Influence of Long-Term Aging on HMA Made with Gel and Sol Asphalt Cements

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Abstract. This study evaluated the effect of long term ageing (LTA) on the performance traits of dense graded asphalt mixes (DGAMs) made from gel and sol asphalt cement binders. The LTA was adopted at 85 °C and between four and eight days using forced draft oven to reproduce the in-service aging that occurs over many years in the field. The performance assays contains: Marshall traits, tensile and compressive strength under wetting and drying conditions, bending strength at zero and -10°C, cohesion at 60°C, tensile strength ratio, and recovered strength index were adopted on DGAMs. A mechanistically-design tool was explored for estimating the enhancement in paving life or thickness reduction of DGAMs and base course for similar service life caused from LTA of DGAMs. Assays results notified that the LTA increases DGAMs strength towards: (1) rutting; (2) moisture sensitivity; (3) cracking; and (4) cohesion failure. In addition, it was found that sol asphalt cement performs slightly better than gel asphalt cement, especially in the case of moisture susceptibility and flexural strength properties.

Keywords: Aging; Asphalt; Performance traits; Service age; Pavement responses

1. Introduction

Asphalt has long been classified as gel or sol type. Gel-type asphalts usually exhibit pronounced non-Newtonian behavior, whereas sol-type asphalts are more Newtonian. Gel-type asphalts generally contain large amounts of asphaltenes, and sol-type asphalts are characterized by low asphaltene content. Using the classical asphalt science terminology, sol-type asphalts are more compatible, while gel-type asphalts are less compatible. Less compatible (gel-type) asphalt is known to be highly susceptible to oxidative
age hardening. While highly compatible (sol-type) asphalt is not susceptible to ageing (Shin-Che, 2008).

Aging of asphalt mixes and water in base course and roadbed are the two essential environment factors that affect performance of flexible pavements. Asphalt stiffness is affected by aging, which causes the stress in the pavement. In turn, the stress variation can affect other underlying paving courses, which depends on asphalt layer stress (Al-Hadidy and Tan, 2007).

Several studies reported aging influences on binders’ traits using ASTM and SuperPave assaying methods. These methods are generally simple and consume little time (Soon-J. Lee et.al., 2009; Bell, 1994; Mansour and Amin, 2017; Shifeng et al., 2017; MinBai, 2017; Dongmei Zhang et. al., 2017; Soon-J. Lee et.al., 2009). In contrast, researches on asphalt mixes ageing consume higher time and efforts. The evaluation of the mixes traits under ageing influences may be more benefits than for binders.

For asphalt mixes, the recommended lab method for short-term oven aging (STOA) is to heat the loose mixture in a forced draft oven (FDO) for 4 hr at 135 °C while for the hardener mixes, STOA of 2 hr at 154 °C is commonly utilized (Soon-J. Lee et.al., 2009). Whereas, the lab method for long-term aging (LTA) is to put the specimens in FDO for 4d to 8d at 85°C or 2d to 4d at 100°C. The LTA-conditions equivalent of older than 3yr mixes in the field as documented by Bell (1994) and Al-Hadidy (2018).

Mansour and Amin (2017) examined ageing and environment influences on recycled pavement asphalt (RPA) and steel slag aggregates (SSA) fracture resistance subjected to freezing and thawing (FT) cycles and LTA. It was notified that ageing improves fracture RPA/SSA-mixtures resistance.

Shifeng et al (2017) documented that ageing varied the physiochemical traits of rubber-bitumen blends (RBB). The RBB stiffness was found higher under influences of ageing.

MinBai (2017) examined ageing influences on the low temperature traits of styrene-butadiene-styrene (SBS)/bitumen containing rejuvenators utilizing: penetration, ductility at 5 °C, force ductility, Fraass point, dynamic shear rehometer, and bending beam rehometer assaying method. It was depicted SBS/bitumen including rejuvenators give higher elasticity.

Dongmei Zhang et. al., (2017) evaluated ageing influences on the rheological trait, physical traits and chemical constitutes of SBS-70 and SBS-90/ asphalts utilizing thin film oven assay, pressure aging vessel, and ultraviolet radiation methods. It was depicted SBS-70 is less damage to ageing than SBS-90.

Soon-J. Lee et.al. (2009) examined the influences of STOA on asphalt mixes utilizing the gel-permeation chromatography (GPC) method. Nine-asphalt mixes, adopting three various asphalt sources, were introduced and five-STOA procedures were utilized to examine the mixes. For comparison, the rolling thin film oven (RTFO) ageing was also performed for nine-asphalt binders. The asphalt mixes ageing, containing polymer-modified mixes, could be complied at different STOA factors. Statistical analyses of the GPC assay results depicted that ageing at 154°C for 2 hr and a 135°C for 4 hr are not significant. The RTFO ageing procedure was depicted to have less influence on binder ageing than the STOA procedures of asphalt mixes.

Al-Hadidy and Tan (2007) reported effects of aging on the performance traits of asphalt mixes containing polypropylene. The aging was adopted under 85 °C and between 2 and 4 days. Assays results notified that aging affects the performance traits of the mixes.

2. Study objectives

The research objectives are to document the influence of long-term ageing (LTA) of sol and gel asphalt cement binders on: (1) Marshall traits of dense-graded asphalt mixes (DGAMs); (2) Tensile and compressive strength of DGAMs at 25 and 60oC; (3) Moisture damage of DGAMs; (4) Bending strength traits of DGAMs at lower temperatures; (5) Cohesion of DGAMs at 60oC; and (6) Index of aging of DGAMs. Besides, explore regeneration formulas among the performance assays (Marshall stability, tensile strength, and compressive strength): a) for their utilized in the absence of the tensile and compressive strength assays, and /or b) the engineer does not select to utilize those assays, and reported the advantages of LTA-DGAMs course in pavements utilizing a mechanistically design tool. Gathering the above objectives could supply well understanding of LTA effects on the performance traits of DGAMs, so that their performance in the site can be exactly estimated.
3. Materials and Methods

3.1. Materials
Two types of 40-50 penetration grade asphalt cement binders, namely; gel type taken from Baiji refinery (200 Km. North Baghdad the capital) and sol type brought from Qayarah refinery (350 Km North Baghdad the capital) were adopted in this research. Traits of sol and gel asphalts are depicted in Table (1).

Aggregates were brought from Ashor co. in Mosul city located in the Iraqi northern region. Figure (1) depicts the used gradation tolerances by the ASTM (D3515) (2015) for DGAMs and the utilized gradation in this study at the middle of the tolerances.

The aggregates traits, such as crushing, wear, soundness, water absorption, and specific gravities values were calculated and the assay results are depicted in Table (2).

Table 1. Physiochemical traits of Baiji and Qayarah Asphalt Binders

| Trait                                | Value | ASTM Spec. | SCRB Spec. |
|--------------------------------------|-------|------------|------------|
| Penetration (25°C, 100g, dmm)        | Gel   | Sol        | Gel        | Sol        |
|                                      | 42    | 41         | 40-50      | 40-50      |
| Softening point, °C                  | 58    | 52         | 50-58      | 51-62      |
| Ductility (25°C, cm)                 | >100  | >100       | ≥100       | ≥100       |
| Specific gravity                     | 1.051 | 1.049      | 1.01-1.06  | ---        |
| Flash point, °C                      | 275   | 263        | ≥240       | ≥240       |
| Loss due to heat and air, %          | 0.375 | 0.386      | ≤0.2       | ≤0.75      |
| Kinematic viscosity (135 °C, Centi stock) | 500.0 | 500        | ≥400       | ---        |
| Sulphur (S3) (X–Ray), %              | 6.3   | 7.6        | 6.5 %      | 6.5 %      |
| Asphaltenes, %                       | 11.2  | 6.70       | ---        | ---        |
| Solubility in CCl4, %                | 99.4  | 99.7       | ≥99        | ≥99        |
| Recovered ductility (25°C, cm)       | 80    | 97         | ---        | ≥50        |
| Recovered penetration, %             | 66    | 68         | ---        | ≥55        |
| Recovered softening deg., °C         | 5     | 4          | ---        | ≤10        |

Figure 1. Gradation boundaries
Calcium carbonate (CaCO₃) was utilized as a filler. It was finer than 0.075mm sieve (ASTM D854, 2015) and 2.731 sp. gr.

3.2. Mixture Design

DGAMs optimal binder dosage (OAD) is selected to justify 4±1% air voids. Five binder dosages from 4% to 6% with increment of 0.5% for each type of asphalt were utilized in DGAMs design. It was noticed that at 4.0% air voids, the OAD was 5.0% for the two types of asphalts. This OAD was adopted in producing all other LTA mixes to obtain consistency throughout the research.

Three groups of specimens are blended at OAD (155±5 °C, 2 min) (Asphalt Institute, 1984). The 1st group was coded as unaged (DGAM0h). The 2nd group included placing of the consolidated specimens at (85°C, 4 days) into a Forced Draft Oven (FDO) and coded as (DGAM4d). The 3rd group included placing of the consolidated specimens at (85°C, 8 days) into FDO and coded as (DGAM8d). These LTA conditions used methods illustrated in (Bell, 1994).

Then, the loose specimens were compacted with 75 blow/face (This number of blow equivalent to 1379 kPa tire pressure) by Marshall hammer at viscosity of (280 ± 30 Cst) (Asphalt Institute, 1984). After that, the samples were extruded from the mold (ASTM, 2015), and put in air for 1 day. 26 samples for each DGAMs group were assay with three for stability, cohesion at 60 °C, indirect tensile strength (ITS) at 25 °C, ITS at 60 °C, compressive strength (CS) at 25 °C, and CS at 60 °C, four for flexural strength (FS) at 0°C, and four for FS at -10°C. Thus, for each type of asphalt, seventy-eight specimens were assay for DGAMs groups.

3.3. Laboratory Tests Used

Four assays in lab were depended. The assays adopted were Marshall stability, ITS at 25 and 60oC, CS at 25 and 60oC, bending strength at 0 and -10oC, and cohesion at 60oC. Besides, the moisture influence assay was explored utilizing the ratio of tensile strength (TSR= ITS60oC/ ITS25oC) (ASTM D-4123, 2015), and index of retained strength index (IRS= CS60oC/CS25oC) (ASTM D-1074, 2015). Higher value of TSR or IRS notifies that DGAMs are more resistant to water effects. SCRIB (2003) requires IRS ≥70%, whereas, SCDOT Bradley et al. (2004) requires a TSR≥85% and ITS60oC≥448kPa, respectively. Index of aging (A.I) was calculated by divided the LTA cohesion of DGAMs to unaged one.

Rutting strength was obtained from Marshall Quotient (MQ). Bending assay was performed on (300 × 50 × 48 mm) beams extruding from a consolidated (300 × 300 × 50 mm) sample. Four beam samples were tested at zero and -10oC utilizing a universal bending machine.

Resilient modulus (MR) of DGAMs is an important mechanical trait for pavement structural design. Thus, it is preferable to predict MR of DGAMs Dynamic ITS assay at 25°C was adopted (ASTM D-4123, 2015) for MR evaluation.

4. Mechanistic Empirical (M-E) Tool

M-E tool was utilized in this research to examine LTA-DGAMs advantages in forms of Layer Thickness Reduction (LTR) and Traffic Benefit Ratio (TBR). The adopted methodology has good capability of

| Trait                  | Coarse Agg. | Fine Agg. |
|------------------------|-------------|-----------|
| Bulk spec.gr.          | 2.6520      | 2.5410    |
| Apparent spec.gr.      | 2.6930      | 2.5920    |
| Crushing,%             | 99.0        | 47.0      |
| Wear,%                 | 19.0        | -----     |
| Soundness,% Na2SO4     | 0.968       | 0.664     |

Table 2. Aggregate traits
characterizing various material traits and loading options, and has the ability to examine various design options on an economic basis.

Two design options were adopted in this research are as follows:

1. Similar service life for LTA and unaged pavement models. It would lead to decreasing in base, or DGAMs thickness and has been notified in forms of LTR; and

2. Similar pavement models for unaged and LTA-DGAMs. It would result in more pavement service life due to LTA and has been notified in forms of TBR.

As input values, DGAMs modulus was examined, and typical moduli of asphalt, base, subbase and subgrade in Iraq were depended as shown in Figure (2).

The surface deflection (\(w_o\)), the horizontal strain in tension (\(\varepsilon_t\)) at the bottom of binder course, and the vertical compressive strains (\(\varepsilon_c\)) developed at the top of the subgrade in LTA pavement model were determined under the left tire utilizing BISAR program with \((40 \times 10^3 \text{ N and set of dual tires of } 21 \text{ cm dia.})\). The \(w_o\), \(\varepsilon_t\) and \(\varepsilon_c\) responses were adopted for estimating the enhancement in paving service life or decreasing in DGAMs and base course thickness for similar LTA-DGAMs service life DGAM.

![Figure 2. Pavement Design and Considered Loading: Dual Tires](image)

5. **Assays Results and Discussion**

5.1. **Statistical Analyses**

Values of the Marshall, ITS, CS, TSR, IRS, FS, and cohesion assays were analysed statistically with a 0.05 \(\alpha\). For distinguishes, it should be notified that the samples were prepared at OAD.
5.2. Regression Analyses

The variations in the performance traits with LTA-DGAMs were reported at highest and ambient paving temperature. Statistical analyses (Pearson relation \( r \) and 2-tailed, probability) was performed to justified that a linear relation has adequate precision for calculation Marshall stability, ITS and CS traits of DGAMs for LTA.

Figure 3 depict the linear relations between the engineering assays and documents the LTA linear regression of DGAMs adopted at 5% significant level for gel and sol asphalt cement. The values are average of all lab mixes examined at 25oC and 60oC. The analyses satisfied that linear relations could be utilized for obtaining of ITS and CS traits of DGAMs at 25oC and 60oC. These relations were explored: a) for their utilized in the absence of the tensile and compressive strength assays, and /or b) the engineer does not select to utilize those assays.

5.3. DGAMs Optimization

Statistical analyses program (SPSS) was utilized to introduce an ideal table based from the DGAMs assays. Duncan internship was adopted to calculate the difference among groups. This difference was notified for each DGAMs group by addition of letter(s). If the same letter(s) among two or more groups, this means that no significant can be obtained among sets. Table 3 tabulated the relations from the analyses.
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Figure 3. Relations among DGAMs engineering assays with R value

Table 3. DGAMs Optimization Summary

| Mixture type | DGAM$_{0h}$ | DGAM$_{4d}$ | DGAM$_{8d}$ |
|--------------|-------------|-------------|-------------|
| Gel asphalt cement |             |             |             |
| Stability, kN | 11.80±0.37  | 17.23±0.17(s) | 16.82±0.14(s) |
| CS25°C, kPa   | 6278±50     | 1746±19(s)  | 1688±27(s)  |
| CS60°C, kPa   | 5279±118    | 1630±44(s)  | 1508±34(s)  |
| ITS25°C, kPa  | 1408±22     | 6603±41(s)  | 7014±45(s)  |
| ITS25°C, kPa  | 1154±25     | 6151±77(s)  | 6381±32(s)  |
| Flexural modulus, kPa, 0 °C | 5012±132     | 6345±158(s) | 5974±280(s) |
| Flexural modulus, kPa, -10 °C | 5490±142     | 6846±156(s) | 6499±243(s) |

| Mixture type | DGAM$_{0h}$ | DGAM$_{4d}$ | DGAM$_{8d}$ |
|--------------|-------------|-------------|-------------|
| Sol asphalt cement |             |             |             |
| Stability, kN | 13.13±0.35  | 17.79±0.11(s) | 16.31±0.23(s) |
| ITS25°C, kPa  | 1637±34     | 1864±65(s)  | 1798±81(s)  |
| ITS60°C, kPa  | 1648±16     | 1755±23(s)  | 1663±52(s)  |
| CS25°C, kPa   | 6480±35     | 7327±51(s)  | 7894±28(s)  |
| CS60°C, kPa   | 5300±182    | 6748±37(s)  | 7208±68(s)  |
| Flexural modulus, kPa, 0 °C | 5160±99     | 6523±114(s) | 6393±121(s) |
| Flexural modulus, kPa, -10 °C | 5642±175     | 6997±158(s) | 6804±137(s) |
5.4. Marshall Prospects

The Marshall prospects of LTA-DGAMs were examined and the values are found in Figure 4. From this Figure, it can be notified that 4d and 8d-LTA increases stability of gel and sol virgin DGAMs by 46% and 43%, and 37% and 24%, respectively, whereas, 4d and 8d-LTA flow values reduces by 37%, and 24%, and 35% and 30%, respectively.

Figure 4 also noticed that 4d and 8d-LTA increases the voids in mineral aggregates (VMA) for gel and sol by 0% and 1.5%, and 2% and 4%, respectively. This noticed that DGAMs durability increases with LTA. Besides, air voids (Av) was obtained between 3-5%.

Figure 4. Marshall Prospects LTA-DGAMs (a- Stability, b- Flow, c- Av, d- MQ., e- VMA, & f- VFB)

MQ values of gel and sol virgin DGMAs were noticed higher by 132% and 99%, and 111% and 78% 4d and 8d-LTA, respectively. LTA-DGAMs notify well rutting strength and could be adopted for higher traffic pavements. Higher values of VMA and stability may be caused by the interlocking occurred between thiophen = oxygen, carbon = oxygen and carbon-hydrogen chain in bitumen.

5.5. Moisture Susceptibility

ITS for LTA-DGAMs are found in Figure 5. The results depict that ITS, and TSR raised for LTA. For DGAM0d, DGAM4d, and DGAM8d, average ITS values of wet-DGAM samples containing gel and sol asphalt cement are 1.154, 1.630, and 1.508 MPa, and 1.468, 1.755, and 1.663 MPa, respectively. For these, coefficients of variation (COV) of results were 1.96, 2.65, and 2.52%, and 0.95, 1.17, and 3.3%, respectively. Means values of ITS for dry-DGAM samples containing gel and sol asphalt cement are 1.408, 1.746, and 1.688 MPa, and 1.637, 1.864, and 1.798 MPa respectively. For these results, COV was 1.38, 1.0, and 1.18%, and 1.84, 3.09, and 3.96%, respectively. From these, % TSR values determined for DGAM0d, DGAM4d, and DGAM8d containing gel and sol asphalt cement 82, 93, and 89%, and 90, 94, and 93%, respectively. The higher ITS and TSR values after LTA may be related to that the asphaltenes /maltenes ratio.
The CS variation with LTA is found in Figure 6. From this Figure, it can be depicted that CS for DGAM0d, DGAM4d, and DGAM8d samples containing gel and sol asphalt cement ranges from 6.278 to 5.279 MPa, 6.603 to 6.151, and 7.014 to 6.381 MPa, and 6.48 to 5.3 MPa, 7.327 to 6.784, and 7.894 to 7.208 MPa at 25°C and 60°C, respectively. For these results, COV was 0.7 to 1.98, 0.54 to 1.1, and 0.56 to 0.44%, and 0.48 to 3.0, 0.61 to 0.48, and 0.32 to 0.8%, respectively. The research notified that CS of virgin DGAMs containing gel and sol asphalt cement at 4d and 8d-LTA was increased by 5 and 17%, and 12 and 21%, and 13 and 17% and 22 and 24% at 25°C and 60°C, respectively. From Figure 6, it was depicted that the IRS of virgin DGAMs containing gel and sol asphalt cement was increased by 11% and 8%, and 13% and 11% for DGAM4d, and DGAM8d, respectively. Besides, the notifications and statistical analyses depict that the ITS was the best assay for stripping examination of paving mixes.

5.6. Dynamic ITS Assay
Dynamic ITS assay was conducted at 25°C (ASTM D-4123, 2015) to assess the resilient moduli (MR). LTA-DGAMs depicted higher MR than virgin DGAMs as found in Figure 7. Assay results depict that MR for DGAM0d, DGAM4d, and DGAM8d samples containing gel and sol asphalt cement are 4010 MPa, 6100 MPa, and 5540 MPa, and 4460 MPa, 6100 N/mm², and 5540 N/mm² at 25°C, respectively, the MR raises by 52% and 38%, and 37% and 24% for 4d, and 8d-LTA, respectively. Thus, LTA has enhanced the MR of DGAMs. This is related to the LTA-DGAMs higher viscosity.
5.7. Low Temperature Prospects

Paving materials at lower temperatures show elastic behavior that is defined by stress-strain curve (i.e. stiffness moduli) (Busby and Rader, 1972) which, in flexural examination, is named the flexural stiffness ($S_t$) and calculated from equ.1.

$$S_t = \frac{(P \times L)}{(b \times d^2)}$$

Besides $S_t$, rupture modulus ($S_r$) is an additional factor may be calculated from equ.2.

$$S_r = \frac{(P \times L^3)}{(6 \times b^2 \times d^2 \times \Delta)}$$

Where: ($P$= max. load, $L$= length of beam, $b$= width of beam, $d$= depth of beam, $\Delta$ = deflection at center of the beam).

The flexural assays result of LTA-DGAMs at 0 and -10°C are found in Figure 8. From Fig. 8, the $S_t$ ranges for DGAM0d, DGAM4d, and DGAM8d specimens containing gel and sol asphalt cement were 5.012 to 5.49MPa, 6.345 to 6.846MPa, and 5.974 to 6.499MPa, and 5.160 to 5.642MPa, 6.523 to 6.997MPa, and 6.393 to 6.804MPa at zero and -10°C, respectively. For these results, COV was 2.7 to 2.63, 2.53 to 2.47, and 4.78 to 3.82%, and 1.95 to 3.12, 1.78 to 2.3, and 1.92 to 2.05%, respectively. Similarly, values of $S_r$ for DGAM0d, DGAM4d, and DGAM8d containing gel and sol asphalt cement are 0.633 to 1.204MPa, 1.209 to 1.676MPa, and 1.117 to 1.557MPa, and 0.722 to 1.303MPa, 1.45 to 1.994 MPa, and 1.32 to 1.737MPa at zero and -10°C, respectively. From these results, LTA has positive effects on DGAMs.
5.8. Cohesion Assay

Cohesion is a common assay to examine the binder viscosity. Cohesion of LTA-DGAMs was examined at 60°C (ASTM D-1560, 2015). LTA-DGAMs exhibited more cohesion than virgin DGAMs as found in Figure 9. Assay values depict that cohesion for DGAM0d, DGAM4d, and DGAM8d samples containing gel and sol asphalt cement are 210, 364 and 331, and 218, 339 and 314 at 60°C, respectively, the cohesion of virgin DGAMs containing gel and sol asphalt cement increases by 73 and 57%, and 56, and 44% for 4d, and 8d-LTA, respectively. Thus, LTA has positive effects on the DGAMs-cohesion. The higher cohesion values at 4d-LTA may be related to that the asphaltenes percentage at this ageing period remains within the specification limits (≤25%).

5.9. Aging Sensitivity

Aging sensitivity was examined by A.I. which equals to (cohesion of LTA-DGAMs /cohesion of virgin DGAMs). Fig. 10 depicted that LTA raises A.I. due to the higher bonds between binder and aggregates. Assay results depict that A.I. for DGAM4d, and DGAM8d samples containing gel and sol asphalt cement are 1.74, and 1.58, and 1.56, and 1.44 at 60°C, respectively. The findings agree with those reported by John and David (2003).
5.10. Aging Benefits

Commonly flexible pavements structural distresses are the surface cracking and rutting. Cracking in paving layers is caused from fatigue which is generated by the traffic repetitions, whereas, rutting is from the deformations occurs at other layers. \( \varepsilon_t \) and \( \varepsilon_c \) in pavement have been took as indices of fatigue and rutting. Yang (2012) takes 1.27 cm rut depth to be a failure limit for flexible pavement and the rutting in Eq. (3) is used:

\[
N_d = 1.365/\left[ 10^9 * (\varepsilon_c^{4.477}) \right]
\]  

Where \( N_d \) = number of cumulative standard axles to produce a rutting of 12.7mm.

The \( w_o \) and \( \varepsilon_t \) in LTA pavement model were determined for different DGAMs and base course thicknesses utilizing BISAR program with \((40\times10^3 \text{ N and set of dual tires of 21cm dia.})\). For LTA model, thickness of the DGAMs of 5.0cm, binder course of 5.0cm, and subbase layer of 20cm were remained fixed and the thickness of base layer was changed. Similarly, thickness of DGAMs was changed for fixed binder (5.0cm), base (20cm), and subbase (20cm).

Figs. 11 and 12 depicts the \( w_o \) and the \( \varepsilon_t \) variation. The results of \( w_o \) and \( \varepsilon_t \) were utilized to examine the advantages of LTA-DGAMs containing gel and sol asphalt cement in forms of LTR and TBR. The TBR (equ. 4) depicts the pavement service life extension caused by LTA:

\[
TBR = N_{dA}/N_{du}
\]  

Where \( N_d \) = No. of traffic passes to produce \( w_o \); and \( U \) and \( A \) notify unaged and LTA pavement models. Al-Hadidy (2009) reported the advantages of polypropylene-asphalt pavement in forms of LTR (equ. 5) for similar service life.

\[
LTR = \left[ (D_U - D_A)/D_A \right] \times 100
\]
DU and DA = DGAMs and base course thicknesses of unaged and LTA models.

The results of BISAR analyses in Figure 11 depicted that the \( \varepsilon_t \) and the \( \varepsilon_c \) in the designed standard pavement model with gel DGAMs of 4010 N/mm\(^2\) is 345µm and 251µm. Similarly, (Fig. 12), these values for gel DGAM with 4460 N/mm\(^2\) is 340µm and 248µm, respectively. For fixed binder thickness, base course and subbase course, these levels of strain were gained for pavement model containing gel DGAM4d thicknesses of 43mm. Whereas, these values were found to be 46mm and 43mm, respectively.

If the pavement model is remained the same for unaged and LTA-DGAMs containing gel asphalt cement, the \( \varepsilon_c \) decreases from 251µ for unaged model to 240µ for DGAM4d; giving the TBR of 1.2. Similarly, for unaged and aged DGAM containing sol asphalt cement (Fig. 12), the \( \varepsilon_c \) decreases from 248µ for unaged model to 239µ for DGAM4d; giving the TBR of 1.2. It means that LTA pavement will have a life 1.20 times that of unaged pavement. These results depict that for a fixed thicknesses of gel DGAMs, binder layer, and subbase these levels of strain were gained for a base course thickness of 85mm, in DGAM4d pavement model, respectively. From these results, it was depicted that DGAMs and base course of unaged pavement model decreases by 14% and 57% for DGAM4d, for similar service life of unaged and LTA pavements. Similarly, (Fig. 13), for a fixed thickness of sol DGAMs, binder course, and subbase, these levels of strain were gained for a base course thickness of 90mm, for DGAM4d pavement model. From these results, it was depicted that DGAMs and base course thickness of unaged pavement model decreases by 14% and 55% for DGAM4d. Thus, the paving model can be designed using any of the discussed alternatives.

The pavement can also be designed for any intermediate thickness to decrease DGAMs or base course thickness, besides obtaining additional TBR. For e.g., for gel DGAM4d, the base thickness can be
decreased theoretically below 85mm (57%LTR) for εc of 251μ. Besides, for all analyzed options, the Wc was reduced by 3 to 4%. It depicts that the overall pavement strength be higher due to utilizing LTA-DGAMs course.

6. Conclusions

Among the examination and analyses the following conclusions can be notified:

A- A review of Marshall, ITS, CS, cohesion, IRS, and TSR results depicted the following:

1. Marshall prospects depicted that the MQ of unaged DGAMs containing gel and sol asphalt cement increased by 132% and 99%, and 111%, and 78% at 4d, and 8d-LTA, respectively. It can be depicted that the LTA-DGAMs give well rutting strength and could be adopted for higher traffic pavements.
2. Dry ITS containing gel and sol asphalt cement increases 24 and 20, and 14, and 10% at 4d and 8d-LTA, respectively.
3. The increase in CS containing gel and sol asphalt cement at 4d and 8d-LTA was depicted to be 5 and 17%, and 12 and 21%, and 13 and 28%, and 22 and 36% at 25°C and 60°C, respectively.
4. The tensile strength ratio for DGAM0d, DGAM4d, and DGAM8d containing gel and sol asphalt cement was found to be 82, 93 and 89%, and 90, 94 and 93%, respectively. This depicts that LTA gives a positive advantage to moisture resistance.
5. It was depicted that the IRS of virgin DGAMs containing gel and sol asphalt cement increases by 11% and 8%, and 13% and 11% for DGAM4d, and DGAM8d, respectively
6. The Sr for unaged DGAMs containing gel and sol asphalt cement at 4d and 8d-LTA was notified to be 27 and 25%, and 19 and 18%, and 26 and 24%, and 24 and 21% at zero and -10°C, respectively.
7. From these results, it is revealed that LTA-DGAMs exhibit well than virgin DGAMs at low temperatures, which is a preferable trait of LTA-DGAMs.
8. The resilient moduli for DGAMs containing gel and sol asphalt cement at 25°C temperatures increases by 52% and 38%, and 37% and 24% for 4d, and 8d-LTA, respectively.
9. The cohesion of virgin DGAMs containing gel and sol asphalt cement increases by 73 and 57%, and 56 and 44% for 4d, and 8d-LTA, respectively. Thus, LTA has enhanced DGAMs cohesion, which depicts that LTA make the asphalt viscosity higher.
10. It was depicted that A.I for DGAMs containing gel and sol asphalt cement increases by 74, and 58%, and 56, and 44% for 4d, and 8d-LTA, respectively. These findings agree with those gained by John and David (2003).
11. Statistical relations among the DGAMs assays are explored: a) for their utilized in the absence of ITS and CS assays, and/or b) the engineer does not select to utilize those assays.; and
12. Statistical analyses program (SPSS) was utilized to introduce an ideal table based from the DGAMs assays. Results gained from such analyses can be utilized to get the LTA options for any field conditions. Perfect choosing based on the option examined by the designer.

B- Mechanistically-empirical design tool results depicted the following:

1. If the pavement model is remained the same for unaged and aged DGAM containing gel and sol asphalt cement, the pavement gives TBR value of 1.2 for 4d-LTA.
2. It was depicted that gel DGAMs and base layer thickness of unaged pavement model decreases by 14% and 57% for DGAM4d, respectively, for similar service life of LTA and unaged pavements.
3. It was depicted that sol DGAMs and base layer thickness of unaged pavement model decreases by 14% and 55% for DGAM4d for similar service life of LTA and virgin pavement.
4. The LTA-DGAMs pavement as a wearing layer has advantages in decreasing the construction paving material. Perfect choosing based on the option examined by the designer for decreasing the individual layer thickness; and
5. It was found that sol asphalt cement performs slightly better than gel asphalt cement, especially in the case of moisture susceptibility and flexural strength properties.
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