# MECHANISTIC EVALUATION OF LIME-MODIFIED ASPHALT CONCRETE MIXTURES

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## ABSTRACT

Frequently, Load associated mode of failure (rutting and fatigue) as well as, occasionally, moisture damage in some sections poorly drained are the main failure types found in some of the newly constructed road within Baghdad as well as other cities in Iraq. The use of hydrated lime in pavement construction could be one of the possible steps taken in the direction of improving pavement performance and meeting the required standards.

In this study, the mechanistic properties of asphalt concrete mixes modified with hydrated lime as a partial replacement of limestone dust mineral filler were evaluated. Seven replacement rates were used; 0, 0.5, 1, 1.5, 2, 2.5 and 3 percent by weight of aggregate. Asphalt concrete mixes were prepared at their optimum asphalt content and then tested to evaluate their engineering properties which include moisture damage, resilient modulus, permanent deformation and fatigue characteristics. These properties have been evaluated using indirect tensile strength, uniaxial repeated loading and repeated flexural beam tests. Mixes modified with hydrated lime were found to have improved fatigue and permanent deformation characteristics, also showed lower moisture susceptibility and high resilient modulus. The use of 2 percent hydrated lime as a partial replacement of mineral filler has added to local knowledge the ability to produce more durable asphalt concrete mixtures with better serviceability.

## الخلاصة

أظهرت بعض الطرق المبلطة حديثا بالخرسانة الاسفلتية في بغداد وباقي محافظات القطر تدهورا مبكرا بالاداء نتيجة فشل الكلال والتشوهات الدائمية وفي بعض الاحيان نتيجة الفشل تحت تاثير الدور المخرب للماء. ان استخدام الجير المطفأ ($Ca(OH)_2$) في انتاج الخرسانة الاسفلتية ممكن ان تكون واحدة من الخطوات التي يمكن اتخاذها في اتجاه تحسين الخصائص المتعلقة بالاداء للتبليط الاسفلتي لجعله يطابق متطلبات المواصفة من خلال توفير المقاومة اللازمة لانواع الفشل المذكورة انفا.
لقد تم في هذه الدراسة تقييم الخصائص الميكانيكية لخلطات الخرسانة الاسفلتية والتي تحوي على نسب مختلفة من الجير المطفأ وهذه النسب هي (٠,٠ ، ٠,٥ ، ١,٠ ، ١,٥ ، ٢,٠ ، ٢,٥ و ٣ % من وزن الركام)، وتمت الاضافة عن طريق الاستبدال الجزئي للمادة المالئة التقليدية ( مطحون حجر الكلس). حيث تم اجراء فحوصات الشد غير المباشر، المرونة الاستردادية، الحمل المحوري المتكرر وكذلك فحص الانحناء المتكرر للنماذج المختبرية والتي اعدت باستخدام النسب المثلى للاسفلت لتقييم الخصائص المتعلقة بضرر الماء ، معامل المرونة الاستردادي، التشوهات الدائمية وكذلك خاصية الكلال.
لقد بينت النتائج بان استخدام الجير المطفأ يحسن الى حد كبير خصائص الاداء المتعلقة بضرر الماء وكذلك يحسن معامل المرونة الاستردادي ومقاومة التشوهات الدائمية والكلال. ان استخدام نسبة ٢% من الجير المطفأ كاستبدال جزئي للمادة المالئة التقليدية قد أضاف إلى الخبرة المحلية المتوفرة في هذا المجال إمكانية أنتاج خرسانة إسفلتية لاغراض التبليط بديمومة أعلى ومستوى خدمة أفضل.

**Key words**: Asphalt concrete, Hydrated lime, Mechanical properties

## 1-INTRODUCTION

In the recent five years, some of the newly constructed asphalt concrete pavements in Baghdad as well as other cities across Iraq have shown premature failures with consequential negative impact on both roadway safety and economy. Frequently, Load associated mode of failure (rutting and fatigue) as well as, occasionally, moisture damage in some sections poorly drained are the main failure types found in those newly constructed road. Investigations on the reasons beyond these failure showed that it can be grouped into two categories, extrinsic and intrinsic, the first one due to the heavy axle loading coupled with relentless high summer temperatures ( ambient air temperature for nearly three month can reach 50 degree Celsius and pavement surface temperature can reach up to 60 degree Celsius) , whereas the second category is limited to the mixture itself , improper gradients, excess use of natural sand and lack of mineral filler all of these factors acts either in collect or in single manner for the deterioration in the mix strength and also loss of durability of asphalt concrete pavement.

Based on the preceding it is clear that there is a real need to the development of modified asphalt concrete mixtures to improve the overall performance of pavements. The use of hydrated lime in pavement construction could be one of the possible steps taken in this direction. In the United States of America, Hydrated lime has been added to hot mix asphalt pavements for over 30 years, improving the mixtures in many ways and increasing the life of highways. Extensive experimental studies have revealed that the use of hydrated lime in Hot-Mix Asphalt (HMA) mixtures can reduce permanent deformation, long-term aging, and moisture susceptibility of mixtures. In addition, it increases the stiffness and fatigue resistance of mixtures. The structure of hydrated lime consists of different size fractions. The larger size fraction performs as a filler and increases the stiffness of the bituminous mixture. The smaller size fraction increases binder film thickness enhancing viscosity of the binder, and improving the binder cohesion and stiffness.

In view of this , the primary objective of this study is to evaluate the mechanical properties of asphalt concrete mixtures containing hydrated lime (as a partial replacement of limestone filler) based on the following tests, Marshall properties (Mix Design), Indirect tensile test (Moisture susceptibility) , uniaxial repeated load test ( Resilient Modulus and permanent deformation) and repeated flexural beam test ( fatigue characteristics).

## 2-BACKGROUND

Hydrated lime which is also known as calcium hydrate ($Ca(OH)_2$) has been used in asphalt mixes for a long time, both as mineral filler and as an antistripping additive. Researchers observed that when hydrated lime coats an aggregate particle, it induces polar components in asphalt cement to bond to the aggregate surface. This effect also inhibits hydrophilic polar groups in the asphalt from congregating on the aggregate surface (McGennis et al. 1984). In addition, lime can neutralize acidic aggregate surfaces by replacing or coating acidic compounds and water-soluble salts on the aggregates and can react pozzolanically to remove deleterious materials (Epps et al. 2003).

Petersen et al. [1987] selected four AC-10 asphalts on the basis of variable chemical composition and geographical usage in paving industries and evaluated the effects of hydrated lime on asphalt concrete performance. A comparative study was also carried out by replacing lime with a high-calcium limestone, pulverized to match the physical fineness of the hydrated lime. It was reported that hydrated lime treatment reduced asphalt age hardening, increased the high-temperature stiffness of both unaged and aged asphalts, and also increased the asphalt tensile-elongation at low temperatures. They also stated that the relative response to hydrated lime treatment varied as a function of asphalt cement source. Furthermore, the comparison study between limestone powder and hydrated lime showed that hydrated lime outperformed the limestone powder considering age hardening, tensile strength, and the elongation to break properties of asphalt binder.

Al-Suhaibani [1992] evaluated the mineral filler properties of hydrated lime and other local fillers available in Saudi Arabia. The mechanical properties of the mixes were studied using tests such as the resilient modulus test, the indirect tensile strength test, Hveem stability, and Marshall criteria. The research results revealed that the amount and characteristics of the mineral fillers can have an effect on the rutting susceptibility of flexible pavements, and that the use of hydrated lime can improve resistance of the mixes to rutting. The lime showed improved stiffening properties when incorporated into the mixture.

Shahrour and Saloukeh [1992] conducted a research study to evaluate the influence of ten types of different fillers (including hydrated lime) on the physical properties of filler-bitumen mixtures and two types of asphalt mixtures namely- Asphaltic concrete (AC) and Dense Bitumen Macadam (DBM) commonly used Dubai, U.A.E. The mixtures were designed using Marshall mix design method, and the fillers were incorporated in various ratios to the mixtures. Marshal parameters (% VFB, % VIM, % VMA, and Bulk Specific Gravity) for asphalt mixtures were reported to be not significantly affected by changing the type of filler at specific filler contents. On the other hand, Penetration, Ring and Ball Softening point, Viscosity, and Kinematic Viscosity tests on the filler-binder mixtures (mastics) showed that all types of mineral fillers acted as an extender to the binder with minimal stiffening effect. But comparing to others, hydrated lime showed superior stiffening performance. The authors also recommended to use hydrated lime as a mineral filler in a ratio of 0.5 to 0.8 of the bitumen content in the asphalt mixtures. Afterwards Paul, 1995; Khosla et al., 2000; McCann and Sebaaly, 2003; Khattak and Kyatham, 2008 conducted numerous researches to evaluate the influence of hydrated lime on the moisture damage of HMA pavements. In those studies, hydrated lime was reported to improve the resistance against the moisture induced damages of HMA mixtures. By maintaining a good adhesion between the aggregate and the asphalt cement in the presence of water, hydrated lime worked successfully as an antistripping agent. Its ability to reduce viscosity building polar components in the asphalt binder enabled hydrated lime to show effect as an oxidation reducing agent. Also, its ability to increase mixture stiffness by filling air voids in the mixture with its tiny particles makes it effective mineral filler

Baig et al. [1998] conducted a study to investigate the effectiveness of using hedmanite (rockwool natural fibers) and lime as filler in improving the performance of HMA mixtures that could withstand the major pavement distress problems in the desert climate of Saudi Arabia. Locally used quarried limestone and the 60/70 penetration grade asphalt were used while the Marshall mix design method was implemented to produce mixtures. Resilient modulus test, Marshall stability test, Split tensile strength test, and Fatigue and permanent deformation test were conducted and the results indicated that the use of these fillers improved the resilient modulus, fatigue property, and resistance to rutting compared to the control mix. Among two fillers, the stability loss and tensile strength loss were higher in hedmanite mixes while lime modified mixes showed better resistance to rutting and the adverse effect of water. Consequently, the researchers opted for lime as filler than hedmanite to produce better quality asphalt concrete mixtures.

Lime-treated mixtures also showed cost efficiency in terms of pavement life. Sebaaly et al. [2003] conducted a research to quantify the improvements of pavement performance that contained lime. Performances of HMA mixtures from the northwestern part of Nevada were evaluated both in the laboratory and in the field. In the laboratory evaluation, both lime treated and untreated sections were sampled and then evaluated through laboratory test. On the other hand, pavement performance data from pavement management system (PMS) were used to assess field performance of lime treated and untreated sections. The study showed that lime treatment on HMA mixtures significantly improved their moisture resistance and resistance to multiple freeze-thaw cycles than that of untreated HMA mixtures. From the long-term pavement performance data it was also evident that under similar environmental and traffic conditions, lime treated mixtures provided better performance with lesser maintenance and rehabilitation activities. Again, the analysis of the impact of lime on pavement life indicated that lime treatment extended the performance life of HMA pavements by an average of 3 years which represented an average increase of 38% in the expected pavement life.

Hydrated lime can be introduced into asphalt mixes by several methods: lime slurry to dry or wet aggregate, dry lime to wet aggregate, dry lime to dry aggregate and dry lime to asphalt. Although little research has been done to quantify the difference in effects of these methods, it is sufficient to say that asphalt mixes benefit from the addition of hydrated lime, no matter how it is introduced into the mix (Epps et al. 2003). Typically, the amount of hydrated lime added is 1 to 2 percent by weight of the mix, or 10 to 20 percent by weight of the liquid asphalt binder but If an aggregate has more fines present, it may be necessary to use more lime additive due to the increased surface area of the aggregate.

## 3- MATERIAL CHARACTERAZATION

The materials used in this work, namely asphalt cement, aggregate, and fillers were characterized using routine type of tests and results were compared with State Corporation for Roads and Bridges specifications (SCRB, R/9 2003)

### 3-1 Asphalt Cement

The asphalt cement used in this work is a 40-50 penetration grade. It was obtained from the Dora refinery, south-west of Baghdad. The asphalt properties are shown in Table (1) below.

**Table 1 Properties of Asphalt Cement**

| Property | ASTM designation | Penetration grade 40-50 | |
|---|---|---|---|
| | | Test results | SCRB specification |
| 1-Penetration at 25C,100 gm,5 sec. (0.1mm) | D-5 | 47 | 40-50 |
| 2- Rotational viscosity at 135◦C (cP.s) | D4402 | 519 | …… |
| 2- Softening Point. (◦C) | D-36 | 47 | …… |
| 3-Ductility at 25 C, 5cm/min,( cm) | D-113 | >100 | >100 |
| 4-Flash Point, (◦C) | D-92 | 289 | Min.232 |
| 5-Specific Gravity | D-70 | 1.041 | …… |
| 6- Residue from thin film oven test<br>- Retained penetration,% of original<br>- Ductility at 25 C, 5cm/min,( cm) | D-1754<br>D-5<br>D-113 | <br>59.5<br>80 | <br>>55<br>>25 |

## 3-2 Aggregate

The aggregate used in this work was crushed quartz obtained from Amanat Baghdad asphalt concrete mix plant located in Taji, north of Baghdad, its source is Al-Nibaie quarry. This aggregate is widely used in Baghdad city for asphaltic mixes. The coarse and fine aggregates used in this work were sieved and recombined in the proper proportions to meet the wearing course gradation as required by SCRB specification (SCRB, R/9 2003). The gradation curve for the aggregate is shown in Figure (1).

Routine tests were performed on the aggregate to evaluate their physical properties. The results together with the specification limits as set by the SCRB are summarized in Table (2). Tests results show that the chosen aggregate met the SCRB specifications.

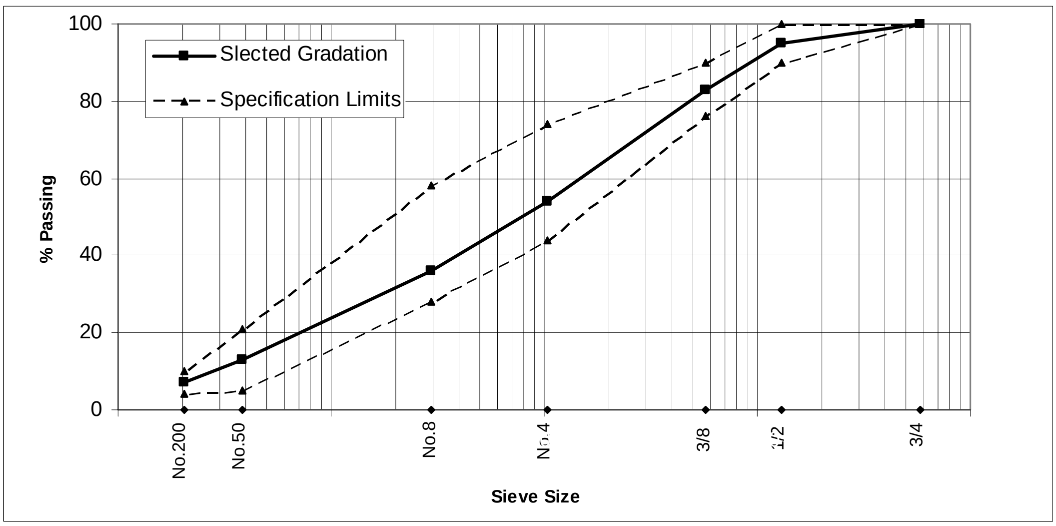


**Fig. 1 Aggregate Gradation**

**Table (2) Physical Properties of Aggregates**

| Property | ASTM designation | Test results | SCRB specification |
|---|---|---|---|
| <u>Coarse aggregate</u> | | | |
| 1. Bulk specific gravity | C-127 | 2.614 | …… |
| 2. Apparent specific gravity | | 2.686 | …… |
| 3. Water absorption,% | | 0.441 | …… |
| 4. Percent wear by Los Angeles abrasion ,% | C-131 | 17.5 | 30 Max |
| 5. Soundness loss by sodium sulfate solution,% | C-88 | 3.4 | 10 Max |
| 6. Fractured pieces, % | | 9٨ | 9٠ Min |
| <u>Fine aggregate</u> | | | |
| 1. Bulk specific gravity | C-127 | 2.664 | …… |
| 2. Apparent specific gravity | | 2.696 | …… |
| 3. Water absorption,% | | 0.724 | …… |
| 4. Sand equivalent,% | D-2419 | 57 | 45 Min. |

## 3-3 Filler

The filler is a non plastic material that passing sieve No.200 (0.075mm). In this work, the control mixes were prepared using limestone dust as a mineral filler at a content of 7 percent, this content represent the mid-range set by the SCRB specification for the type IIIA mixes of wearing course. Mixes in which the limestone dust was partially replaced by a hydrated lime were also prepared. The replacement percentages were 0, 0.5, 1.0, 1.5, 2, 2.5 and 3% by total weight of aggregate. The limestone dust and hydrated lime were obtained from lime factory in Karbala governorate, south east of Baghdad. The chemical composition and physical properties of the fillers are presented in Table (3) below:

**Table (3) Properties of Fillers**

| Filler type | Chemical Composition ,% | | | | | | | Physical Properties | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cao | $Sio_2$ | $Al_20_3$ | Mgo | $Fe_2o_3$ | $So_3$ | L.O.I | Specific gravity | Surface area* ($m^2$/kg) | % Passing sieve No. 200( 0.075) |
| Limestone Dust | ٦٨,٣ | 2.23 | - | ٠,٣٢ | - | ١,٢٠ | ٢٧,٣ | 2.41 | ٢٤٤ | ٩٤ |
| Hydrated Lime | 56.1 | 1.38 | 0.72 | ٠,١٣ | 0.12 | 0.21 | ٤٠,٦ | ٢,٧٨ | ٣٩٨ | ٩٨ |

* Blain air permeability method (ASTM C204)

## 4- EXPERIMENTAL WORK

The experimental work was started by determining the optimum asphalt content for all the asphalt concrete mixes using the Marshall mix design method. To investigate the stiffening effect of hydrated lime on the filler-asphalt mortar, filler-asphalt mixes were then prepared and tested using the conventional binder tests, penetration and softening point. Also, asphalt concrete mixes were made at their optimum asphalt content and tested to evaluate the engineering properties which include moisture damage, resilient modulus, permanent deformation and fatigue characteristics. These properties have been evaluated using indirect tensile strength, uniaxial repeated loading and repeated flexural beam tests.

## 4-1 Marshall Mix Design

A complete mix design was conducted using the Marshall method as outlined in AI's manual series No.2 (AI, 1981) using 75 blows of the automatic Marshall compactor on each side of specimen. Based upon this method, the optimum asphalt content is determined by averaging the three values shown below:

Asphalt content at maximum unit weight
Asphalt content at maximum stability
Asphalt content at 4% air voids

For each percentage of hydrated lime content, six Marshall specimens were prepared with a constant increments rate in asphalt cement content of 0.2 percent. The selected asphalt cement content starts from 4.2 percent for the control and 0.5 percent hydrated lime mixes and increased 0.2 percent for each 1 percent increase in hydrated lime content, so for the mixes with 3 percent hydrated lime, the starting value for asphalt cement content was 4.8 percent. This procedure is followed since it was found earlier in this work that the use of low asphalt content was not sufficient to provide proper coating for the aggregate with high content of hydrated lime. The complete summary of Marshall test data is shown in appendix A.

## 4-2 Conventional Binder Test

To investigate the stiffening effect of hydrated lime upon the filler- asphalt mixture, the penetration as well as softening point tests was conducted according the ASTM –D5 and ASTM D 36, respectively for the mixes prepared using 7 percent filler but with different hydrated lime contents as a partial replace of limestone filler and corresponding optimum asphalt cement content.

## 4-3 Indirect Tensile Test

The moisture susceptibility of the asphalt concrete mixtures was evaluated using ASTM D 4867. The result of this test is the indirect tensile strength (ITS) and tensile strength ratio (TSR). In this test, a set of specimens were prepared for each mix according to Marshall procedure and compacted to 7±1 % air voids using different numbers of blows per face that varies from (34 to 49) according to the hydrated lime replacement rate. The set consists of six specimens and divided into two subsets, one set (control) was tested at 25°C and the other set (conditioned) was subjected to one cycle of freezing and thawing then tested at 25°C. The test (shown below in fig. (2)) involved loading the specimens with compressive load at a rate of (50.8mm/min) acting parallel to and along the vertical diametrical plane through 0.5 in. wide steel strips which are curved at the interface with specimens. These specimens failed by splitting along the vertical diameter. The indirect tensile strength which is calculated according to (Eq.1) of the conditioned specimens (ITSc) is divided by the control specimens (ITSd), which gives the tensile strength ratio (TSR) as the following (Eq.2).

$$ITS = \frac{2P}{\pi t D} \qquad \text{eq. (1)}$$

$$TSR = \frac{ITS_c}{ITS_d} \qquad \text{eq. (2)}$$

where
ITS= Indirect tensile strength
P = Ultimate applied load
t = Thickness of specimen
D = Diameter of specimen
Other parameters are defined previously


**Fig. 2 Photograph for ITS test**

## 4-4 Uniaxial repeated loading test

The uniaxial repeated loading tests were conducted for cylindrical specimens, 101.6 mm (4 inch) in diameter and 203.2 mm (8 inch) in height, using the pneumatic repeated load system (shown below in fig.(3)). In these tests, repetitive compressive loading with a stress level of 20 psi was applied in the form of rectangular wave with a constant loading frequency of 1 Hz (0.1 sec. load duration and 0.9 sec. rest period) and the axial permanent deformation was measured under the different loading repetitions. All the uniaxial repeated loading

tests were conducted at 40°C (104°F). The specimen preparation method for this test can be found elsewhere (Albayati, 2006).
The permanent strain (εp) is calculated by applying the following equation:

$$\varepsilon_p = \frac{p_d \times 10^6}{h} \quad \text{eq. (3)}$$

where
εp= axial permanent microstrain
pd= axial permanent deformation
h= specimen height
Also, throughout this test the resilient deflection is measured at the load repetition of 50 to 100, and the resilient strain (εr) and resilient modulus (Mr) are calculated as follows:

$$\varepsilon_r = \frac{r_d \times 10^6}{h} \quad \text{eq. (4)}$$

$$M_r = \frac{\sigma}{\varepsilon_r} \quad \text{eq. (5)}$$

where
εr= axial resilient microstrain
rd= axial resilient deflection
h= specimen height
Mr= Resilient modulus
σ = repeated axial stress
εr= axial resilient strain


**Fig. 3 Photograph for the PRLS**

The permanent deformation test results for this study are represented by the linear log-log relationship between the number of load repetitions and the permanent microstrain with the form shown in Eq.6 below which is originally suggested by Monismith et. al., (1975) and Barksdale (1972).

$$\varepsilon_p = aN^b \quad \text{eq. (6)}$$

where
εp= permanent strain
N=number of stress applications
a= intercept coefficient
b= slope coefficient

## 4-5 Flexural Beam Fatigue Test

Within this study, third-point flexural fatigue bending test was adopted to evaluate the fatigue performance of asphalt concrete mixtures using the pneumatic repeated load system, this test was performed in stress controlled mode with flexural stress level varying from 5 to 30 percent of ultimate indirect tensile strength applied at the frequency of 2 Hz with 0.1 s loading and 0.4 s unloading times and in rectangular waveform shape. All tests were conducted as specified in SHRP standards at 20°C (68°F) on beam specimens 76 mm (3 in) x 76 mm (3 in) x 381 mm (15 in) prepared according to the method described in (Al-khashaab, 2009). In the fatigue test, the initial tensile strain of each test has been determined at the 50th repetition by using (Eq.7) shown below and the initial strain was plotted versus the number of repetition to failure on log scales, collapse of the beam was defined as failure, the plot can be approximated by a straight line and has the form shown below in (Eq. 8).

$$\varepsilon_t = \frac{\sigma}{Es} = \frac{12h\Delta}{3L^2 - 4a^2} \quad \text{eq. (7)}$$

$$N_f = k_1(\varepsilon_t)^{-k2} \quad \text{eq. (8)}$$

where
$\varepsilon_t$ = Initial tensile strain
σ =Extreme flexural stress
Es =Stiffness modulus based on center deflection.
h =Height of the beam
Δ =Dynamic deflection at the center of the beam.
L = Length of span between supports.
a =Distance from support to the load point (L/3)
$N_f$= Number of repetitions to failure
$k_1$= fatigue constant, value of Nf when $\varepsilon_t = 1$
$k_2$= inverse slope of the straight line in the logarithmic relationship

## 5- TEST RESULTS AND DISCUSSION

### 5-1 Effects of Hydrated Lime on Filler-Asphalt Mixes

The consistency of filler-asphalt mixes with different percentage contents of hydrated lime as partial replacement of limestone dust was determined using the penetration and softening point tests, the result of tests are presented in table (4) and shown graphically in figures (4) and (5).

**Table (4) Penetration and softening point tests result**

| Hydrated Lime Content* , % | | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|---|
| Optimum Asphalt Content, % | | ٤,٧٣ | ٤,٧٥ | ٤,٨٨ | ٤,٩٢ | ٥,٠٧ | ٥,١٣ | ٥,٣٤ |
| Test Results | Penetration at 25C,100 gm,5 sec. (0.1mm) (original=47) | ٣٤ | ٣٢ | ٢٩ | ٢٨ | ٢٦ | ٢٢ | ١٩ |
| | Softening Point, (◦C) (original=47°C) | 51.0 | 54.2 | 58.0 | 59.6 | 61.3 | 64.4 | 69.0 |

* As partial replacement of limestone dust, 7 percent filler content is constant.

As can be seen from the presented data, hydrated lime content has a substantial influence on the the consistency of filler-asphalt mixes. With respect to the penetration test, the penetration decreases with increasing hydrated lime content, for example, the penetration value for 1.5 percent hydrated lime content is 0.875 times the value of 0.5 percent, the constant of proportionality which can be driven from figure (4) is approximately -4.857 (1/10 mm) for each 1 percent increase in hydrated lime content. By contrast, the softening point increases with increasing the hydrated lime content and the constant of proportionality is +5.55 (◦C) for each 1 percent increase in hydrated lime content. From the above results, it may be possible to argue that the higher the replacement rate of limestone dust with hydrated lime, the higher the stiffness of the resulted filler-asphalt mixes.

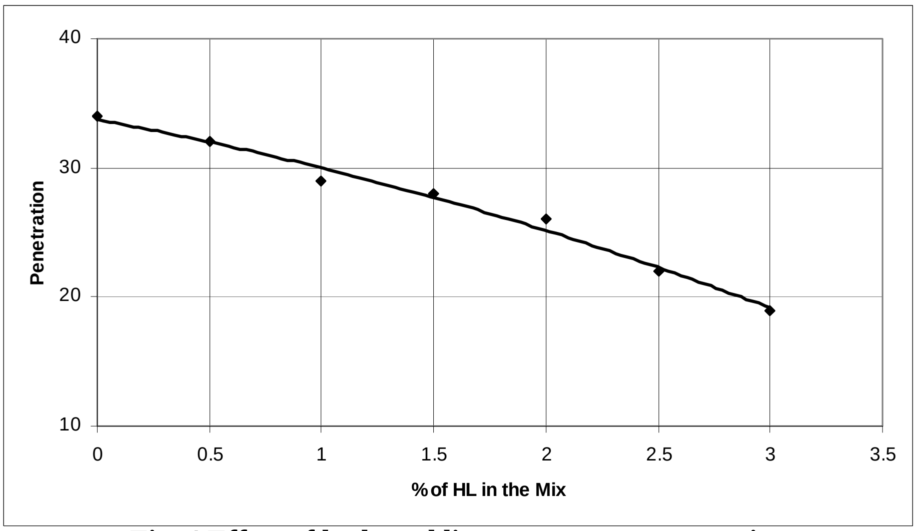


**Fig. 4 Effect of hydrated lime content on penetration**

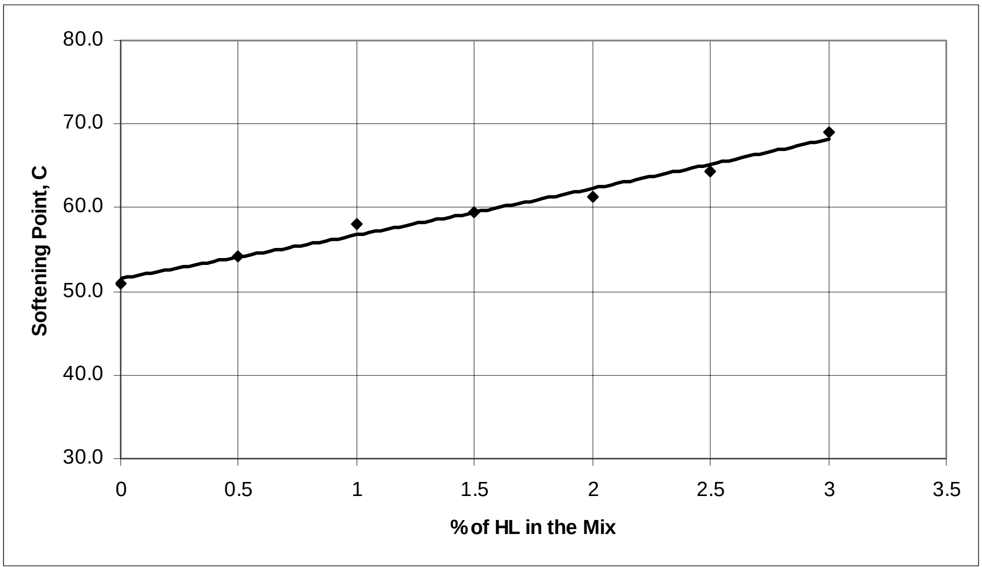


**Fig. 5 Effect of hydrated lime content on softening point**

## 5-2 Effects of Hydrated Lime on Marshall Properties

The variation of Marshall properties with hydrated lime content is shown in figure (6) which is based on the data presented in Table (5). Examinations of the presented data suggest that the mixes with higher hydrated lime content possess higher optimum asphalt cement content, the highest value of optimum asphalt content (5.34%) was obtained with 3% hydrated lime, while the lowest value (4.73%) was obtained with 0% hydrated lime which is the case that the mineral filler entirely consists of limestone dust.

**Table (5) Summary of the Marshall properties of asphalt concrete mixes at optimum asphalt content**

| Hydrated Lime Content* , % | | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|---|
| Optimum Asphalt Content, % | | ٤,٧٣ | ٤,٧٥ | ٤,٨٨ | ٤,٩٢ | ٥,٠٧ | ٥,١٣ | ٥,٣٤ |
| Marshall Properties | Stability, kN | 8.65 | 8.87 | 9.76 | 10.3 | 11.05 | 11.14 | 11.2 |
| | Flow, mm | 3.23 | 3.5 | 3.62 | 3.73 | 3.8 | 3.53 | 3.41 |
| | Density, gm/cm$^3$ | 2.320 | 2.329 | 2.333 | 2.336 | 2.348 | 2.337 | 2.331 |
| | Air Voids, % | 4.3 | 4.14 | 4.03 | 3.94 | 3.71 | 4.21 | 4.7 |
| | VMA , % | 15.83 | 15.45 | 15.49 | 15.42 | 15.12 | 15.57 | 15.97 |

* As partial replacement of limestone dust, 7 percent filler content is constant.

These differences can be attributed to the higher surface area of hydrated lime as compared to that of limestone dust. As shown earlier in this study, the surface area of hydrated lime is 1.63 times that of limestone dust, and hence the demand for asphalt has increased with increasing the replacement rate of limestone dust with hydrated lime. With respect to stability, the results indicate that the stability increases with increasing hydrated lime content, also the increment rate varies with hydrated lime content, the maximum rate obtained is 1.09 kN/1 percent for the hydrated lime content ranged from 0.5 to 2 percent, whereas for the hydrated lime content ranged from 0 to 0.5 percent and from 2 to 3 percent the rate was 0.44 and 0.15 kN/1 percent, respectively. From the stability plot, it may be possible to argue that the maximum benefit can be obtained with the use of 2 percent hydrated lime since further increase in hydrated lime content associated with just slight increases in stability value and require more asphalt cement content as compared to mixes with 2 percent hydrated lime.

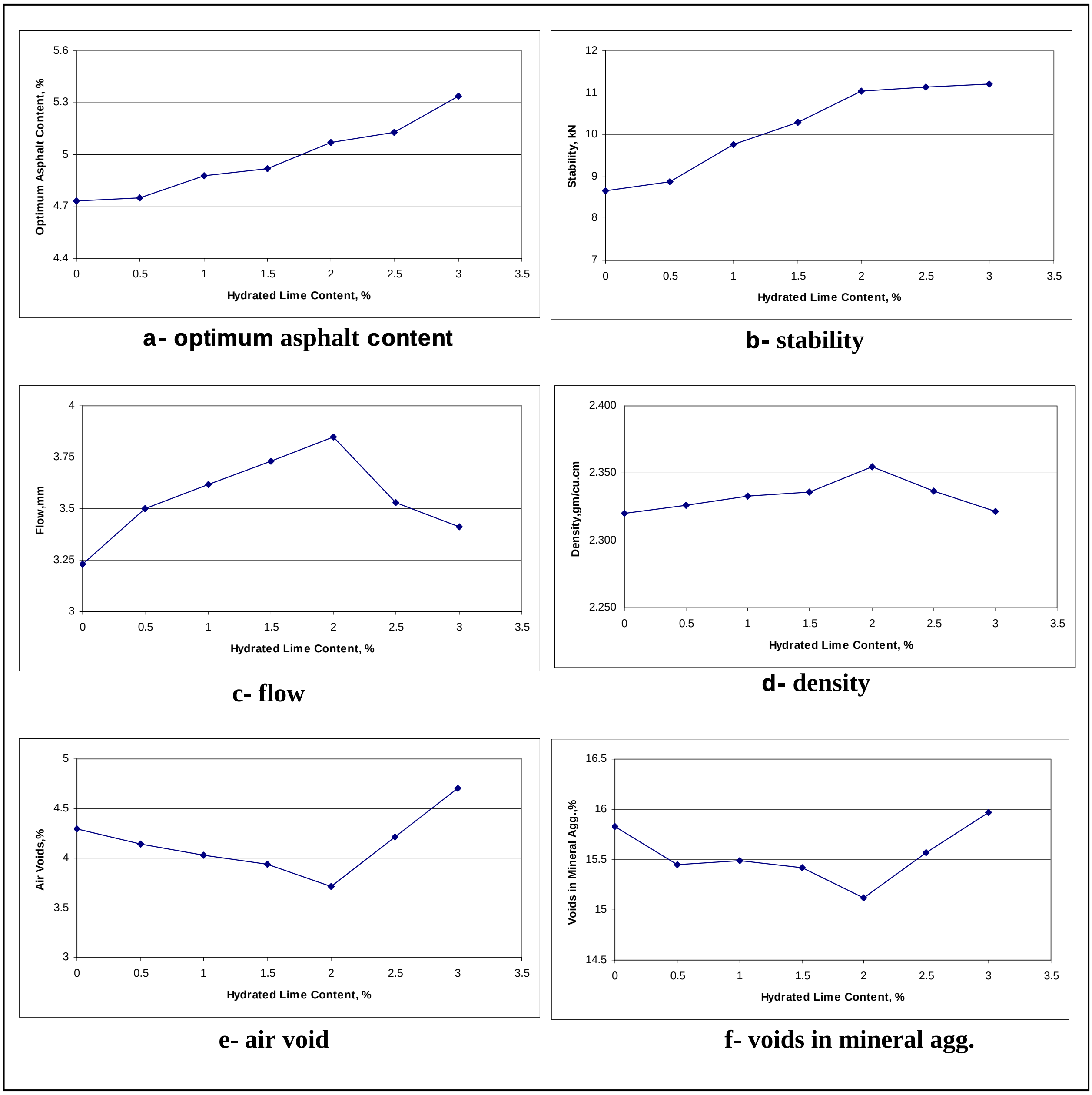


**Fig. 6 Effect of hydrated lime content on Marshall properties**

The results of flow as a function of varying the hydrated lime content is shown in plot "c", its obvious that the flow value increases as the hydrated lime content increases from 0 to 2 percent, and then decreases as the hydrated lime content increases. This is due to the fact that air voids are too low at 2 percent hydrated lime content, addition of hydrated lime higher than this value tend to increase air voids due to insufficient compaction effort so the flow value decrease. The relationship between hydrated lime content and density which is shown in plot "d" follow the same trend of that between the hydrated lime content and Marshall flow, an optimum hydrated lime content which yields the highest Marshall density is 2 percent, further increases in hydrated lime content tend to decrease the Marshall density. As demonstrated in plot "e", the trend observed for the effect of hydrated lime content on air voids values is exactly opposite to that observed between hydrated lime content and flow , for a hydrated lime content from 0 to 2 percent, the air voids decreases with a rate of -0.295 percent for each 1 percent change in hydrated lime content, beyond 2 percent, the air voids content increases rapidly with a rate of +0.99 percent for each 1 percent change in hydrated lime content, this can be easily explained by the fact that the hydrated lime is finer than limestone dust so it can efficiently fill the voids pockets and stiffens the mixes for a certain amount beyond which there will be a lack in the compaction effort resulting in high air voids content. Plot "f" demonstrates the effect of hydrated lime content on voids in mineral aggregate (VMA), as its clear from the plot until a 2 percent of hydrated lime content the VMA decreases as the hydrated lime content increases, the minimum VMA value corresponding to 2 percent hydrated lime is 15.12 percent which means less spaces to be accommodated by asphalt cement, after 2 percent hydrated lime content, an addition of hydrated lime result in increasing the VMA values.

## 5-3 Effects of Hydrated Lime on Moisture Susceptibility

Based on the data shown in Table (6) and Figure (7), it appears that the examined hydrated lime contents have influence on the moisture susceptibility of the asphalt concrete mixes. The indirect tensile strength results for both control and conditioned mixes approximately linearly proportional to the hydrated lime content with constants of proportionality of +92.5 for the former and +150.5 kPa per 1 percent change in hydrated lime content for the latter. It is interesting to note that the improvement rate in the indirect tensile strength for the mixes with hydrated lime, added as part of the mineral filler, is higher in the case of conditioned mixes than that of control mixes. These findings beside that related to tensile strength ratio shown in figure (7) confirm that the resistance to moisture induced damage is enhanced in asphalt concrete pavement modified with hydrated lime.

**Table (6) Moisture susceptibility test results**

| Hydrated Lime Content, % | ITS, kPa | | TSR, % |
|---|---|---|---|
| | Control | Conditioned | |
| 0 | 1290 | 1051 | 81.5 |
| 0.5 | 1342 | 1053 | 78.4 |
| 1.0 | 1373 | 1124 | 81.9 |
| 1.5 | 1441 | 1200 | 83.3 |
| 2.0 | 1496 | 1281 | 85.6 |
| 2.5 | 1532 | 1405 | 91.7 |
| 3.0 | 1554 | 1467 | 94.4 |

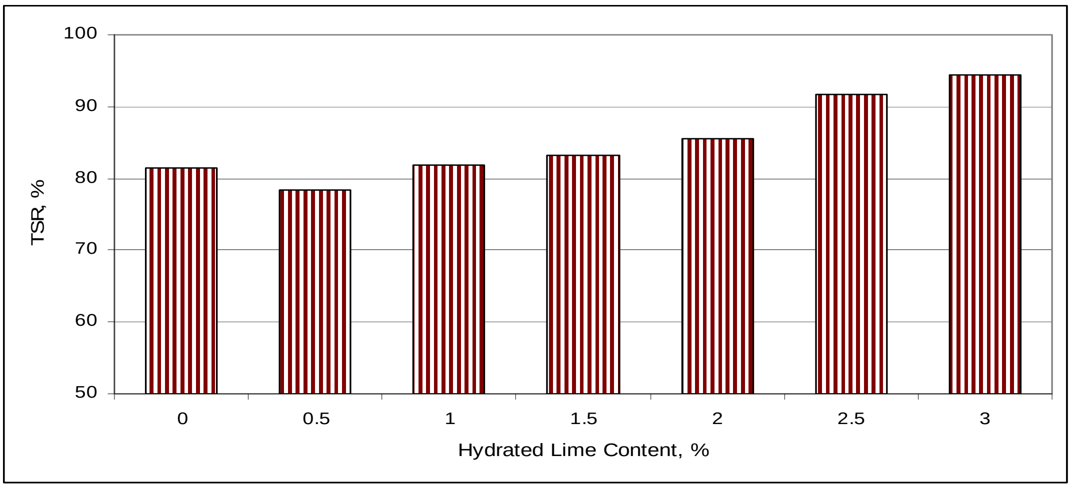


**Fig. 7 Effect of hydrated lime content on tensile strength ratio**

## 5-4 Effects of Hydrated Lime on Resilient Modulus

Table (7) as well as figure (8) exhibits the variation of the resilient modulus values with the hydrated lime content. The relation is in reverse order up to 1 percent content of hydrated lime (i.e., as the hydrated lime content increases the resilient modulus decreases), but further increase in hydrated lime content reflects this relation, the resilient modulus of the mixes with 3 percent hydrated lime (159165 psi) is 1.4 times the value for mixes with 1 percent hydrated lime which was 112995 psi. these results can be explained as follow; since the test was conducted under relatively high temperature (40°C (104°F)), so the low level of hydrated lime content (below 1 percent) is insufficient to stiffening the asphalt concrete mixes whereas the higher values of resilient modulus resulted from the high level of hydrated lime content (above 1 percent) indicate that the hydrated lime did increase the stiffness of the asphalt concrete mix.

**Table (7) Resilient modulus test results**

| Hydrated Lime Content , % | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|
| Resilient Modulus, psi | 121500 | 115425 | 112995 | 126360 | 143370 | 151875 | 159165 |

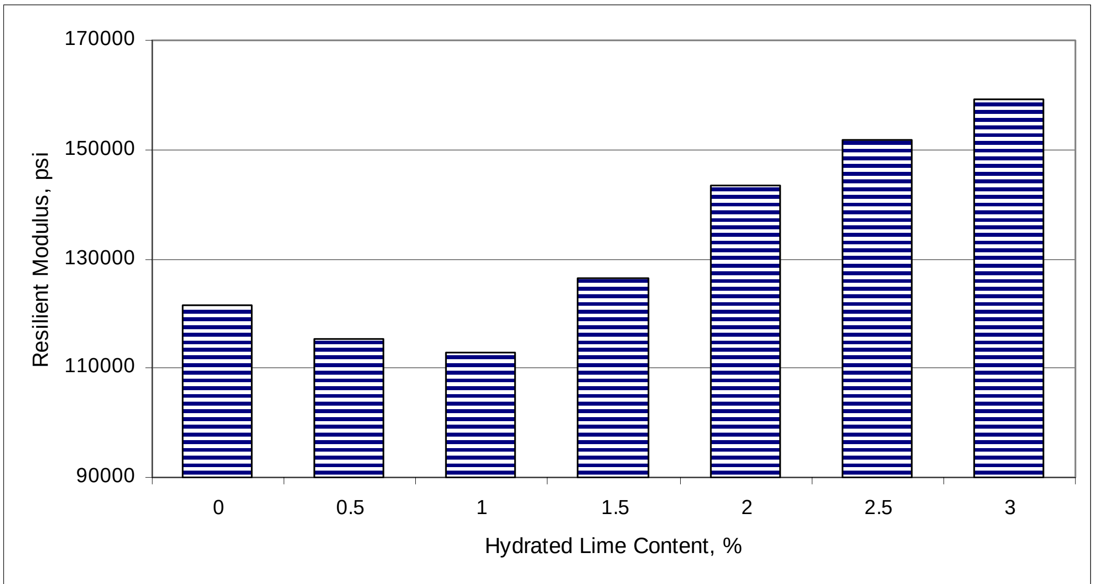


**Fig. 8 Effect of hydrated lime content on resilient modulus**

## 5-5 Effects of Hydrated Lime on Permanent Deformation

The result of permanent deformation tests is shown in figure (9) which is based on the data presented in table (8), Examinations of the presented data suggests that the permanent deformation parameters intercept and slope generally improved with the use of hydrated lime, for mixes containing 0 percent hydrated lime, the slope value which reflects the accumulation rate of permanent deformation is approximately 20 percent higher than that of mixes with 3 percent hydrated lime. For the intercept, the value is slightly increase as the hydrated lime content increases from the 0 to 0.5 percent, but then the addition of extra amount of hydrated lime tend to decrease the intercept value in a rate of 19.7 microstrain per each 1 percent change in hydrated lime content. This finding confirms that the rutting mode of failure in asphalt concrete pavement which is enhanced at hot summer temperature can be reduced into large extent with the introduction of hydrated lime to asphalt concrete mixtures.

**Table (8) permanent deformation test results**

| Hydrated Lime Content , % | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|
| Intercept | 108 | 113 | 102 | 95 | 80 | 70 | 66 |
| Slope | 0.372 | 0.366 | 0.355 | 0.341 | 0.324 | 0.312 | 0.300 |

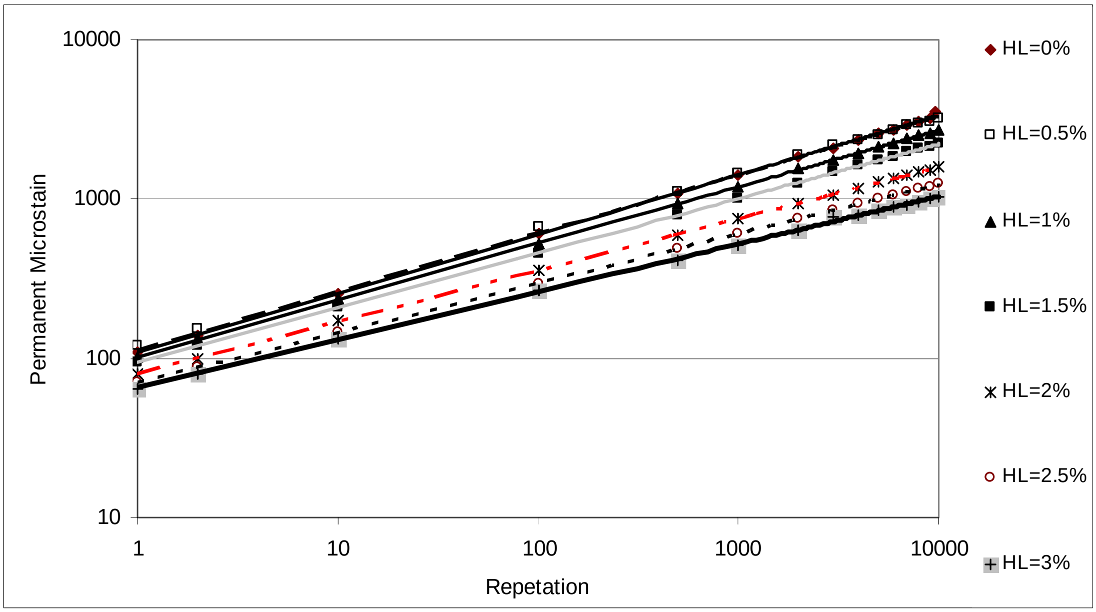


**Fig. 9 Effect of hydrated lime content on resilient modulus**

## 5-6 Effects of Hydrated Lime on Fatigue Performance

The fatigue characteristic curves for all mixtures are presented in Fig. 10. The fatigue parameters k1 and k2 are shown in Table 9. Values of k1 and k2 can be used as indicators of the effects of hydrated lime on the fatigue characteristics of a paving mixture. The flatter the slope of the fatigue curve, the larger the value of. $k_2$ If two materials have the same $k_1$ value, then a large value of $k_2$ indicates a potential for longer fatigue life. On the other hand, a lower $k_1$ value represents a shorter fatigue life when the fatigue curves are parallel, that is, $k_2$is constant. Test results indicate that the use of hydrated lime with a rate of content ranged from 0 to 1 percent does not have significant effect on fatigue life but the mixes with more than 1 percent hydrated lime showed better fatigue performance, the $k_2$ value for mixes with 2 and 3 percent hydrated lime was more than that of 1 percent hydrated lime by 54.4 and 30.6 percent, respectively. Considering $k_1$, it can be concluded from the data shown in table (9) that there is an agreement between the results of $k_1$ and $k_2$ in the field of fatigue resistance, $k_1$ has the smallest value (9.561x E-12) when the hydrated lime content was 3 percent and it was increase as the hydrated lime content decreased from 3 to 1 percent, but for the mixes with 0.5 percent hydrated lime content, $k_1$ value was more than that of 0 percent hydrated lime.

**Table (9) Fatigue test results**

| Hydrated Lime Content , % | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|
| $k_1$ | 1.339 x E-7 | 4.162 x E-7 | 1.780 x E-7 | 1.555 x E-8 | 1.822 x E-9 | 5.499 x E-11 | 9.561 x E-12 |
| $k_2$ | 2.74 | 2.56 | 2.61 | 3.08 | 3.41 | 3.83 | 4.03 |

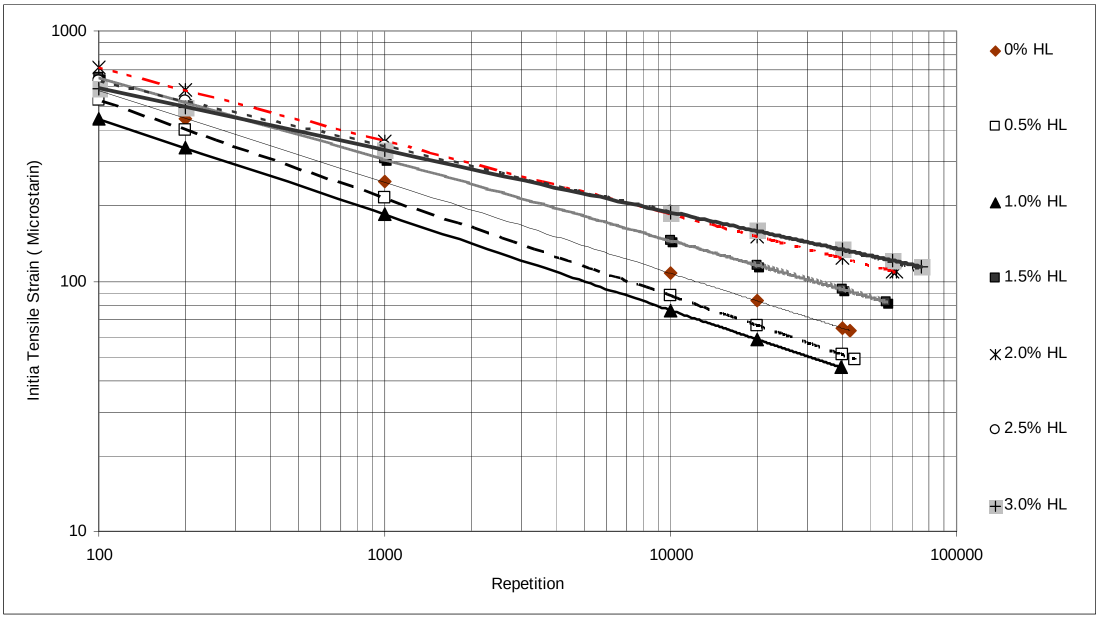


**Fig. 10 Effect of hydrated lime content on fatigue performance**

## 6- CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the results of the laboratory tests and analysis presented in this study:

1. In the filler-asphalt mixes, hydrated lime has shown significant stiffening properties when mixed with asphalt cement as partial replacement for limestone dust. For each 1 percent increase in hydrated lime, the penetration value decreases at a rate of 4.857 (1/10 mm) whereas the softening point increases at a rate of +5.55 (˚C).
2. The addition of different percentages of hydrated lime as a filler substitute has a significant effect on volumetric mixture properties, some of the obtained results can be summarized as follow:
   - The mixes with higher hydrated lime content possess higher optimum asphalt content, the highest value of optimum asphalt content (5.34%) was obtained with 3 percent hydrated lime, while the lowest value (4.73%) was obtained with 0 percent hydrated lime
   - An optimum hydrated lime content which yields the highest density is 2 percent, further increases in hydrated lime content tend to decrease the density
   - For mixes with a hydrated lime content ranged from 0 to 2 percent, the air voids decreases with a rate of -0.295 percent for each 1 percent change in hydrated lime content. Beyond 2 percent, the air voids content increases rapidly with a rate of +0.99 percent for each 1 percent change in hydrated lime content

3. The addition of hydrated lime has improved the indirect tensile strength for both control and conditioned mixes with a rate of +92.5 and +150.5 kPa per 1 percent increase in hydrated lime content, respectively. The resistance to moisture induced damage is enhanced in asphalt concrete pavement modified with hydrated lime
4. The addition of hydrated lime as a filler substitute with a rate ranged from 1.5 to 3 percent has shown an increase in resilient modulus. The resilient modulus for mixes with 3 percent hydrated lime was 1.31 times that for mixes with 0 percent hydrated lime.
5. The permanent deformation parameters, slope and intercept, was significantly effected with the addition of deferent percentages of hydrated lime. The modified mixes show higher resistance to permanent deformation when the percentage of hydrated lime is increased as a filler substitute.
6. The use of hydrated lime as a filler substitute within a range of 1.5-3 percent has improved the fatigue property of the asphalt concrete mixes as determined by flexural test. The $k_2$ value (inverse slope of fatigue line) for mixes with 2 and 3 percent hydrated lime was more than that of 0 percent hydrated lime by 53.6 and 24.4 percent, respectively.
7. The use of 2 percent hydrated lime has shown a significant improvement of asphalt concrete behavior, and has added to the local knowledge the possibility of producing more durable mixtures with higher resistance to distresses.

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# APPENDIX A

## Table (A1) Mix design data

| Marshall Properties | Stability, kN | Flow, mm | Density, gm/cm$^3$ | Air voids, % | Voids in Mineral Aggregate, % |
|---|---|---|---|---|---|
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 0.0 %* | | | | |
| 4.2 | 7.85 | 2.88 | 2.281 | 6.57 | 16.79 |
| 4.4 | 8.18 | 3 | 2.294 | 5.76 | 16.49 |
| 4.6 | 8.78 | 3.1 | 2.311 | 4.62 | 16.04 |
| 4.8 | 8.08 | 3.25 | 2.325 | 3.97 | 15.71 |
| 5.0 | 7.43 | 3.4 | 2.316 | 4.22 | 16.21 |
| 5.2 | 7.13 | 3.65 | 2.309 | 4.06 | 16.64 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 0.5%* | | | | |
| 4.2 | 8.37 | 2.93 | 2.293 | 6.26 | 16.35 |
| 4.4 | 8.76 | 3.22 | 2.307 | 5.42 | 16.01 |
| 4.6 | 9.45 | 3.31 | 2.322 | 4.53 | 15.64 |
| 4.8 | 8.69 | 3.6 | 2.331 | 3.96 | 15.49 |
| 5.0 | 8.12 | 3.81 | 2.314 | 4.30 | 16.29 |
| 5.2 | 7.58 | 3.93 | 2.308 | 3.91 | 16.68 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 1%* | | | | |
| 4.4 | 8.91 | 3.1 | 2.311 | 5.35 | 15.87 |
| 4.6 | 9.36 | 3.32 | 2.319 | 4.75 | 15.75 |
| 4.8 | 9.88 | 3.56 | 2.321 | 4.40 | 15.86 |
| 5.0 | 9.69 | 3.78 | 2.334 | 3.59 | 15.56 |
| 5.2 | 9.49 | 3.88 | 2.325 | 3.69 | 16.07 |
| 5.4 | 9.23 | 3.94 | 2.32 | 3.77 | 16.42 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 1.5%* | | | | |
| 4.4 | 9.35 | 2.99 | 2.301 | 6.05 | 16.23 |
| 4.6 | 10.14 | 3.12 | 2.318 | 5.08 | 15.79 |
| 4.8 | 10.46 | 3.64 | 2.332 | 4.24 | 15.46 |
| 5.0 | 10.19 | 3.75 | 2.336 | 3.80 | 15.49 |
| 5.2 | 10.12 | 3.8 | 2.328 | 3.86 | 15.96 |
| 5.4 | 9.97 | 3.98 | 2.322 | 3.93 | 16.35 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 2%* | | | | |
| 4.6 | 9.45 | 3.44 | 2.327 | 5.18 | 15.46 |
| 4.8 | 10.19 | 3.65 | 2.333 | 4.66 | 15.42 |
| 5.0 | 11.19 | 3.76 | 2.342 | 4.02 | 15.27 |
| 5.2 | 9.99 | 3.86 | 2.351 | 3.38 | 15.13 |
| 5.4 | 9.72 | 3.94 | 2.33 | 3.97 | 16.06 |
| 5.6 | 9.31 | 3.98 | 2.312 | 4.45 | 16.89 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 2.5%* | | | | |
| 4.6 | 9.84 | 3.21 | 2.319 | 5.88 | 15.75 |
| 4.8 | 9.95 | 3.44 | 2.331 | 5.01 | 15.49 |
| 5.0 | 11.29 | 3.6 | 2.336 | 4.54 | 15.49 |
| 5.2 | 10.76 | 3.74 | 2.342 | 3.94 | 15.45 |
| 5.4 | 9.64 | 3.82 | 2.322 | 4.13 | 16.35 |
| 5.6 | 8.29 | 3.89 | 2.306 | 4.59 | 17.10 |
| Asphalt Content, % (by wt. of total mix) | Hydrated Lime content = 3%* | | | | |
| 4.8 | 10.35 | 3.2 | 2.319 | 6.09 | 15.93 |
| 5.0 | 11.09 | 3.3 | 2.323 | 5.66 | 15.96 |
| 5.2 | 11.4 | 3.4 | 2.331 | 5.07 | 15.85 |
| 5.4 | 10.99 | 3.6 | 2.332 | 4.03 | 15.99 |
| 5.6 | 10.59 | 3.7 | 2.322 | 4.13 | 16.53 |
| 5.8 | 10.11 | 3.9 | 2.319 | 3.98 | 16.81 |