Experimental Study of the Moisture Susceptibility and Fatigue Performance of Hydrated Lime Modified Asphalt Concrete and a Design Application Case Study

[1,3]Ahmed F. Al-Tameemi, [1]Yu Wang*, [2]Amjad Albayati, [1]Jonathan Haynes

1. School of Computing, Science & Engineering, University of Salford, Manchester UK
2. Department of Civil Engineering, University of Baghdad, Iraq
3. Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq

ABSTRACT

Hydrated lime has been recognized as an effective additive used to improve asphalt concrete properties in pavement applications. However, further work is still needed to quantify the effect of hydrated lime on asphaltic concrete performance under varied weather, temperature and environmental conditions and in the application of different pavement courses. A research project has been conducted using hydrated lime to modify the asphalt concretes used for the applications of wearing (surface), levelling (binder) and base courses. A previous publication has reported the experimental study on the resistance to Marshall stability and the volumetric properties, the resilient modulus and permanent deformation at three different weather temperatures. This paper reports the second phase experimental study for material durability, which investigated the effect of hydrated lime content on moisture susceptibility when exposed to a freeze-thaw cycle, and the fatigue life. The experimental results show an improvement in the durability of the modified asphalt concrete mixtures. Optimum hydrated lime contents for different course applications are suggested based on the series experimental studies. Finally, the advantage of using the optimum mixtures for a pavement application is demonstrated.

Keywords

Asphalt concrete, Hydrated lime, Durability, Moisture susceptibility, Fatigue life, Pavement design.

*Corresponding Author, Email: y.wang@salford.ac.uk

INTRODUCTION

Moisture damage, fatigue cracking and accumulated permanent deformation (rutting) are the three major distresses in the property deterioration and the reduction in durability of flexible pavements. To address these problems, hydrated lime ($Ca(OH)_2$) has proven to be an effective additive, able to improve the mechanical properties and durability of asphalt concrete in pavement applications (Lesueur et al. 2016). Previous studies have found that asphalt concretes with added hydrated lime, which is normally used as a partial substitute for the conventional filler, limestone, showed a reduction in hardening age; an increase of flexural stiffness and resilient modulus at moderate and high temperatures; and improved ability to resist permanent deformation (Sebaaly et. al. 2001, Little et al. 2006, Albayati 2012, Albayati and Ahmed 2013). Hydrated lime displays a significant effect on the volumetric properties of concrete mixtures. A high hydrated lime content corresponds to a high asphalt content for mixtures of optimum properties (Albayati 2012). This means that the use of hydrated lime has less influence on the quantity of the main binder component of asphalt concrete. Compared with other conventional mineral fillers, such as fly ash and phosphogypsum, hydrated lime showed greater improvement in stiffness and rutting resistance of the modified asphalt concrete (Al-Suhaibani et al. 1992; Satyakumar et al. 2013).

When moisture is present in asphalt concrete it causes loss of strength and stiffness through a progressive process. The propagation of moisture damage generally occurs by two main mechanisms: loss of adhesion (stripping) and loss of cohesion (softening). Loss of adhesion happens at the interface between the aggregate and asphalt binder, while the loss of cohesion happens inside the matrix of the asphalt binder (mastic). Both laboratory and field studies have confirmed that hydrated lime is effective in controlling moisture damage for asphalt concrete (Al-Qadi et al. 2014). Hydrated lime has also proven to be effective to improve general mechanical properties, including fracture strength and fatigue life, of rubber modified hot asphalt mixtures at a hot weather temperature of 35°C (Othman 2011). The particle size plays an important role in the effect of hydrated lime on asphalt binder mechanisms. A study of the rheological characteristics of the foamed warm mix asphalt indicated that nano-sized hydrated lime modified asphalt binders exhibited a lower rutting potential. However, regular-sized hydrated lime modified asphalt binder presented a lower possibility to fatigue cracking (Diab and You, 2014).

Hydrated lime has a high Rigden air void value or high porosity at both dry and compacted states, which is nearly twice that of conventional mineral fillers (Lesueur et al. 2013). It also has a very high specific surface area, which is nearly ten times that of the conventional mineral fillers. The stiffening effect of hydrated lime may be partially explained by its high Rigden air void value and specific surface area, because high specific surface area increases the contact of hydrated lime particles with asphalt cement particles. Additionally, hydrated lime is an active filler, which precipitates the calcium ions on aggregate surfaces. The high content of calcium ions helps to create a chemical bond between silica in the aggregate and the acidic radical composition in bitumen in the form of water-insoluble salts (Ishai & Craus, 1977). It consequently improves the bitumen–aggregate adhesion (Blazek et al. 2000). Hydrated lime also slows down bitumen ageing because of the acid–base reactions between hydrated lime and the acids naturally present in the bitumen (Little & Petersen, 2005).

Hydrated lime has been reported upon in general for antistrip purposes in its pavement wearing surface application and at the range just up to 2% of the total asphalt concrete weight (EuLA_EN_2011_12_28). So far, using hydrated lime for other pavement layer application and the behaviour at varied temperature conditions have been little reported. The use of hydrated lime to modify asphalt concrete used for the whole pavement structure still faces insufficient knowledge from laboratory experiments and field tests. For this reason, extensive studies of the major mechanical behaviours of asphalt concrete are still required in order to understand how to quantify the usage of hydrated lime for the applications of different purposes and under varied environmental conditions. In an effort to enrich our knowledge in this aspect, a systematic research has recently been conducted using hydrated lime to modify the asphalt concrete mixtures intended for the application of three types of pavement course, i.e., wearing (or surface), levelling (or binder) and base at varied temperature conditions. A previous publication (Al-Tameemi et al., 2016) has reported the 1st phase work, the experimental study on the volumetric and Marshall properties, resistance to permanent deformation and the resilient modulus of hydrated lime modified mixtures under three temperatures. The experimental results suggested that an optimum 2.5% replacement of conventional lime stone filler using hydrated lime should be adopted in practice for all applications and weather conditions. This paper reports the 2nd phase of the research, the experimental study of the moisture susceptibility and fatigue performance of the modified mixtures. Finally, a case study has been investigated using the optimum mixtures for a pavement structure design and predicts effectiveness for real world applications.

EXPERIMENTS

Raw Materials and Mixture

The component materials used in this research were asphalt cement of 40-50mm penetration grade, aggregates, and mineral fillers (limestone dust and hydrated lime). The raw material properties have been reported in a previous paper (Al-Tameemi *et al*. 2016). Control mixes at first were prepared using limestone dust as the only mineral filler at the proportion of 7%, 6% and 5% by the total weight of the aggregate for the mixes used for wearing, levelling and base course applications, respectively. Meanwhile, referring to the control mix, other modified mixes were prepared using hydrated lime to replace the limestone dust filler at five different rates, they are 1.0, 1.5, 2.0, 2.5 and 3.0% by the total weight of the aggregates. Hydrated lime was added to the mixtures in the dry state. Table 1 gives the mix designs. Table 2 shows the particle size distribution of the aggregates and mineral fillers together against the specification defined in SCRB/R9 (2003).

Experimental Procedure

For the designed mixtures in Table 1, at first, the Marshall stability and flow tests were conducted to obtain the optimum asphalt content for the control and hydrated lime modified mixes in terms of the required stability, air void content and density. Thereafter specimens were prepared, which took the determined optimum asphalt content, and tested for moisture susceptibility and fatigue life.

Optimum Asphalt Content (OAC)

The Marshall stability and flow tests followed the Marshall method summarized in the manual series No. 2 produced by Asphalt Institute (1984). The asphalt cement (without mineral filler), taking percentages of the total weight of the mixtures, were in the range of 4.3~5.5 for the wearing course, 4.0~5.2 for the levelling course, and 3.7~4.9 for the base course, respectively. Different mixes were prepared at an interval of 0.3% in each range.

In accordance with the standards ASTM-D6926-10 (2010) and ASTM-D-1559 (2004), three cylindrical specimens of the size of 101.6 mm in diameter and 63.5 mm in length were made for the mixes each. These specimens were cured for 1/2 to 3/4 hours in a water bath at 60°C, after which they were compression tested across the diameter at a constant loading rate of 50.8mm/min (or 2 inch/min) until failure.

The test results were plotted in terms of the percentage of asphalt (by total weight of the mix) on a linear scale. Each point shown on subsequent graphs is an average result of the tests of the three specimens of a specific mixture. Thereafter, the Optimum Asphalt Content (OAC) was determined by taking the average of the three asphalt contents of the mixtures of the same hydrated lime content and respectively meeting the three criteria below:

- The maximum unit weight (density)
- The maximum stability
- 4% air voids.

Moisture Susceptibility Test

The test followed the ASTM standard (ASTM-D4867/D4867M−09). For each mix, six specimens of 101.6 mm diameter × 63.5 mm in length were cast according to the optimum asphalt content. Using the Marshall method, the cast specimens were compacted on both cylindrical ends to achieve a targeted 7.0 ± 0.5% air void content, aiming to accelerate the laboratory moisture damage test. The six specimens of each mix were thereafter divided into two sets, which were tested later, respectively, under unconditioned (dry) and conditioned (saturated) states (Fig. 1(a)).

For the unconditioned state test, specimens were placed in a water bath for one hour at 25 °C. Thereafter, they were taken out and surface dried with a towel prior to being tested for ultimate indirect tensile strength using the splitting method (Fig. 1(b)). The load was applied at a constant deformation rate of 50.8mm/minute across the cylinder diameter, via two rigid steel plates. The ultimate value of the applied load was recorded and the indirect tensile strength was calculated using Eq. (1) as defined by Neville & Brooks (1987).

$$\boldsymbol{S_t = \frac{2P}{\pi LD}} \qquad (1)$$

where S_t is the tensile strength; P is the maximum load applied; L is length of the specimen and D is the diameter.

For the conditioned state test, the specimens were put in a flask filled with water at an approximate temperature of 25 °C. A vacuum of 70kPa or 525mmHg was applied for 5 minutes to achieve a desired saturation level in the range of 70~80% in terms of the specifications in both the ASTM D4867 and the modified AASHTO T283 in 2003. Thereafter, each specimen was wrapped using a plastic film and sealed using tape. These wrapped specimens were transferred in airtight plastic bags containing approximately 3 ml distilled water in each bag and sealed again using tape. These bagged specimens were then placed in a freezer for 16 hours under a controlled temperature of -18 °C. After removal from the freezer, the bagged specimens were immediately immersed in a water bath of 60°C for 24 hours. Then all specimens were removed from the plastic bags and wraps, and placed in another water bath at 25 °C for one hour. Thereafter, specimens were taken out and dried using a towel, and then tested the indirect tensile strength following the same procedure described for the unconditioned state test. For the sake of comparison, a parameter called tensile strength ratio (TSR) is defined for each mix using Eq. (2).

$$\boldsymbol{TSR = \frac{S_{tm}}{S_{td}} \times 100} \qquad (2)$$

were, S_{tm} is the conditioned tensile strength and S_{td} is the unconditioned tensile strength.

Fatigue Test

The fatigue life test used the four point bending method (Fig. 1 (c) and (d)) which produces a pure constant bending in the section of the beam between the two applied loads (Fig. 2(a)). Repeated loads were applied until the failure of the beam and the maximum number of repeated load cycles was taken as the fatigue life of the each mixture. A stress controlled fatigue test method, rather than the strain-controlled test specified by AASHTO T321, was adopted because the available pneumatic loading system was only able to provide a stress-control function. Four load levels were applied by vertical downward (push) force P for each mixture, being 223, 310, 402 and 490 N.

Each load was applied in a rectangular repeated form with 0.1 seconds of loading followed by 0.4 seconds of resting (no loading) as illustrated in Fig. 2(b). There were three specimens prepared for each mix and tested. The final result for each mix took the average of the three. Each specimen was put in the test chamber at a controlled temperature of 20 ± 1 °C for six hours before the test to allow an even temperature distribution within the specimen to develop before conducting the test. A digital camera was used to record the failure process occurring at the mid-span of the beam during testing. The vertical deflection of the beam at mid-span was measured using a Linear Variable Displacement Transducer (LVDT) installed and connected to a data acquisition system. The specimen beams had dimensions of 76mm × 76 mm × 381 mm. The failure of the beam was taken when the specimen broke (completely split into two parts). In each test, an initial tensile strain was determined at the 200th repetition in terms of Eq. (3).

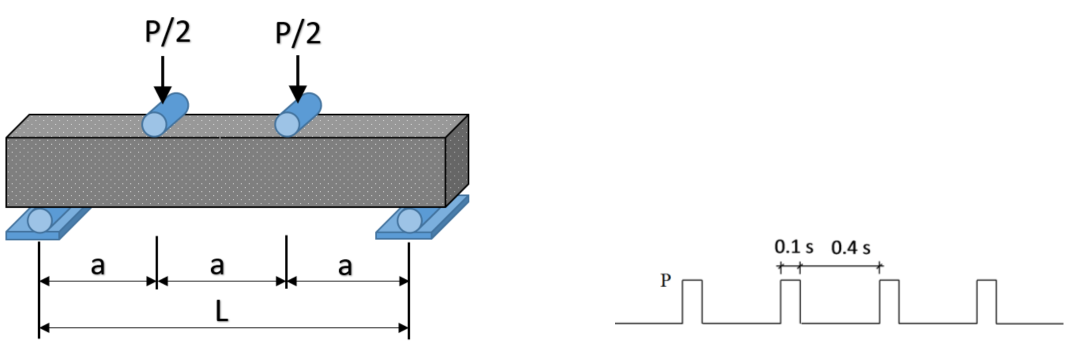
$$\boldsymbol{\varepsilon_t = \frac{12h\Delta}{3L^2 - 4a^2}} \quad (3),$$

where ε_t is the tensile strain; h is height of the beam; Δ is the deflection at the centre of the beam; L is the length of span between two supports; a is the distance from support to the load point (L/3). The relation of the initial strain versus the maximum number of repetitions to failure was plotted as the result.

(a) Specimens for splitting tensile test (b) Indirect splitting tensile test

(c) Specimens for fatigue test (d) Fatigue test

Figure 1. The specimens and experimental setup



(a) The four point bending flexure test (b) The applied repeated load

Figure 2. The principle for fatigue test

RESULTS AND DISCUSSION

Moisture Susceptibility

Figure 3 shows the splitting tensile strength results of the mixtures for three pavement structure courses, under the unconditioned and conditioned states. Fig. 4 shows the effect of hydrated lime addition on the splitting tensile strength ratio. Fig. 5 shows the percentage improvement in the splitting tensile strength of the hydrated lime modified mixtures against that of the control mix. From these results it can be seen that in general 2.5% hydrated lime content gives the optimum improvement for all the three pavement course mixtures at both unconditioned and conditioned states. Although the improvement for the unconditioned state is better than that for the conditioned state, the influence of the hydrated lime on the tensile strength ratio is not significant with a variation range of less than 0.15 (Fig. 4). Fig. 5 shows that the improvement for the unconditional state is in the range of 40~68% while that for the conditioned state is in the range of 18~45% at 2.5% of hydrated lime content. The improvement for the mixtures used for levelling and base course are quite similar and better than the improvement for the wearing course mixture.

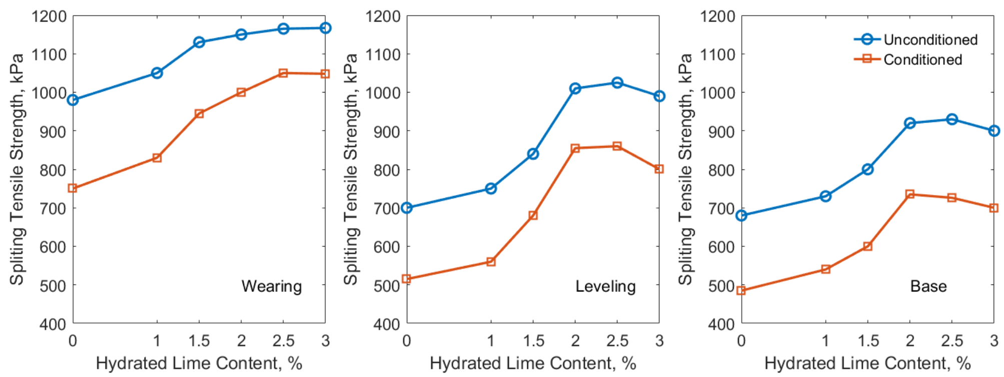


Figure 3. Splitting tensile strength of the mixtures of different hydrated lime contents

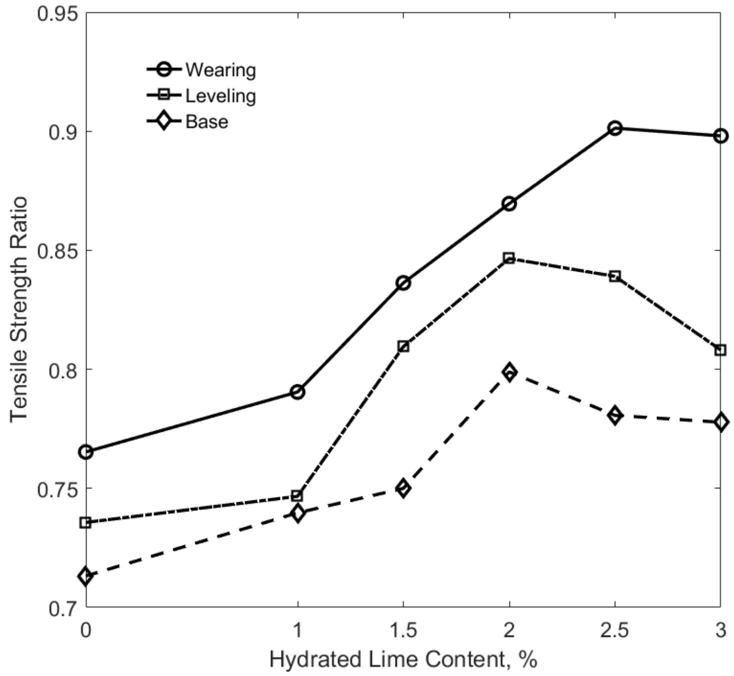


Figure 4. The effect of hydrated lime on the tensile strength ratio (TSR)

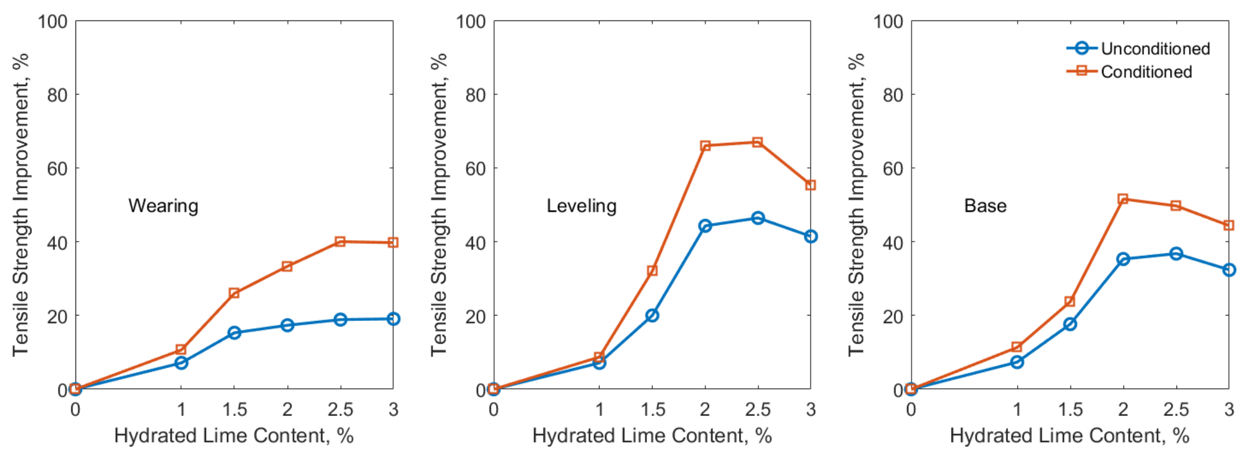


Figure 5. Improvement on the splitting tensile strength

Fatigue Life

Figure 6 shows the relationship between the defined initial tensile strain (ε_{t_200th}) and the maximum number of load repetitions (N_f) up to failure of the beam tested, for the three pavement courses. The results show that in general, the 2.5% hydrated lime (HL) content produced the maximum fatigue life time for all three layer applications, and with the most significant improvement in the case of the wearing course mixture. 3% HL is comparable to the 2.5% HL for the Base mix, but shows less fatigue life used for Wearing and Leveling mixes, particularly at smaller initial strain or lower load conditions.

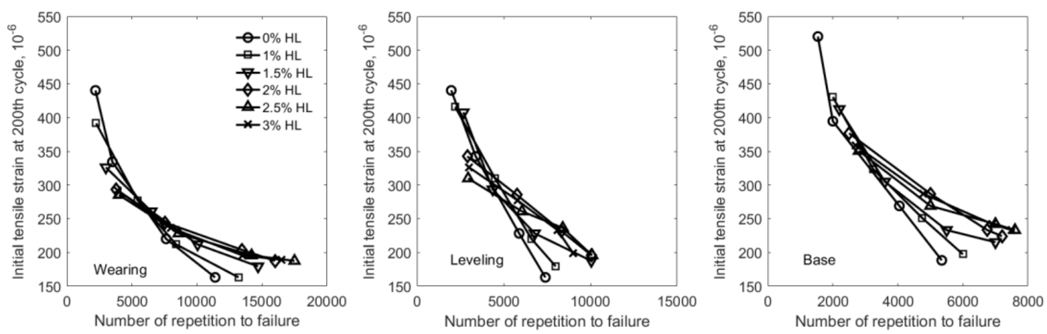


Figure 6. Relation between initial tensile strain and the number of load repetition to failure

The data for the control and 2.5% HL mixes content are extracted from Fig. 6 and replotted as Fig. 7, showing the fatigue life at different initial strains for the three application courses. It can be seen that the optimum modified mixtures are more rigid than the control mixtures. The strain increases after an initial 200 repetitions is less than approximately 100 microstrain for all these mixtures. Fig. 8 replots the Fig. 7 data in terms of the applied loads. It clearly shows that improvement in the fatigue life is significant for all the three mixtures.

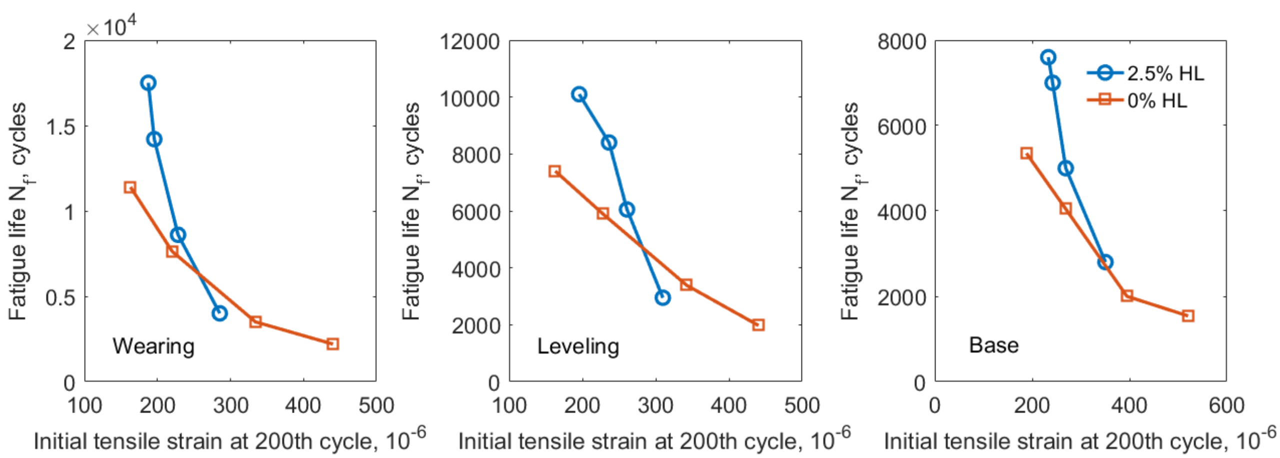


Figure 7. Fatigue life comparison of the modified mixture with 2.5% hydrated lime in terms of the initial strain

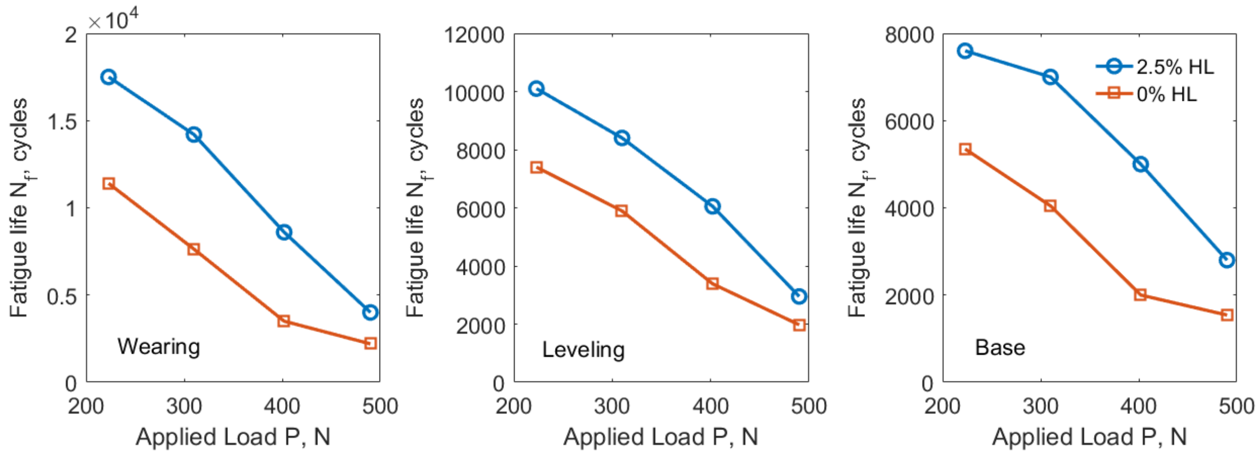


Figure 8. Fatigue life comparison of the modified mixture with 2.5% hydrated lime in terms of the applied load

For the sake of pavement structural design, a power function in the form of Eq. (4) is used to characterize the deformation and fatigue life relationship, i.e., the ε_{t_200th} vs N_f curves. Fig. 9 shows the results using Eq. (4) to fit the data from Fig. 6. The data present an almost linear relationship in a log-log graph.

$$\boldsymbol{\varepsilon_{t\_200th} = k_1 (N_f)^{-k_2}} \tag{4}$$

where k_1 and k_2 are two constants.

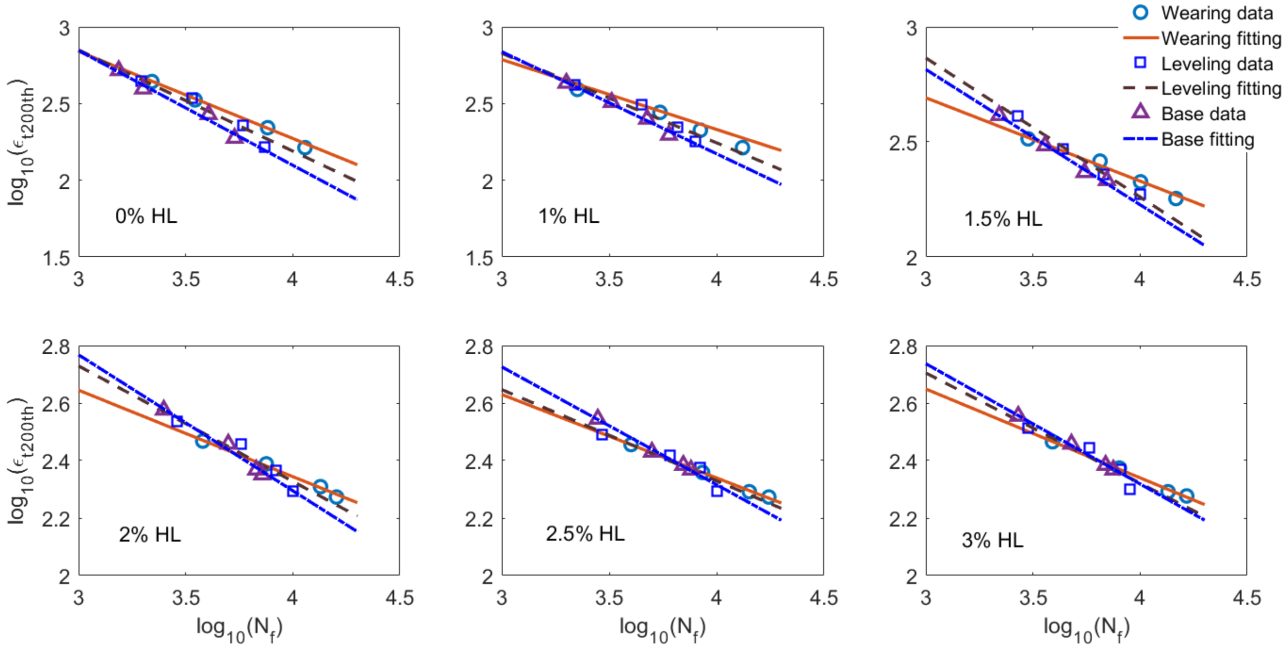


Figure 9. The characterized ε_{t_200th} vs N_f relation

For the relationships shown in Fig. 9, the two parameters, k_1 and k_2, define the interception and the slope, which relate to the initial tensile strain and the rigidity under repeated loading, respectively. Fig. 10 shows the variation of k_1 and k_2 in terms of the hydrated lime content. It can be seen that the two constants are minimised at the 2.5% hydrated lime content, for all three application mixtures, which correspond to the smallest initial deformation and highest stability and rigidity.

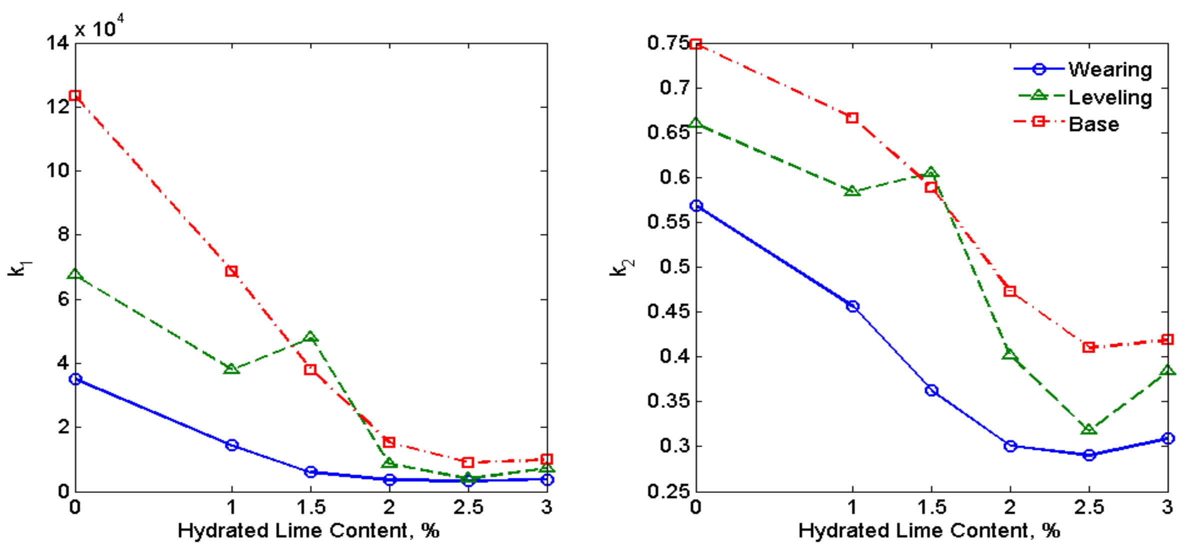


Figure 10. The variation of k_1 and k_2 with hydrated lime content

Together with the results of the resilient modulus, permanent deformation (rutting) (Al-Tameemi et al. 2016) and moisture susceptibility, it can be seen that 2.5% HL addition provides an optimum result. Fundamentally, the improvement of hydrated lime addition on asphalt concrete property relies on two mechanisms, i.e. the micro-void filling (hydrated lime particles themselves are porous, which absorb the asphalt cement particles to form a hardened mastic phase) and the enhancement of reactive surface bonding between the asphalt cement and aggregate. For a specific mixture, when the total aggregate surface area is a certain constant, too much hydrated lime will reduce the effective asphalt cement quantity acting as the active binder in the mix.

A Case Study - Pavement Design Application

To evaluate the benefit, this section investigates a case study using the modified asphalt concrete mixtures with the optimum 2.5% hydrated lime content for a pavement structure designed for a specific geological and transportation scenario.

Application Conditions

The application is set for an urban area in the City of Baghdad in Iraq, for which, with a recorded annual temperature range of 4~44 ^{o}C, an average temperature 23 ^{o}C is assumed according to the data published by the Iraqi Meteorological Organization and Seismology (IMOS). Much research has been conducted to estimate the vertical temperature distribution profile of pavement structures (Chandra et al. 1988, Diefenderfer et al 2002). In this paper, a simple model developed by Albayati and Alani (2015) and recommended by the Baghdad Road Authority was adopted. The model has predicted temperature profiles which prove to be comparable with other models, such as the Witczak model (1972) and SHRP (Strategic Highway Research Programme 1994) model (Albayati and Alani, 2015). It takes the form of Eq. (5):

$$\boldsymbol{T_{pave} = 1.217 \times T_{air} - 0.354 \times Z} \qquad (5),$$

where T_{pave} (^{o}C) represents the temperature in pavement structure; T_{air} (^{o}C) represents the air temperature; Z (cm) is the depth in pavement below the surface.

Table 3 lists the estimated traffic conditions. All traffic loads are converted to an 80kN (18kip) Equivalent Single Axle Load (ESAL) as shown in Fig. 11 in accordance with the AASHTO load equivalency factors (AASHTO, 1993).

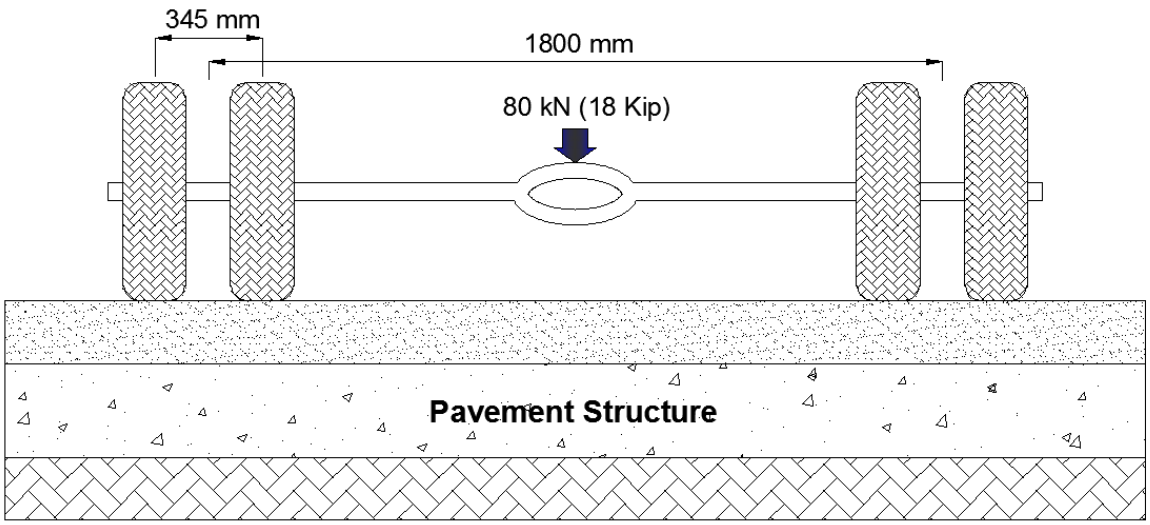


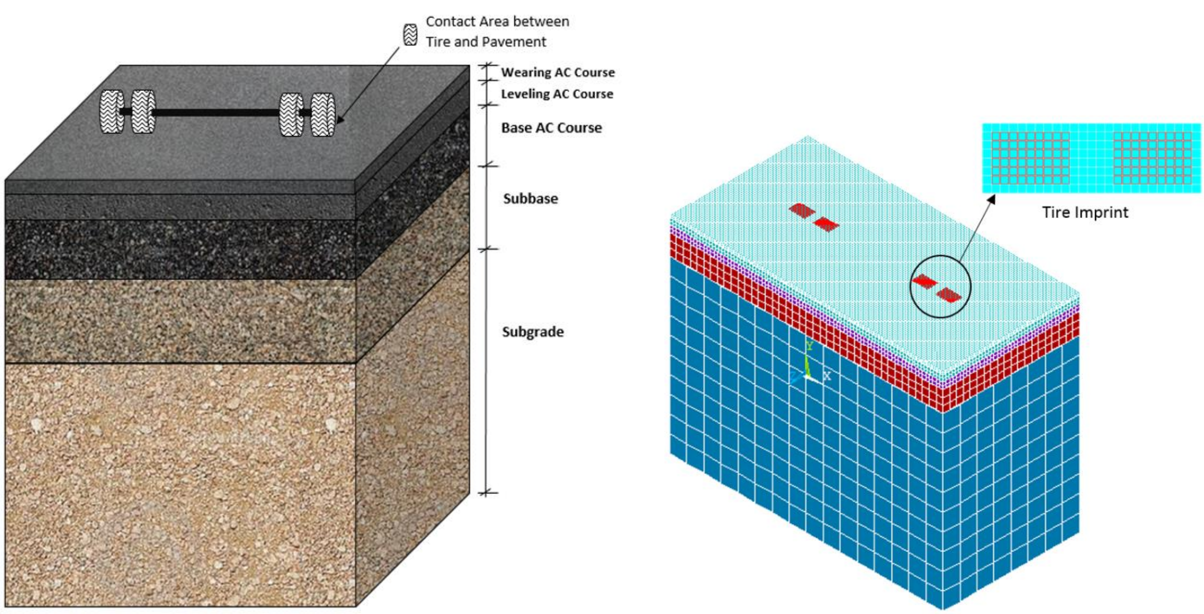
Figure 11. The 80 kN (18-kip) ESAL Configuration

Finite Element Model

A 3D finite element model shown in Fig. 12 was created for the pavement structure, which consists of five layers, i.e., three asphalt concrete layers (wearing, levelling and base) and two foundations (subbase and subgrade). The contact area between the tire and pavement surface depends on the contact pressure. In terms of the suggestion by Huang (2004) the contact pressure is smaller than the tire pressure for high-pressure tires (trucks), because the wall of tires is in tension. For simplicity, in pavement design, the contact pressure is generally assumed to be equal to the tire pressure in the consideration that the higher the axle loads, the higher tire pressures and the more destructive effects on pavements (Huang, 2004). There are three contact stresses non-uniformly distributed in the area (Ling et al. 2017). However, using the static vertical deformation and bending tensile strain as the criteria for comparison, this study assumes a uniform vertical stress in response to the traffic axle load but neglects the stress in other directions. Fig. 13(a) presents the approximate shape of the contact area for each tire, which consists of a rectangle and two semi-circles, where the characteristic parameter, L, is approximated to be:

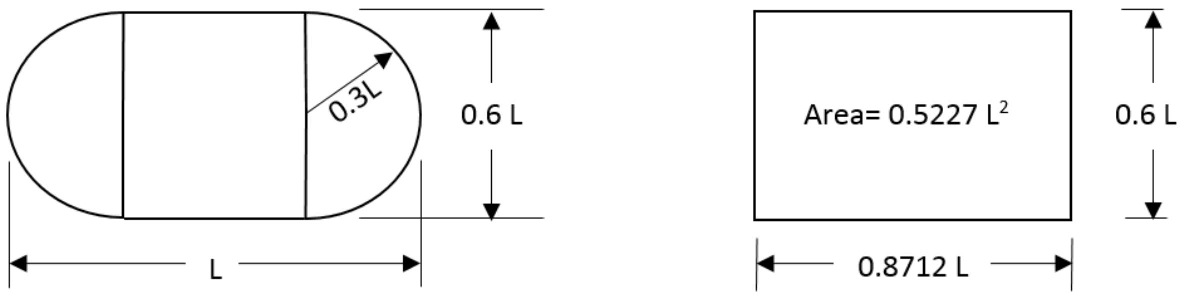
$$L = \sqrt{\frac{A_c}{0.5227}} \qquad (6),$$

where A_c represents the contact area between the tire and pavement, which can be acquired by dividing the applied load on each tire by its pressure. The contact area illustrated in Fig. 13(a) was suggested by Portland Cement Association (PCA) in 1966 for the design of rigid pavements. In 1984, the PCA proposed a method based on the finite element approach in which an equivalent rectangular contact area was adopted. Similar to recent work by Ling et al (2017), this study uses an equivalent rectangular tire imprint to represent the contact area between tire and pavement as defined in Fig. 13(b). As the total load is 80 kN (18 Kip) and there are dual tires on each side of the axle, the load on each tire is 20 kN. The pressure of the tire is 600 kPa (87 psi). Therefore, by dividing the load using the pressure, the contact area between tire and pavement is 0.03334 m^2. Therefore, the dimensions of the rectangular equivalent area are: Length = 0.8712×0.2525 = 0.22 m, and Width = 0.6×0.2525 = 0.15 m



(a) Pavement structure (b) FE model

Figure 12. Pavement structure and FE model



(a) Actual Area (b) Equivalent Area

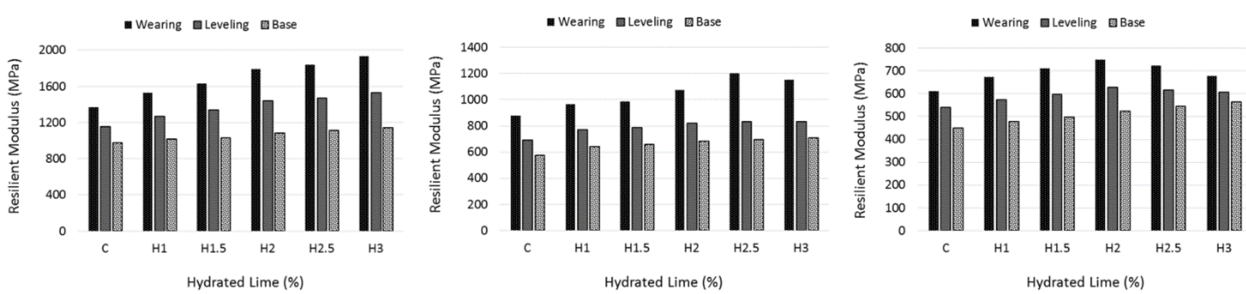
Figure 13. Estimation of the contact area between tire and pavement (Huang, 2004)

Material Properties

The material properties used in the FE modelling are given below.

- **Resilient Modulus of Asphalt Concrete Layers**

Figure 14 shows the measured resilient modulus of the hydrated lime modified concretes used for the three asphalt layers under three different temperatures. The work was conducted in the 1st phase of this research (Al-Tameemi et al., 2016). A simplified polynomial, i.e.: $M_r = aT_{pave}^2 + bT_{pave} + c$, is used to characterise the thermal effect on the resilient modulus, where M_r represents the resilient modulus of the modified asphalt concrete, T_{pave} is the temperature estimated using Eq. (5).

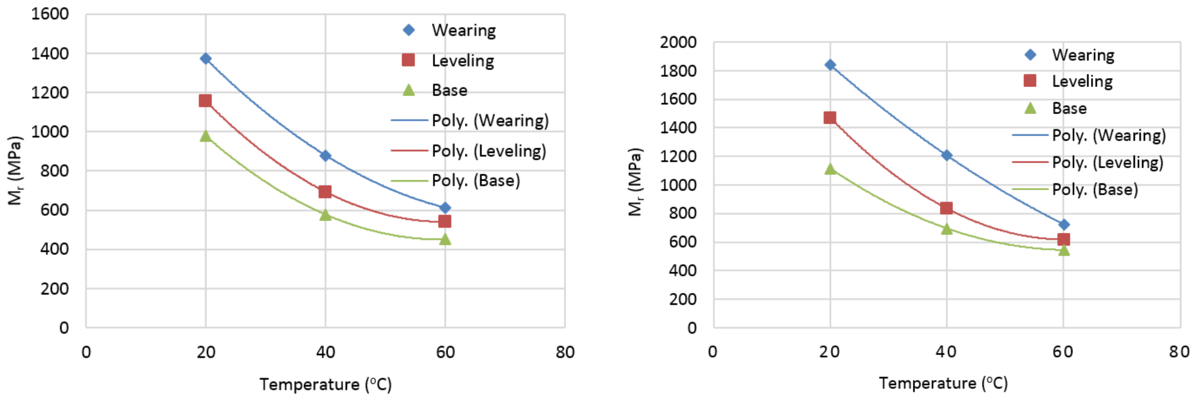


20ºC 40ºC 60ºC

Figure 14. Hydrated lime influence on resilient modulus at three temperatures

C – Control 0% hydrated lime, H1~H3 – 1% ~3% hydrated lime

Fig. 15 shows the modelling results using the polynomial to fit the data of the 0% and 2.5% hydrated lime in Fig. 14. Table 4 lists the corresponding three fitting parameters, a, b and c.



(a) Control mix of 0% hydrated lime (HL)   (b) Optimum mix of 2.5% hydrated lime (HL)

Figure 15. Modelled resilient modulus of the control and modified mixtures

- **Resilient Modulus of Subbase and Subgrade Layers**

The models proposed by Claessen et al. (1977) at the Shell Oil Company were adopted to estimate the property of these two foundation layers. For the granular subbase, its resilient modulus is assumed to depend upon the property of the subgrade layer underneath, i.e.:

$$\boldsymbol{M}_{\boldsymbol{r}(\boldsymbol{subbase})} = \boldsymbol{K} \times \boldsymbol{M}_{\boldsymbol{r}(\boldsymbol{subgrade})} \qquad (7),$$

where $K = 0.2h^{0.45}$, and h (mm) is the thickness of the subbase layer. The K has a value in a range of 2~4. The property of the subgrade layer itself is determined according to the measurement of the California Bearing Ratio (CBR) following the test procedure defined in ASTM D-1883, which is given below:

$$\boldsymbol{M}_{\boldsymbol{R}\,(\boldsymbol{subgrade})} = \mathbf{1450}\boldsymbol{CBR} \qquad (8),$$

where CBR is 4.5% in this study.

- **Poisson Ratio**

Poisson ratio is a fundamental property which influences the mechanical behaviour of pavement structures, particularly in the analysis of deformation of pavement structures when the viscoelastic material properties have to be explicitly described. In this paper, however, the pavement structure was considered as an elastic system with a relatively small deflection. In elastic range Poisson ratio variation is very small, so its influence of on stress and strain is assumed to be negligible (Huang 2004). Under such conditions, the Poisson ratio is usually assumed to be a reasonable value instead of determining it from actual tests (Southgate et. al., 1977). The data listed in the Table 5 were adopted in this study.

FEA Results and Pavement Performance Prediction

The finite element analysis aims to find an optimum pavement design using the optimum hydrated lime modified concretes in comparison with using the control concretes without hydrated lime. Two different thicknesses of the wearing layer, four different thicknesses of the levelling layer and three different thicknesses of the base layer were selected. Totalling seven designs using a combination of these layer thicknesses, which give different total thicknesses of the pavement structures, were investigated. For all the cases, the subbase thickness was set as 300 mm and subgrade depth was set as 2500 mm. Fig. 16 shows the seven structural designs.

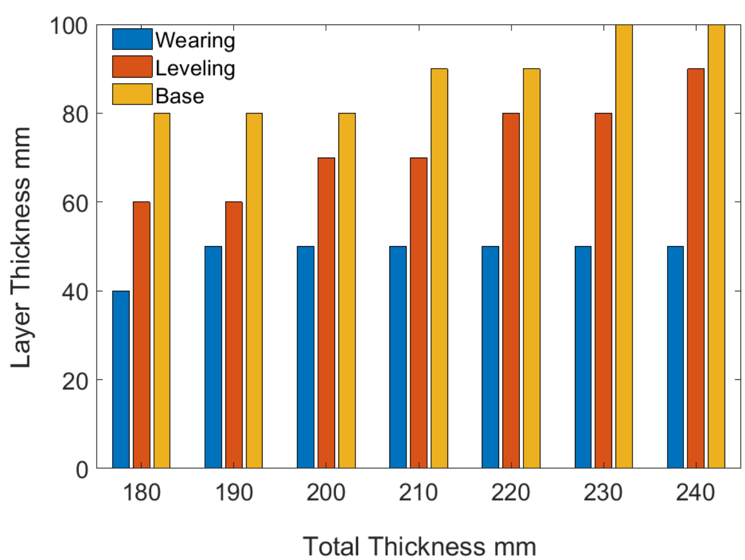


Figure 16. The pavement structure of varied thickness of the asphalt layers

Figure 17 shows a comparison of the tensile strain at the middle of the bottom of the asphalt concrete layers (bottom of the base layer), and the compressive strain at the middle of the top of the subgrade. It can be seen that the optimum structure is that of a total thickness of 210 mm with 50 mm of wearing, 70 mm of levelling and 90 mm of base, for which optimum hydrated lime modified mixes present the best improvement compared with using the control mixes.

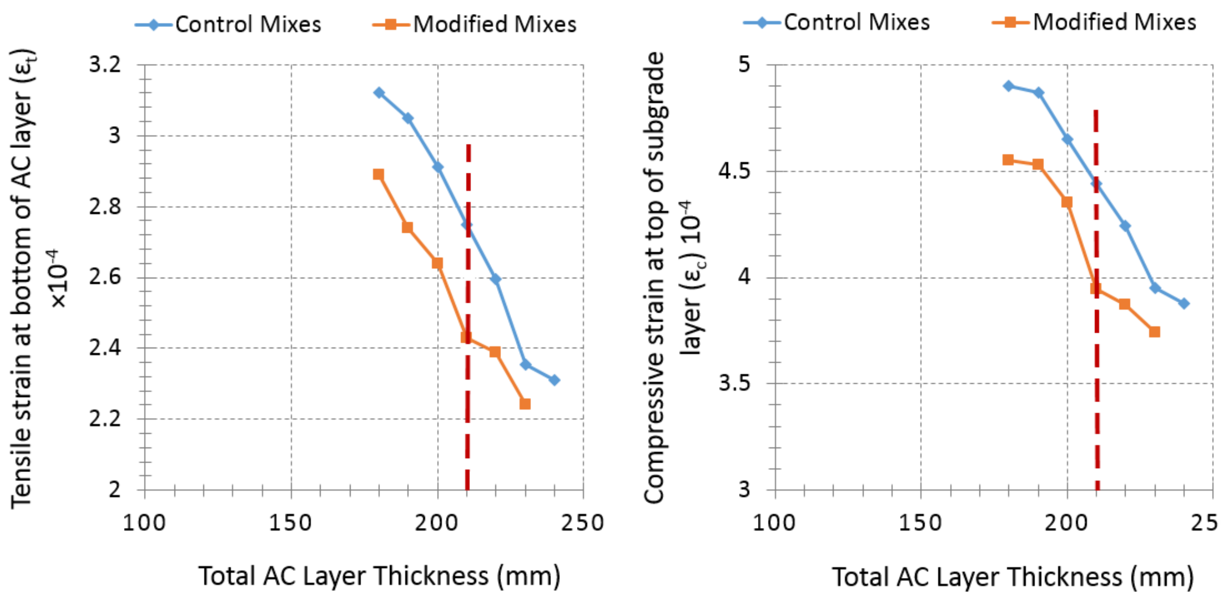


Figure 17. Comparison of tensile strain and compressive strain at critical points

Base on the FEA results, Fig. 18 shows the predicted fatigue life and the maximum number of load cycles for a rutting criteria, which are estimated using two empirical models adopted in KENPAVE (Huang 2004), i.e.:

$$\boldsymbol{N_f = 0.0796 \times \varepsilon_t{}^{-3.291} \times M_r{}^{-0.854}} \tag{9},$$

$$\boldsymbol{N_d = 1.365 \times 10^{-9} \times \varepsilon_c{}^{-4.447}} \tag{10},$$

where N_f is the number of load repetitions to failure; ε_t is the horizontal tensile strain at the bottom of asphalt concete layer, which took the maximum value of the three layers in this study; M_r is resilient modulus of asphalt concrete layer of the maximum ε_t; N_d is the number of load repetition to a criteria 127 mm (0.5 inch) permanent deformation (rutting depth); ε_c is the vertical strain at the surface of the subgrade. It can be seen that the pavement structure of total thickness 210 mm using the optimum hydrated lime modified concretes gives the best result in terms of the improvement on that using the control material under the condition to satisfy the requirement in Table 3.

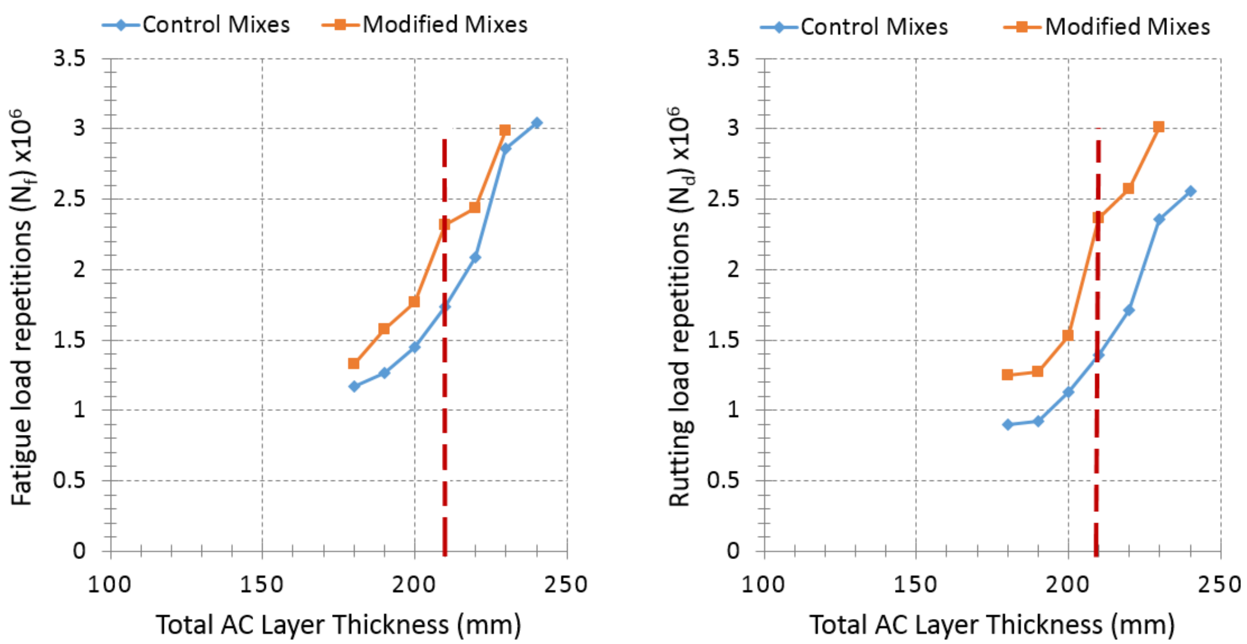


Figure 18. Predicted fatigue life and permanent deformation

Figure 19 compares the degree of improvement of all the designs using the 2.5% hydrated lime modification on that using the control material without the addition of hydrated lime, where the degree of improvement is defined as: $improvement = \frac{HL\ concrete - Control\ concrete}{Conctro\ concrete}$. It shows that the structure of the 210 mm total thickness provides a significant percentage improvement on both fatigue life and rutting resistance because of the enhancement of the rigidity of the hydrated lime modified concretes.

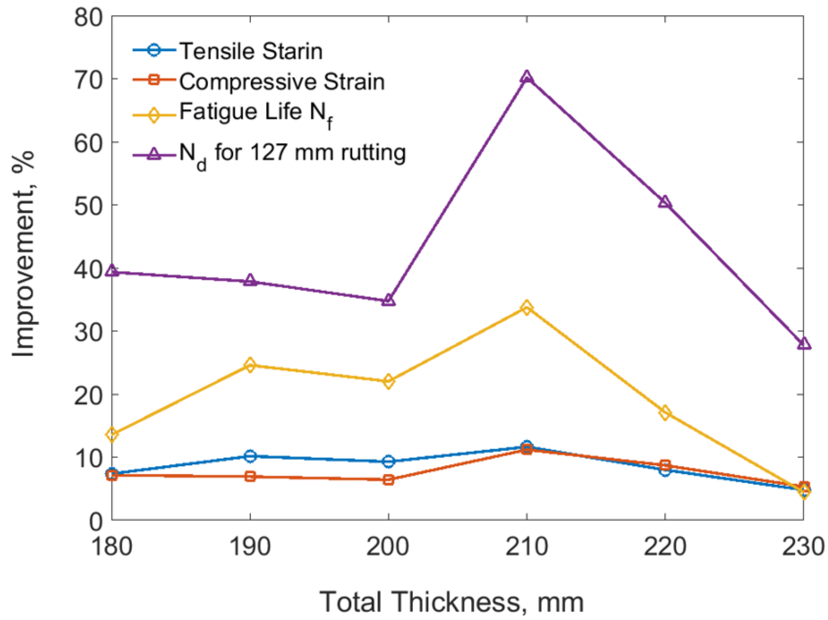


Figure 19. Improvement of structural mechanical properties and durability

CONCLUSIONS

This paper has reported an experimental study of the durability of hydrated lime modified asphalt concretes used for three different pavement courses, and a case study using the optimum mixes for a pavement design. Together with the results from previous work (Al-Tameemi et al., 2016), in which the volumetric and Marshall properties, permanent deformation and resilient modulus at various temperatures were evaluated, the follow conclusions can be drawn from this series of studies:

1. The addition of hydrated lime will enhance the mechanical properties and durability of asphalt concrete in terms of the resilient modulus, rutting resistance, moisture susceptibility under freeze-thaw conditions, and fatigue life.
2. Hydrated lime can be used not only for antistrip purposes in the mixtures for wearing course but also in the mixtures for other structural courses to produce an integration of the improvements in mechanical and durability behaviour of pavement structures.
3. The improvement of the mechanical properties works in a relatively wide range of weather temperatures.
4. A high hydrated lime content does not mean a definite improvement for the durability of mixtures because extra hydrated lime will reduce the effective amount of asphalt cement, the

active binder. In general, an optimum maximum of 2.5% hydrated lime content by total weight of aggregate to replace the same weight of conventional mineral filler is suggested for all practices in terms of both mechanical behaviour and durability improvement.

5. A design case study shows that using hydrated lime for all the asphalt layer courses reduces the tensile strain at the bottom of the base layer and the compressive strain on the top of the subgrade, and improves the total fatigue life of the whole pavement structure.
6. Using the mixtures of 2.5% hydrated lime addition for the three asphalt layers, an optimum pavement structure in the case study has showed 30% improvement on fatigue and 70% improvement on permanent deformation (rutting).

ACKNOWLEDGEMENT

Funding: This study was funded by the Iraqi Ministry of Higher Education and Scientific Research Scholarship Program.

Conflict of Interest: The authors declare that they have no conflict of interest.

REFERENCES

Albayati, A. & Ahmed, M., 2013, Assessment of the Impact of Different Hydrated Lime Addition Methods on Fatigue Life Characteristic. *Eng. & Tech. Journal*, **31**: 489-511.

Albayati A., 2012, Mechanistic Evaluation of Lime-Modified Asphalt Concrete Mixtures, 7th RILEM International Conference on Cracking in Pavements, ed. by A. Scarpas, N. Kringos, I. Al-Qadi and L. A, Springer Netherlands. **4:** 921-940.

Albayati, A. H. K. & Alani, A. M. M., 2015, Temperature Prediction Model for Asphalt Concrete Pavement, 14th Annual International Conference on Asphalt, Pavement Engineering and Infrastructure, 11th – 12th February, LJMU Liverpool, UK.

Al-Qadi I.L., Abuawad I.M., Dhasmana H., Coenen A.R., 2014, Effects Of Various Asphalt Binder, Additives/Modifiers On Moisturesusceptible, Asphaltic Mixtures, Research Report FHWA-ICT-14-004, Illinois Center for Transportation Series No. 14-004, UILU-ENG-2014-2004, ISSN: 0197-9191.

Al-Suhaibani A., Al-Mudaiheem J. and Al-Fozan F., 1992, Effect of Filler Type and Content on Properties of Asphalt Concrete Mixes, in SPT 1147 Effects of Aggregates and Mineral Fillers on Asphalt Mixtures Performance, ed. By R. C. Meininger, ASTM, Philadelphia PA, 107–130.

Al-Tameemi A., Wang Y., Albayati A., 2016, Experimental study of the performance related properties of asphalt concrete modified with hydrated lime, Journal of Material Civil Engineering, **28**(5) , 04015185-1.

Asphalt Institute, 1984, Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Manual Series No. 2. Lexington, KY.

ASTM D6926-10, 2010, Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus, ASTM International, West Conshohocken, PA, USA.

ASTM-D-1559, 2004, Road and Paving Materials, Annual Book of ASTM Standards, Volume 04.03, American Society for Testing and Materials, West Conshohocken, USA.

ASTM-D4867/D4867M−09, The Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures.

Blazek J., Sebor G., Maxa D., Ajib M., Paniagua H., 2000, Effect of hydrated lime addition on properties of asphalt. *Petroleum and Coal*, **42**(1): 41–45.

Chandra D, Lytton R.L., and Yang W., 1988, Effects of Temperature and Moisture on Low-Volume Roads, Texas Transportation Institute Texas AIM University System.

Claessen, A., Edwards P., Sommer P., Uge P., 1977, Asphalt Pavement Design: The SHELL Method, Proceedings 4th International Conference on The Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Michigan, USA.

Diab A. and You Z., 2014, Rheological Characteristics of Nano-sized Hydrated Lime-Modified Foamed Warm Mix Asphalt, Pavement Materials, Structures, and Performance GSP 239 © ASCE 2014.

Diefenderfer B.K., Al-Qadi I.L., Reubush S.D., Freeman T.E., 2002, Development And Validation Of A Model To Predict Pavement Temperature Profile, Research Report, Concorr Inc, Virginia Tech Transportation Institute, and Virginia Transportation Research Council.

EuLA_EN_2011_12_28, 2011, Hydrated Lime, A Proven Additive, For Durable Asphalt Pavements, critical literature review, EuLA - European Lime Association Rue des Deux Eglises 26, B-1000 Brussels, Belgium.

Huang, Y., 2004, Pavement Analysis and Design, 2nd Edition, Prentice Hall, Englewood Cliffs, New Jersey, USA.

Ishai I. and Craus J., 1977, Effect of the filler on aggregate-bitumen adhesion properties in bituminous mixtures. *Proceedings of the Association Asphalt Paving Technologists,* **43**:228-258, Lino Lakes, MN: Association Asphalt Paving Technologists (AAPT).

Lesueur D., Denayer C., Ritter H.-J., Kunesch C., Gasiorowskie S., d'Alto A., 2016, The use of hydrated lime in the formulation of asphalt mixtures: European case studies, 6th Eurasphalt & Eurobitume Congress, 1-3 June 2016, Prague, Czech Republic.

Lesueur D., Petit J., Ritter H.-J., 2013, The mechanisms of hydrated lime modification of asphalt mixtures: a state-of-the-art review, Road Materials and Pavement Design, **14**(1):1-16.

Ling, M., Luo, X., Hu, S., Gu, F., and Lytton, R. L., 2017, Numerical Modeling and Artificial Neural Network for Predicting J-Integral of Top-Down Cracking in Asphalt Pavement. Transportation Research Record: Journal of the Transportation Research Board, 2631: 83-95.

Little D. N. and Peterson J. C., 2005, Unique Effects of Hydrated Lime Filler on the Performance-Related Properties of Asphalt Cements: Physical and Chemical Interactions Revisited, Journal of Materials in Civil Engineering, **17(2)**: 207-218.

Little D. N. Epps J. A. and Sebaaly P. E., 2006, The Benefits of Hydrated Lime in Hot Mix Asphalt, National Lime Association.

Neville A.M. and Brooks J.J., 1987, Concrete Technology, Longman Scientific & Technical, Longman Group UK Ltd. England.

Othman A.M., 2011, Evaluation of Hydrated Lime Effect on the Performance of Rubber-Modified HMA Mixtures, Journal of Elastomers and Plastics, **43**: 221-237.

Satyakumar M., Chandran R. S. and Mahesh M. S., 2013, Influence of Mineral Fillers on the Properties of Hot Mix Asphalt, International Journal of Civil Engineering and Technology, **4**: 99-110.

SCRB/R9, 2003, General Specification for Roads and Bridges, Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges, Ministry of Housing and Construction, Republic of Iraq.

Sebaaly P. E., Hilty E. and Weizel D., 2001, Effectiveness of Lime In Hot Mix Asphalt Pavement, University of Nevada, Reno, USA.

Strategic Highway Research Program (SHRP), 1994, The Superpave Mix Design System, Manual of Specifications, Tests Methods, and Practices, SHRP-A-379, National Research Council, Washington, D. C., USA.

Southgate, H. Deen R., Havens J., Drake W., 1977, Kentucky Research: A Flexible Pavement Design and Management System, Proceedings 4th International Conference on Structural Design of Asphalt Pavements, Vol. II, the University of Michigan, Ann Arbor, Michigan, USA.

Witczak, M., 1972, Design of Full Depth Air Field Pavement, Proceedings, 3rd International Conference on the Structural Design of Asphalt Pavements, London.

Table 1. Filler contents in the mixes for different applications.

Hydrated Lime Content (% in weight)	Wearing Course		Levelling Course		Base Course	
	Mixture*	Limestone Content (% in weight)	Mixture*	Limestone Content (% in weight)	Mixture*	Limestone Content (%in weight)
0	CW	7	CL	6	CB	5
1	H1W	6	H1L	5	H1B	4
1.5	H1.5W	5.5	H1.5L	4.5	H1.5B	3.5
2	H2W	5	H2L	4	H2B	3
2.5	H2.5W	4.5	H2.5L	3.5	H2.5B	2.5
3	H3W	4	H3L	3	H3B	2

* Mixture Nomenclature - C: control, W: Wearing, L: Levelling, B: Base, H: hydrated lime

Table 2. Aggregate Gradations of Asphalt Concrete Courses

Sieve Size		Wearing Course		Leveling (Binder) Course		Base Course	
inch	Mm	Selected grade % passing	Specification limits	Selected grade % passing	Specification limits	Selected grade % passing	Specification limits
1.5	37.0	-	-	-	-	100	100
1	25.0	-	-	100	100	95	90-100
¾	19.0	100	100	95	90-100	83	76-90
½	12.5	95	90-100	80	70-90	68	56-80
⅜	9.5	83	76-90	69	56-80	61	48-74
No. 4	4.75	59	44-74	50	35-65	44	29-59
No. 8	2.36	37	28-58	35	23-49	32	19-45
No. 50	0.3	13	5-21	13	5-19	11	5-17
No. 200	0.075	7	4-10	6	3-9	5	2-8

Table 3. Traffic Information for Estimating the 80-kN ESAL

- Road: 2-lane road
- Traffic Analysis Period = 15 years
- Assumed current AADT = 2500 (during the first year)
- Directional distribution factor = 50 %
- Lane distribution factor =100%
- Percentage of Trucks = 45%
- Annual growth rate = 4 %

Vehicle type	Percentage of *ith* vehicles P_i %	Number of vehicles/lane per year n_i	Equivalent Axle Load Factor EALF	Growth Factor G_f	ESALs
Passenger-vehicles (PCU)	55	250937.5	0.0008	20.02	4019.015
Single-unit trucks:					
2 axle, 4 tire	10	45625	0.003	20.02	2740.238
2 axle, 6 tire	10	45625	0.21	20.02	191816.6
3 axle or more	5	22812.58	0.61	20.02	278590.8
Tractor semitrailers and combinations:					
4-axle or less	5	22812.5	0.62	20.02	283157.9
5-axle	10	45625	1.09	20.02	995619.6
6-axle or more	5	22812.5	1.23	20.02	561748.7
Total	100	456250			2317693

The Estimated Design ESALs = 2.318×10^{6}

Table 4. Parameters for the Modelled Resilient Modulus

	Control Mix, 0% HL			Optimum Mix, 2.5% HL		
Layer	a	b	c	a	B	c
Wearing	0.2819	-41.527	2089.7	0.1898	-43.033	2623
Leveling	0.3877	-46.413	1929.3	0.5248	-63.299	2526.7
Base	0.3404	-40.406	1649.3	0.3359	-41.117	1802.6

Table 5. Poisson Ratios for Different Paving Materials (Southgate et. al., 1977)

Material	Range	Typical Value
Asphalt concrete	0.30 - 0.40	0.35
Unstabilized granular subbase and base	0.30 - 0.45	0.4
Silty subgrade	0.35 - 0.45	0.45
Clay subgrade	0.4 – 0.5	0.5