how these materials can help increase pavement serviceability by minimizing rutting and moisture damage. This study evaluates the Hydrated Lime (HL) effect by two methods (wet and dry hydrated lime) on the durability of the warm mix asphalt. The first method, HL, has been supplemented to the asphalt binder with three ratios (0.5%, 1%, and 1.5%) by weight of asphalt (Wet HL). Then, the second method was added via the aggregate weight as a replacement filler using three percentages (1%, 2%, and 3%) (Dry HL). The mechanical qualities, including Marshall Mix design, moisture susceptibility, and permanent deformation, were evaluated through experimental tests. Results showed that the mechanical characteristics and the fineness of the HL particle sizes are positively correlated.

Keywords: Warm asphalt mixture, Hydrated lime, Marshall Mix design, Indirect tensile strength, Permanent deformation

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تاثير النورة المطفأة النانوية على ديمومة الخلطة الاسفلتية الدافئة

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الخلاصة

لقد كان الفشل السابق لأوانه في تبليط الخرسانة الإسفلتية هو الشاغل الرئيسي لشركات ومهندسي إنشاء الطرق في السنوات الأخيرة بسبب الارتفاع الكبير في حجم المرور والأحمال وكذلك ارتفاع درجات الحرارة في الصيف وانخفاض درجات الحرارة في الشتاء. وعليه نال استخدام المضافات في الخلطات الخرسانية الإسفلتية الكثير من الاهتمام لزيادة أداء وعمر التبليط . ركز العديد من الباحثين على الكيفية التي يمكن بها لهذه المواد المعدلة أن تساعد في زيادة قابلية خدمة التبليط عن طريق تقليل التآكل والتلف الناتج عن الرطوبة. تهدف هذه الدراسة إلى تقييم تأثير النورة المطفأة بطريقتين (النورة المطفأة الرطب والجاف) على ديمومة خليط الأسفلت الدافئ. في الطريقة الأولى ، تمت إضافة النورة إلى رابط الأسفلت بثلاث نسب (0.5٪ ، 1٪ ، 1.5٪) من وزن الأسفلت (الطريقة الرطبة) ، اما بالطريقة الثانية فقد تمت الاضافة عن طريق الوزن الكلي كبديل للفلر باستخدام ثلاث نسب (1٪ ، 2٪ و 3٪) (الطريقة الجافة), تم إجراء اختبارات تجريبية لتقييم الخواص الميكانيكية ، بما في ذلك خصائص مارشال، وقابلية مقاومة الرطوبة ، والتشوه الدائم. أظهرت النتائج أن هناك علاقة إيجابية تظهر بين الخواص الميكانيكية ونعومة حبيبات النورة النانوية.

الكلمات المفتاحية: الخليط الاسفلتي الدافىء, النورة المطفأة ,طريقة مارشال , قوة الشد الغير المباشر , التشوهات الدائمية

1. INTRODUCTION

It is known that the warm mix asphalt technology has enticed the grave care of investigators through recent periods. And the investigators have been continually annoyed to enhance the procedural qualification of such asphalt. WMA's Similar or better performance than HMA's should be ensured to avoid future problems. It is important to deal with the major problems of WMA mixtures before deciding to adopt and apply this technology in the field. Hydrated lime is investigated and studied in this research. The production of WMA with different dosages of hydrated lime by two methods was produced to know if it has to improve the durability of warm mix asphalt and equal performance of HMA mixture. This goal is adapted to achieve the principle of Sustainability.

Consequently, concerning the increase of its ecological advantages and the fuel ingesting descent, such type of asphalt can be presented as an appropriate alternative to hot asphalt **(Arabani et al., 2015)**. The requisite energy reduction for heating the materials in the mixing period is the highly significant Warm Mix Asphalt (WMA) benefit, and such a decrease ends in a lower WMA project cost. Other benefits compared to the usual Hot Mix Asphalt (HMA), like the smaller amount of asphalt fumes through the manufacture, the lay-down, and the toxic gas emissions decrease from the plants of asphalt being accessible **(Galooyak et al., 2010; Zhu et. al., 2018)**. The use of WMA has been augmented fast in recent times. For instance, the WMA superstructure projects have been conducted in different American states, like Washington, Alabama, Florida, Indiana, Kansas, Maryland, Missouri, Ohio, Vermont, Alberta, Ontario, Wisconsin, Texas (San Antonio), Tennessee, and North Carolina. The warm mixes have taken certain care in Australia and Europe since about 2000 **(Abbas et al., 2010; Golestani et al., 2012)**.

To increase the tensile strength of the asphalt mixture, nano-hydrated lime (NHL) was used as an anti-stripping agent and an asphalt binder modification. A pair of NHL materials having (50 nm) and (100 nm) particle sizes being utilized **(Diab et al., 2013; Al-Tameemi et al., 2016; Al-Tameemi et al., 2019)** in the current investigation to study the NHL adaptation influence upon creep as well as recovery of WMA binders that foamed employing Advera® regarding the rutting. NHL was supplemented to the asphalt binder at three ratios (20%, 10%, and 5%) via the asphalt binder weight. Also, the tests of creep and recovery were achieved at (3) various levels of stress, 3 Pa (creep for 100 sec and recovery for 600 sec), 10 Pa (creep for 20 sec and recovery for 600 sec), and 50 Pa (creep for 1 sec and recovery 300 sec). These tests were conducted at 58°C. Also, the outcomes were compared with those of Regular Hydrated Lime (RHL). The total outcomes depicted that the pure asphalt binders that foamed employing Advera® manifested a bigger perpetual deformation (rutting) perspective compared to the binder adapted with the RHL and the NHL that foamed employing Advera®. As NHL rises, the non-recoverable obedience reduces (rutting reduces). Also, it was inferred that the RHL use with a usual dose (20% via binder weight) could be substituted via supplementing (5% via binder weight) of (50 nm NHL) about the rutting.

Other hydrated lime replacement filler methods were used by **(Albayati et al., 2022)**. Five various HL percentages as an incomplete substitution of the normal limestone filler in the asphalt concrete mixtures were investigated for the wearing course use objectives. The experimental tests evaluated the mechanical properties, including plastic flow resistance, perpetual deformation, volumetric properties, resilient modulus, and moisture vulnerability. The outcomes elucidated that an encouraging relationship was between the HL particle sizes' fineness and the mechanical properties, which was (7%) of the overall aggregate weight. Also, other mixtures were arranged with an incomplete substitution of the lime dust employing the HL with (1.0, 1.5, 2.0, 2.5, and 3.0%) of the overall aggregate weight. Also, the measured HL was supplemented to the mixtures in a slurry form, which was arranged via blending with water (500 mL) utilizing a shear blender at a speed of (3600 rpm) for a period of (10 min). Afterwards, this slurry is put into the aggregate in a pan and left for a time of (2 min) for mixing and soaking the aggregate. Then, the aggregate being marinated was placed into an oven at a (110°C) precise temperature for a time of (24 h) before being utilized for making the mixtures of asphalt concrete, from which the experimental specimens were cast. And the supplement above protocol was implemented before **(Preti et al., 2021; Mohammed, 2013; Albayati et al., 2022; Debbarma et al., 2022).**

This work aims to assess the performance of the warm mix asphalt (WMA) modified with hydrated lime by two methods (dry method) and (wet method) used for the preparation of mixtures under Marshall mix design. Indirect tensile strength and Permanent deformation tests with and without the optimum of hydrated lime affect the durability of the mixture.

2. MATERIALS

The used materials in the experimental part of this research are presented with their characteristics in the subsequent sections:

2.1 Asphalt Cement

Asphalt binder (40-50) was of penetration grade and delivered from the Dora refinery. Various tests were performed to obtain the physical properties of the asphalt cement. See **Table 1.**

Table 1. Properties of the asphalt cement

Laboratory test and conditions	Test Results	**(SCRB\R9, 2003)** Specification
Penetration @ 25°C,100 gm and 5 sec **(ASTM D5, 2021)**	44	40 – 50
Ductility @25°C ,5cm\min **(ASTM D113, 2021)**	280	Min 100
Softening Point (°C) **(ASTM D36, 2021)**	46	----------
Specific gravity @ 25° C **(ASTM D70, 2021)**	1.02	----------
Flashpoint (°C) **(ASTM D92, 2021)**,	280	Min 232

2.2 Aggregate

In the present work, the aggregate origin for specimen preparation was crushed quartz delivered from the A-Nibaie quarry. The physical properties of aggregates are listed in **Table 2.** Also, the aggregate gradations were chosen by the **(SCRB/R9, 2003)** of wearing courses (see **Table 2)**.

Table 2. The Physical properties of the aggregate

Property	Coarse aggregate	Fine aggregate	Specification
Bulk specific gravity	2.615	2.625	-----
Apparent specific gravity	2.642	2.661	-----
Water absorption, %	0.362	0.480	-----
Los Angeles abrasion, %	20.8	-----	Max 30%
Soundness	4.1	-----	Max 12%

2.3 Selection of Aggregates Gradation

The aggregate's nominal ultimate size selected for the gradation of aggregate utilized in the mixture of asphalt concrete for the trail samples for the wearing course was (12.5 mm) in accordance with the Iraqi State Corporation for Roads and Bridges (SCRB) as given in **Table 3.** The aggregate's particle size distribution is revealed in **Fig. 1.**

2.4 Mineral Filler

A control mixture was arranged utilizing Portland cement, which passed the sieve No. 200 (0.075 mm) for mineral filler at (7%) content via the overall weight of aggregate. Such content is at the range midpoint for type (A) mixtures for the wearing course uses established via the specification of SCRB. For the other method for using hydrated lime, three mixtures were arranged to employ hydrated lime for partly replacing the Portland cement utilizing (1%), (2%), and (3%) of the overall weight of aggregate. **Table 4** lists the physical properties of Portland cement.

Table 3. Gradation of asphalt Mixture for wearing course

Sieve size		Selected gradation	Specification Limit **(SCRB/R9, 2003)**
mm	inch		
19mm	3\4”	100	100
12.5mm	1\2”	95	90-100
9.5mm	3\8”	83	76-90
4.75mm	No.4	59	44-74
2.36mm	No.8	37	28 - 58
0.3mm	No.50	13	5 - 21
0.075mm	No.200	7	4 - 10

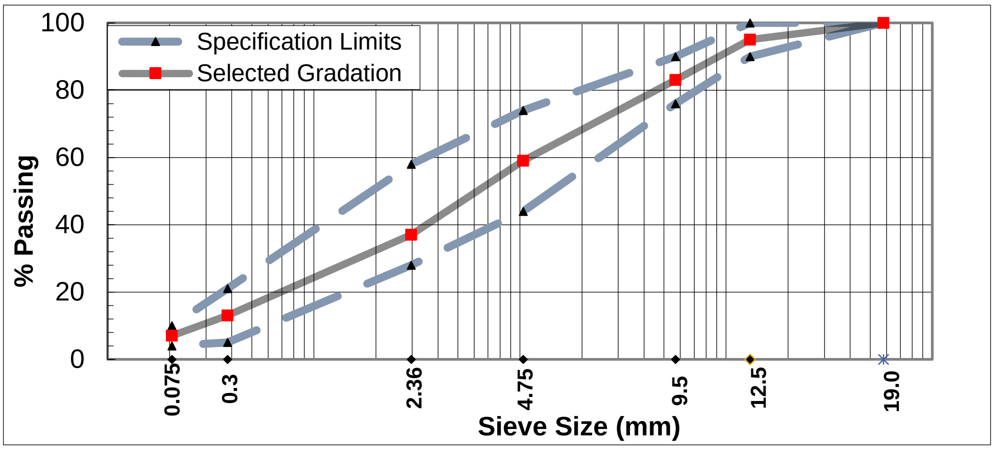

Figure 1. Selected aggregate gradation and specification limits

2.5 WMA Additive

For the production of the WMA, alpha-min ($Na_2O.Al_2O_3.2SiO_2$) powder has been used as an addition. It is a fine powder made of sodium Aluminum silicate that has hydrothermally crystallized and includes almost 21% water by weight. The alpha-min's physical characteristics and chemical makeup are also listed in **Table 5.**

Table 4. The mineral filler's physical properties

Filler type	Specific Gravity	Surface Area (m^2\kg)	%Passing Sieve No. 200 (0.075)
Portland cement	3.20	290	97%

Table 5. Physical and chemical properties of WMA additive, zeolite

Property	Results
ingredients	Na_2O. $Al_2O_3.2SiO_2$ (Sodium Aluminosilicate)
SiO_2	32.8%
Al_2O_3	29.1%
Na_2O	16.1%
LOl	21.2%
Physical state	Granular powder
Color	White
Odor	Odorless
Specific gravity	2.03

2.6 Hydrated Lime (Additions Methods)

Hydrated Lime $Ca(OH)_2$ is a powder chiefly comprised of Calcium Hydroxide $Ca(OH)_2$. It's determined via Hydrating Quicklime (essentially Calcium Oxide, CaO) utilizing a particular hydration device. And quicklime is produced by burning limestone of too elevated purity (made of Calcium Carbonate, $CaCO_3$) at temperatures of about (900°C) in devoted kilns (**Khattak et al., 2013; Nazari et al., 2018)**. According to the National Lime Association (NLA), the usual grades of $Ca(OH)_2$ that's appropriate for the utmost chemical objectives possess (85%) or more passing throughout the sieve No. 200, whereas for distinctive uses, it may be determined as fine as (99.5%) passing the sieve No. 325. The hydrated lime has been recognized to be encouraging the potential materials for the pavements owing to its sole chemical, physical, and mechanical properties. The chief objective of the present work is to investigate the influence of the lime addition technique on the mechanical properties of mixes, noting that the $Ca(OH)_2$ was supplemented via two methods. The first method was supplemented via the aggregate weight as a replacement of mineral filler (dry methods) using three percentages (1%, 2%, and 3%). It was added to the aggregate after heating and mixing until it was homogeneous with the additive hydrated lime to increase the mixture stiffness. The second method (wet methods) added three percentages (0.5%, 1%, and 1.5%) by weight of asphalt. Before the mixing, the asphalt binder was heated at 150°C and blended via a shear mixer blender set at 12000 rpm for 20 min. And the supplement mentioned above protocol was implemented before **(Nejad et al., 2012; Shafabakhsh et al., 2015; Yarahmadi et al., 2022; Albayati et al., 2022)**. **Table 6** lists the physical properties of hydrated lime.

Table 6. Physical properties of hydrated lime

Materials Property	Hydrated lime
Specific gravity	2.41
Specific surface (m^2\kg)	398
100 Mesh (150 µm) passing	100
200 Mesh (75 µm) passing	90

3. EXPERIMENTAL WORK

3.1 Marshall Mix Design

The Marshall technique to design warm mixtures has been utilized for determining the optimal content of asphalt and the volumetric properties, including total voids (AV %), Marshall Specimens were prepared as three specimens for every percentage for asphalt mineral aggregate voids (VMA%) and asphalt-filled voids (VFA%) content, and the average test result was recorded with a diameter of 100 mm (4 in) and a height of 63 mm (2.5 in). The specimens, each of 1200 gm in weight, were arranged utilizing various asphalt contents (from 4% to 5.2% with an increment of 0.3%); they were compacted at a temperature of 115℃ (10℃ minus mixing temperature). The compaction was performed via 75 blows/end according to the **(ASTM D6926-20, 2020)** requests. Also, the compacted specimens were submerged in the water at a temperature of (60℃) for (45 min) before the testing for steadiness, flow, and volumetric characteristics evinced in **Fig. 2**.

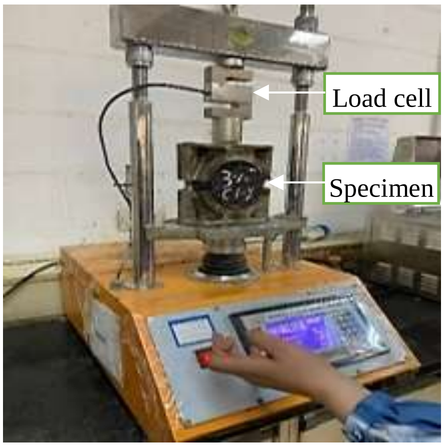

Figure 2. The Marshall Test

3.2 Moisture Susceptibility

The implemented process for evaluating the WMA specimens' moisture susceptibility is **(ASTM D4867/D4867M-09, 2014)**. Six specimens were compacted for every type for the optimum of nanomaterials (Marshall Compaction Technique) to an air void level ranging from (6%) to (8%). One subset of specimens (3 specimens) was examined at (25°C) (unrestricted specimens) in the indirect tension test. While the other subsets were exposed to a single cycle of freezing as well as thawing (for 16 hr at (-18 ± 2°C) and after that for 24 hr at (60 ± 1°C) and finally examined similar to the 1st subset (restricted specimens). Through this test, the specimen being loaded lengthways, the diameter and the splitting force are registered as depicted in **Fig. 3**. The parameters of test parameters are computed as follows: (**ASTM D4867/D4867M-09, 2014).**

$$ITS = \frac{2p}{\pi h D} \quad (1)$$

$$TSR = \frac{C.ITS}{UC.ITS} \quad (2)$$

where:
P is the Load in N
h is the specimen height (thickness) in mm
D is the specimen diameter in mm
C. ITS is the conditioned indirect tensile stress in MPa
UC. ITS is the unconditioned indirect tensile stress in MPa

Figure 3. Indirect Tensile Strength test for WMA specimen

3.3 Uniaxial Repeated Loading Test

Cylindrical specimens having a diameter of 101.6 mm (4 in) and a height of 203.2 mm (8 in) used the pneumatic repeated load system. Specimens were arranged in accordance with the steps clarified in **(Albayati, 2006)**. A uniaxial repetitive compressive stress (20 psi) was implemented through the test with a loading time of (0.1 sec) and a resting time of (0.9 sec) (1 Hz loading frequency), and the perpetual axial deformation was measured at various loading repetitions. The whole tests were carried out at 40°C (104°F). The following equation is used to compute the permanent strain (εp):

$$\varepsilon p = \frac{pd * 10^6}{h} \tag{3}$$

where:
εp is the axial permanent stain ((mm/mm), $*10^{-6}$)
pd is the axial permanent deformation (mm)
h is the height of specimen (mm)
The uniaxial repeated load test was sustained till the specimen's failure and the perpetual deformation factors (the intercept (a) as well as the slope (b)) were computed from the plots of perpetual deformation vs. the load repetition no. Beyond demonstrating them in a log-log scale as clarified in (**Albayati et al ., 2006)** with the form shown in Eq. (2). The test setup and the perpetual deformation readings are portrayed in **Fig. 4.**

$$\varepsilon p = a\mathbf{N}^{\mathbf{b}} \tag{4}$$

where:
εp is the permanent strain
N is the number of stress applications
a is the intercept coefficient
b is the slope coefficient
The uniaxial repeated load experiment was conducted at a similar load state, and the specimens were defined overhead in the permanent deformation tests until the specimens were deformed at a temperature of (40°C). The Indirect tension test was implemented to measure a warm mix's resilient modulus (*Mr*) according to the (**ASTM D4123, 1995).** The resilient modulus was computed in accordance with the following equation:

$$Mr = \frac{\sigma}{\Delta r/h} \tag{5}$$

where:
Mr is the resilient modulus (MPa)
σ is the repeated axial stress (MPa)
Δr is the average of the axial resilient deflection registered (mm)
h is the specimen height (mm)

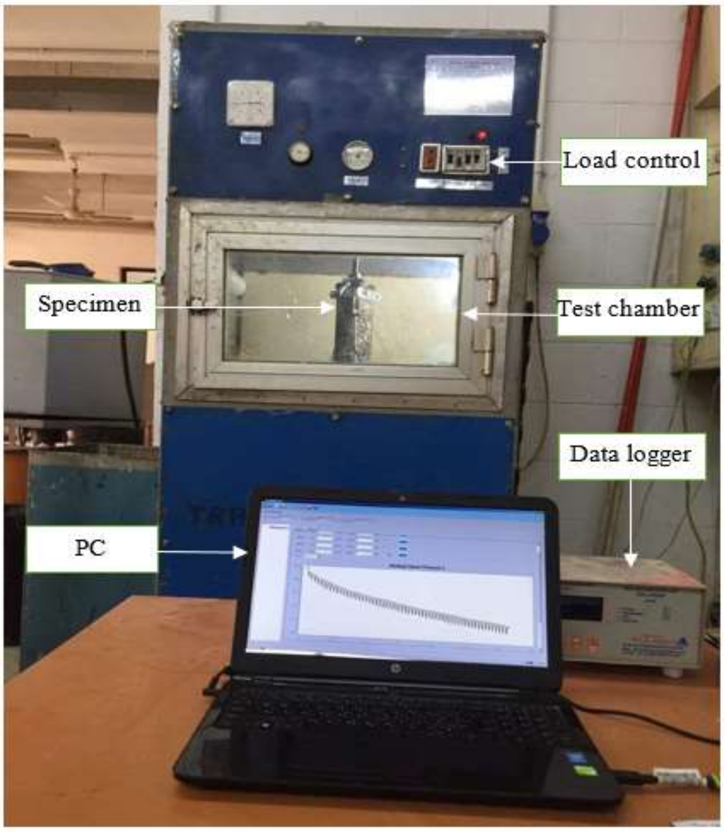

Figure 4. Test setup and perpetual deformation readings

4. RESULTS AND DISCUSSION

Laboratory work study results have been determined and analyzed for identifying the optimal percentage of NHL by the methods and the effect of adding the optimal NHL used in this study on the mechanical properties of asphalt concrete mixtures. Marshall Test was conducted with various asphalt percentages (4, 4.3, 4.6, 4.9, and 5.2 %), and the outcomes have been analyzed for obtaining the optimal asphalt cement. Beyond determining the Optimal Asphalt Content (OAC) and the optimal NHL, three groups of the specimens of asphalt concrete with and without NHL by two methods have been arranged. The outcomes have been analyzed upon many investigational tests, comprising permanent deformation, Marshall Test, and indirect tensile strength. Eventually, the outcomes have been compared with the Iraqi specifications of SCRB.

4.1 Optimal Content of Asphalt

To determine the optimum asphalt content, specimens with a total weight of 1200 grams were prepared with five different asphalt cement contents ranging from 4% to 5.2%, increasing by 0.3% increments, to identify the (OAC). The results from the Marshall test are presented in **Fig. 5**, showing that the OAC aligns with the Iraqi standards **(SCRB R/9, 2003)**. The optimum asphalt binder content was found to be 4.83%, calculated based on the average binder content that achieved the highest stability, and maximum density, and targeted 4% air voids. Furthermore, the peak stability observed was 9.43 kN, and the flow measurement was 3.75 mm, both of which comply with the SCRB specification **(SCRB/R9) 2003)**.

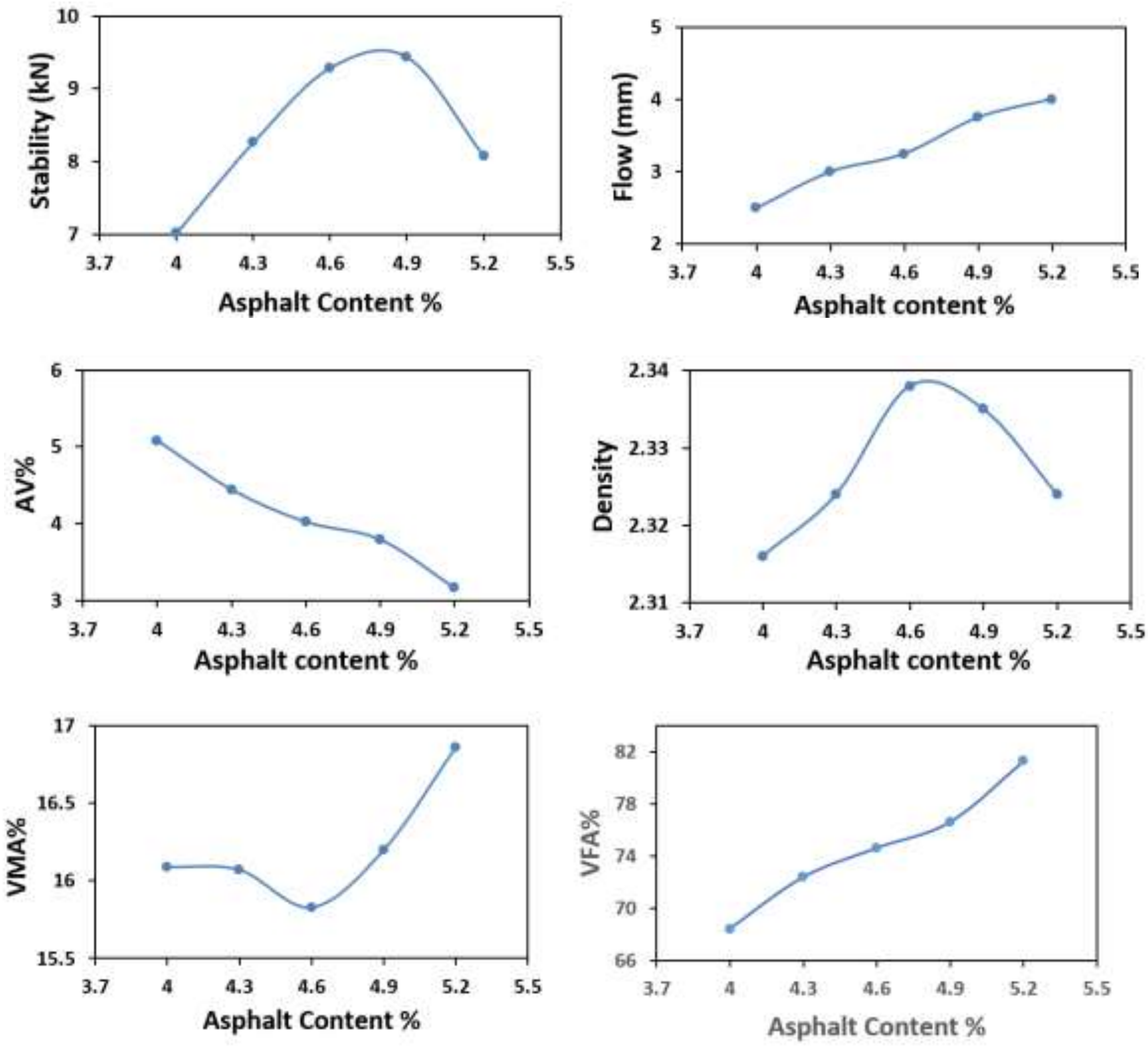

Figure 5. The relation between the asphalt content and Marshall Properties

4.2. Optimum Content of Hydrated Lime by Two Methods.

To obtain the optimum value for each method of additives hydrated lime, Marshall Tests were carried out for the models that contain different values of the hydrated lime. The first method has been supplemented via the aggregate weight as a mineral filler substitution using three percentages (1%, 2%, and 3%). It is added to the aggregate after heating and mixing until it is homogeneous with the additive hydrated lime to increase its stiffness. The second method added three percentages (0.5%, 1%, and 1.5%) by the weight of asphalt, therefore, representing the highest value of stability in any method, which is the optimal value of the nano hydrated lime, as depicted in **Fig. 6**. It is shown that the optimal value from the first method for replacement filler is (3%) and the second's method for adding by weight of asphalt is (1.5%). They have the highest values of stability (10.87 kN and 15.39 kN), respectively, and are higher than the stability from the control mix (9.43 kN).

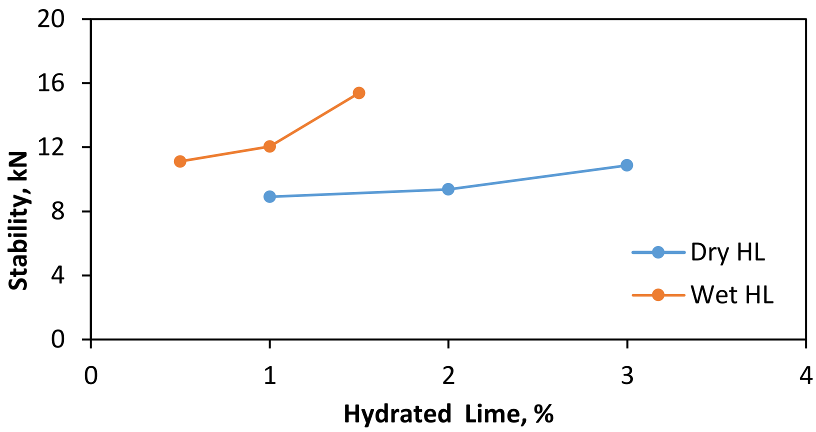

Figure 6. Effect of HL by the two methods on stability

4.3 Effect of Hydrated Lime on the Marshall Properties of WMA

Detailed results of the measured Marshall properties are shown in **Figs. 7 to 12**. **Fig. 7** suggests that the Marshall Stability augmented considerably with the modified binder by (38.72) for 1.5 % HL (wet HL) and (15.27) for 3% replacement filler (dry HL) than the stability for the control mix (CM). The improvement rate was higher for the modified binder for the replacement filler. The ultimate stability has been determined by utilizing (1.5% HL) in the asphalt binder owing to its elevated ratio of surface area to volume, which isn't merely augmenting the asphalt binder stiffness, but also the cohesion force between the aggregates by improving the infiltration into the pores of aggregate.

The Marshall flow results in **Fig. 8** show that the Marshall flow decreases as HL particle size increases. Also, the influence of the particle size possessed a linear relationship with the content of HL. There is a slight decrease in Marshall Flow when with modified binder by (14.13) for 1.5% (wet HL) and (18.39) for 3% (dry Hl), lowering the flow for the control mix. The opposite effect of the HL can be ascribed to the greater capability of the HL fine and ultrafine fine to harden the mixtures of asphalt concrete and, therefore, to reduce the values of flow, but into the limits of the specification of the values (2-4 mm) of Marshall Flow.

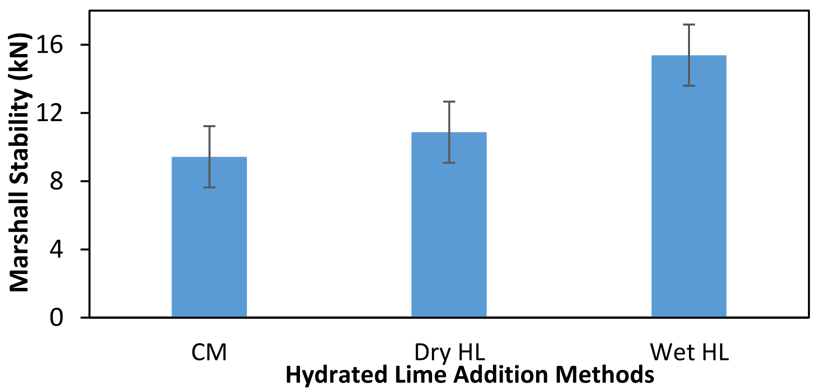

Figure 7. The effect of optimally hydrated lime on stability

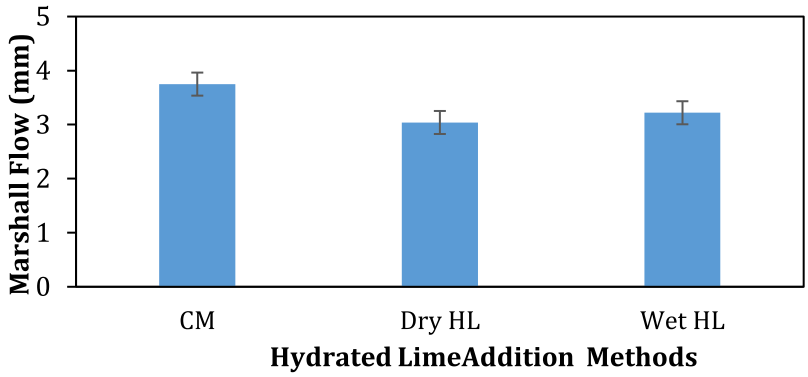

Figure 8. The effect of optimally hydrated lime on flow

Figure 9 presents a comparison of the density variations among different mixes. It can be observed that the control mix (CM), which did not contain NHL, exhibited the highest density. Upon the introduction of NHL, there was a noted decrease in density: a 1.15% reduction when 3% NHL replaced the filler (Dry HL), and a 1.19% reduction when 1.5% NHL was added to the asphalt cement by weight (Wet HL).

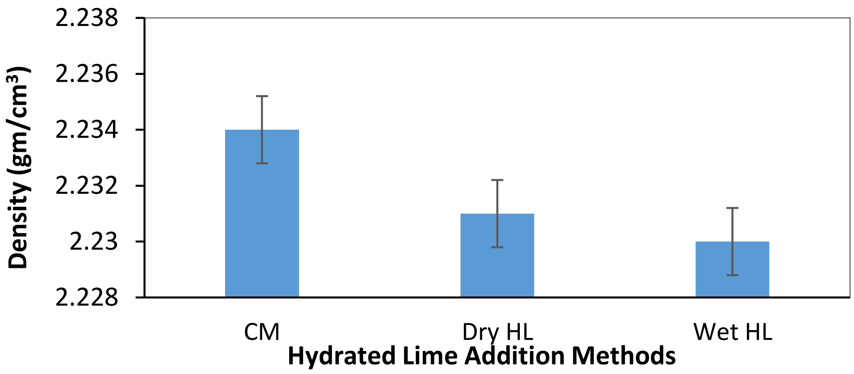

Figure 9. The effect of optimally hydrated lime on density

For the air voids shown in **Fig. 10**, The results show that AV% has increased for two methods for additives HL than the control mix; the increasing percentage increased by (10.32%) for 1.5%HL (dry method) and (9.32%) for 3%HL (wet method) compared to traditional mixtures when it applies to modified asphalt A.C. (40-50). Despite this increase, (%VTM) has been within the required limit specifying (3 – 5%) as an allowable range according to **(SCRB/ R9, 2003)**.

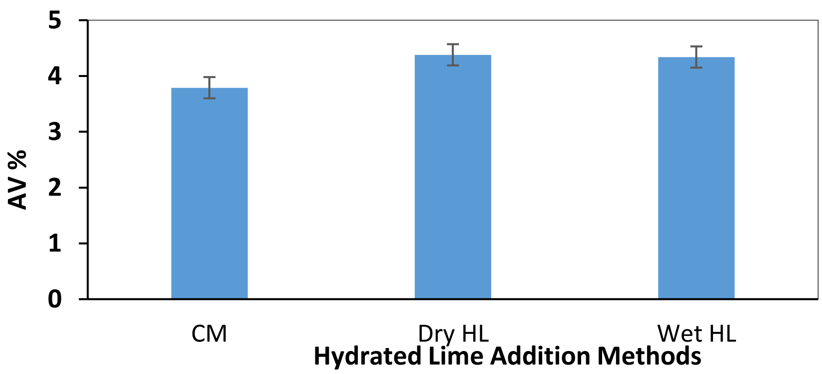

Figure 10. The effect of optimally hydrated lime on AV %

The results of VMA% are shown in **Fig. 11**. The VMA% was increased with the two methods of added HL by (4.88%) for 1.5%HL (dry method) and (5.06%) for 3%HL (wet method) compared to a traditional mixture when applies to modified asphalt A.C. (40-50). It may be partially attributed to a rise in the modified asphalt viscosity and adopting the same optimum asphalt content for all mixture types.

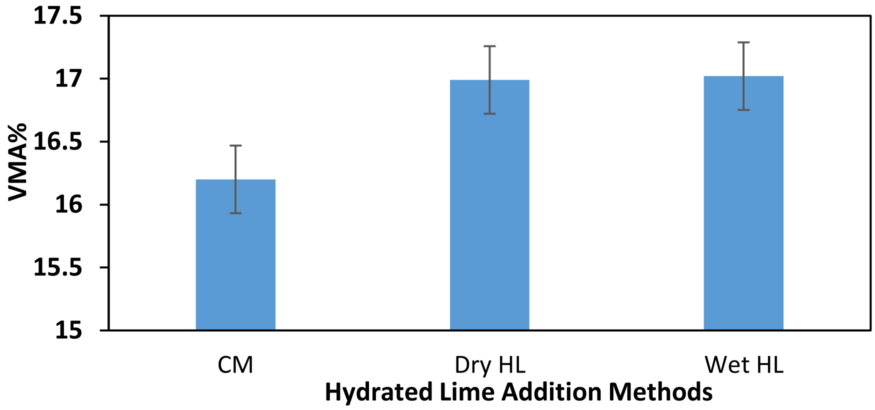

Figure 11. The effect of optimally hydrated lime on VMA %

The VFA % was decreased by (3.11%) for 1.5HL (dry method) and (2.74%) for 3% (wet method) compared to a traditional mixture A.C. (40-50) as shown in **Fig. 12**. The decrease in the VFA percentage is due to the rise in VMA and VA due to the optimum hydrated lime supplement. All values are greater than 70% for OAC, noting that Marshall Criteria for VFA is considered between 65 –75%.

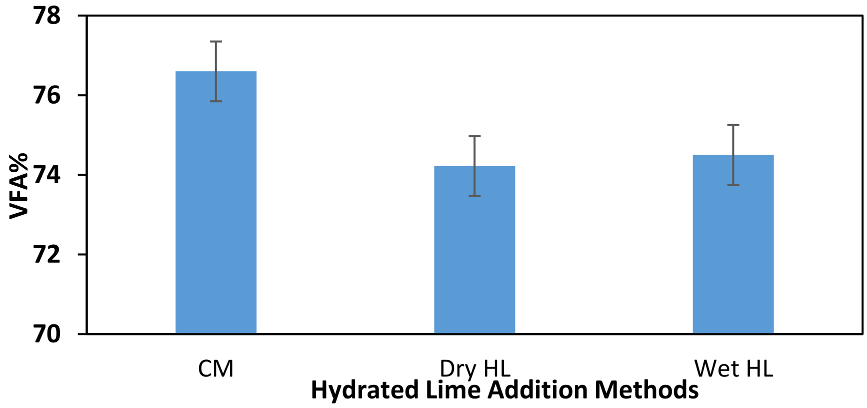

Figure 12. The effect of optimally hydrated lime on VFA %

4.4 Effect of Hydrated Lime on the Tensile Strength and Moisture Susceptibility

In **Fig. 13**, the values of ITS for every dry and wet mixture specimen with and without nano Hydrated lime by two methods beneath the dry and wet circumstances are compared. The values of the ITS of wet mixtures are lower than those of the dry mixtures at the loading test finish. Also, this has been anticipated since the water existence results in a decrease in the asphalt-aggregate adhesion, and therefore the asphalt mix specimen's strength is reduced beneath the loading.

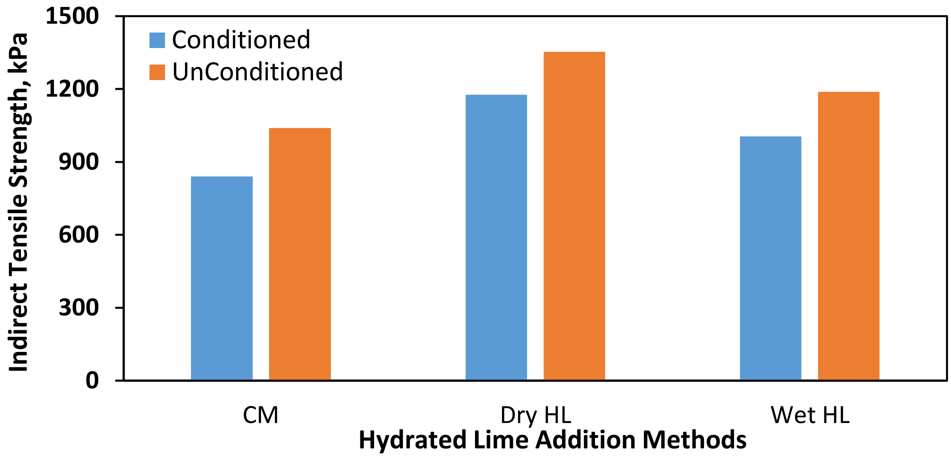

Figure 13. The effect of HL upon the indirect tensile strength (wet and dry)

Tensile Strength Ratio (TSR) has been utilized to estimate the mixes' moisture sensitivity. The proposed least limit of (80%) for indirect TSR being employed for differentiating between the moisture-resistance mixes and the moisture-susceptible mixes as the least value **(AASHTO T283–07, 2007**; **ASTM D4867M-09, 2014; Joni and Alkhafaji, 2020),** see **Fig. 8.** It can be observed from **Fig. 14** that the HL usage by two methods generally enhanced the moisture vulnerability. As well as an optimistic relationship with the size of particles could also be noted in the modified binder (1.5% HL) by weight and (3%HL) replacement filler. And, as the least satisfactory TSR is (80%), the HL usage fulfilled the requirement of the specification. Also, the ultimate gain in the TSR was at in compared to the control mixture (without HL). Enhancement in the moisture vulnerability was due to that the particles of HL could be actively joined with the viscous constituents subjected to oxidative ageing and therefore aid in decreasing the procedure beneath the moisture experience. On the contrary, the particles of HL are involved in the cation exchange in accumulation as well as Pozzolanic reactions into the asphalt mixes; their yields possess a lesser hydrophilic nature, which also aids in decreasing the asphalt concrete's moisture vulnerability **(Karahancer et al., 2014; Albayati et al., 2016; Albayati et al., 2018; Aljbouri and Albayati, 2024).**

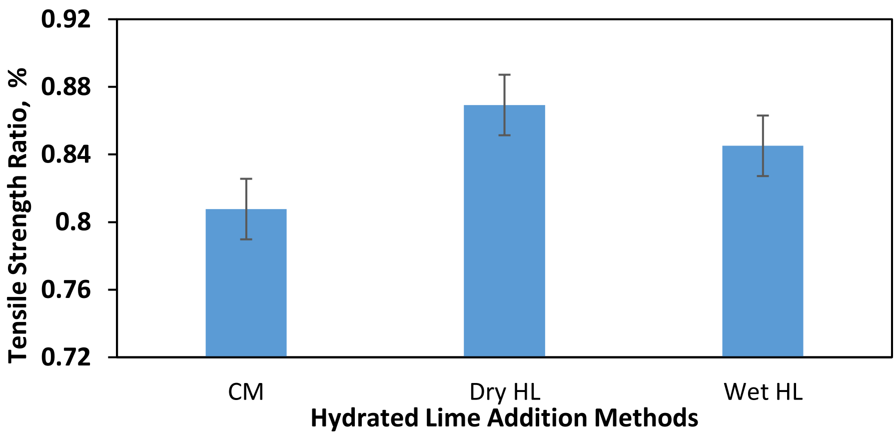

Figure 14. The effect of HL by two methods content upon the TSR

4.5. Effect of Hydrated Lime upon the Permanent Deformation

The test outcomes of the measurement of perpetual deformation beneath the uniaxial repetitive load (plotted upon a log-log scale), two factors, i.e., slope and intercept, are connected with the perpetual deformation potential of the material. The slope and intercept factors of fitting lines are compared in **Fig.10**. The outcomes indicated that the supplement of HL generally enhanced the asphalt concrete's rutting resistance. Utilizing the nano-sized particles created the uppermost enhancement.

The perpetual deformation test results are displayed in **Fig. 15**, depending on the info in **Table 7**. It was observed that the value of the intercept and slope for the dry method at an HL content of 3% by (15.94%), (7.33%) the lowest values being greatly lesser than the optimal values of the control mixture. The percentage of slope values for the wet method at 1.5% HL was the lowest (8.755%) from the control mix. Then, the intercept value for wet methods at 1.5% HL was highest by (14.49%) compared with the unmodified mixture for the control mixture. The permanent strain at the 10000 load repetition that combines the effect of intercept as well as slop reveals that the mixes with hydrated lime by two methods (wet and dry) have had the lowest permanent strain in comparison with the control mix lowest by (21.7% wet and 52.11% dry) percent. The overhead outcomes evinced the greater part of the finest HL kind in creating a high stiffness of asphalt concrete as well as raising stone–stone contact, which caused an effective spreading and a decrease in the strains and stresses into the pavement structure produced via traffic loading, so decreasing the likelihood of a high-temperature rutting mode of the failure.

Table 7. Effect of Nanomaterials upon the coefficient of permanent deformation

Mixtures	40°C		
	Intercept (a)	Slope (b)	(εp) at N=10.000
Control Mix	69	0.4637	2869.801544*
Wet method	79	0.4231	2246.581729
Dry method	58	0.4297	1374.176157

*Control Mix failed at N=7950

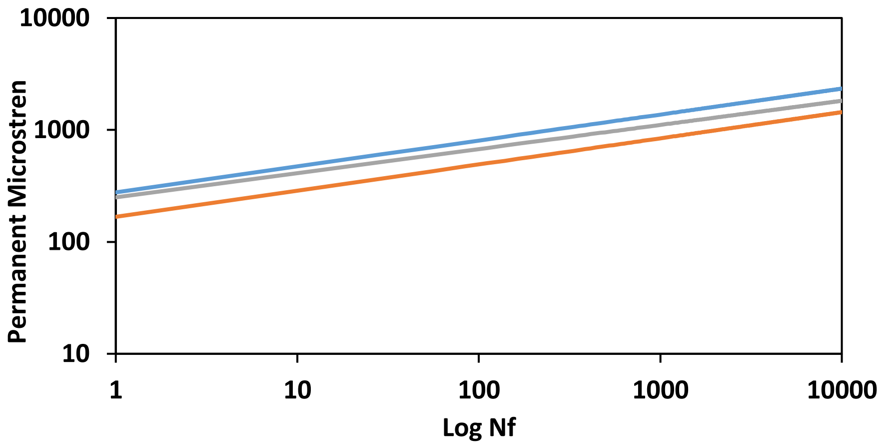

Figure 15. Effect of hydrated lime by two methods upon the permanent deformation.

4.6 Effect of Hydrated Lime upon the Resilient Modulus

The information in **Fig. 16** Additionally, it should be highlighted that there is a direct correlation between the particle size, the resilience modulus, and the proportion of HL supplemented in two ways.

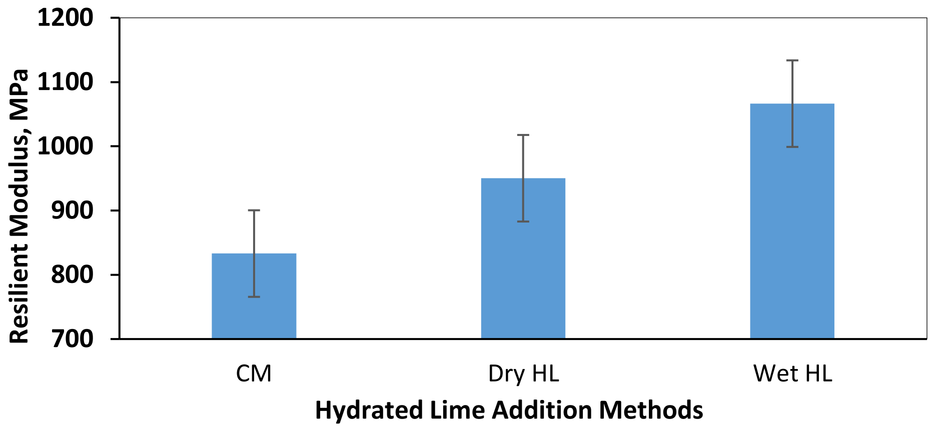

Figure 16. Effect of Hydrated Lime on Resilient Modulus

5. CONCLUSIONS

The present research aims to study the dynamic behavior of warm asphalt mixes having Hydrated Lime additives by two methods (Wet and Dry). The mixes' dynamic behavior was assessed by the tests of Marshall Stability, permanent deformation, and indirect tensile strength. Depending upon the investigational results, the subsequent remarks can be drawn:

1-Regarding the Marshall Stability test, the optimal quantity of hydrated lime to be supplemented as an asphalt mixture modifier by two methods, wet HL was (1.5%), and dry HL was (3%) led to increasing Marshall stability, higher ITS, lower permanent deformation, and higher resistance to moisture damage in comparison to control mix.

2-The result of Marshall Stability increased by (15.27% and 38.73% kN) for (dry and wet HL) respectively, Compared with conventional asphalt mixture. The Marshall Flow decreased by (18.93% and 14.13% mm)) for (dry and wet HL), respectively, lower compared with conventional asphalt mixture.

3-Using (1.5%) and (3%) for HL increases the values of ITS of the samples of asphalt mix in wet and dry circumstances. And, the main cause for such incident is not the appropriate word is the truth that these additives raise the asphalt binder stiffness, the stiffer asphalts being, in general, tougher for peeling from an aggregate or taking lengthier for peeling and therefore possess further moisture impairment resistance.

4-Using (1.5%) and (3%) in the mix of asphalt results in the values of TSR to enhance for the mixes of WMA by (4.93% and 7.40%), respectively. The high tensile strength at the failure is a wanted property for the stiff mixes compared to the control samples.

5-Asphalt mixtures modified with the optimum Hydrated lime have maximum advancement in the strain-indicated resistance to permanent deformation at 10000 load repetition belongs to the modified mixture with (1.5 % wet HL and 3% dry HL) compared to control mixtures.

From this work, it, can be recommended this research dealt with the wearing course layer only, which may not represent the full impression of the behavior of the other layers design, so it is necessary to know the effect of the other layers under the influence of the same research conditions or other according to the requirements.

Nomenclature

Symbol	Description	Symbol	Description
AV	Air voids, %	VFA	Voids filled with asphalt,%
HMA	Hot mix asphalt	VMA	Voids in mineral aggregate,%
T	Test temperature, °C	WMA	Warm mix asphalt

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Credit Authorship Contribution Statement

Rawaa Q. Aljbouri: Writing – original draft. Amjad Khalil Albayati: Writing – review & editing, Validation, Conceptualization.

Declaration of Competing Interest

The authors declare that 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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