Enhanced asphalt mixture behavior by using khawa clay to resist deformation

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Abstract. This paper aims to investigate the effect of adding bentonite (khawa clay) on the asphalt mixture response represented by reducing total accumulative deformation. Asphalt cement with penetration grade of (40-50) and optimum asphalt content of 4.9 was used. Bentonite with different percentages of (0%, 3%, 6%, and 9% by total weight of asphalt cement) was used. The asphalt mixtures were tested by uniaxial creep test under static load at two test temperature (40°C and 60°C) and the applied stress used 600 KPa. From the experimental result of rotational viscosity after and before the addition of bentonite at two temperatures 135°C and 165°C, it can be seen that the viscosity of the asphalt cement was enhanced when adding 9% of Khawa clay to around 126% percent of improvement in viscosity at 135°C and about 195% at 165°C. The improvement in the viscosity of asphalt leads to a decrease in the accumulative strain.

1. Introduction
Asphalt cement is used as an essential element of the pavement material mixtures. It is essential to know the physical and rheological properties to simulate the asphalt binder behavior[1]. This research focuses on the study of the effect of adding (Khawa clay) bentonite on the response of asphalt mixture represented by reduced total deformation; the deformation occurs in asphalt mixture can be predicted by using creep test under static load. Creep tests can be used to determine the accumulation of deformation with time or loading cycles. It is a time-dependent deformation that happens when a material is subjected to loading over time. The stiffness of a material, which is simply the reciprocal of the compliance, is employed to model pavement systems and predict stresses, strains, and distresses [2].

However, when considering the viscoelastic behavior of asphalt materials, it's often more advantageous to use the creep compliance than to use the elastic modulus because the compliance can allow separation of its response over time into time-dependent and time-independent components during a creep test. Deformation over time is measured when a static load is applied to a specimen so that, the creep compliance is then computed using Equation 1.

\[ D(t) = \frac{\varepsilon(t)}{\sigma} \]  (1)

where
D(t) = creep compliance, t = testing time, \( \varepsilon(t) \) = strain at a given time, and \( \sigma \) = constant stress.

The mechanical properties of a linear viscoelastic substance can be defined by the role of creep compliance in creep tests at constant stress [3].

There are two commonly used creep tests: the uniaxial compression tension test and the indirect tensile test (IDT). The direct compressive creep test, usually called the uniaxial creep test, is used to
predict permanent deformation (rutting) on the surface layer of the pavement, whereas the IDT is carried out to characterize Hot Mixture Asphalt (HMA) for thermal cracking prediction at low temperatures [4]. Models illustrating the linear viscoelastic behavior of asphalt concrete were assumed, and the viscoelastic material properties were also obtained in terms of creep compliance, relaxation modulus, and complex modulus. Mechanical models such as the one's Maxwell, Kelvin, and Burger were used. These models were used to describe asphalt concrete response time and temperature dependence [5].

The creep compliance curve is often divided into three different parts [6]:
- Primary creep: the portion wherein the strain rate decreases with loading time.
- Secondary creep: the portion wherein the strain rate is constant with loading time.
- Tertiary creep: the portion wherein the strain rate increases with loading time

A significant increase in creep compliance exists within the tertiary region. The flow time is defined as the reason at which tertiary deformation begins. It has been found that this is a critical time when shear deformation starts under constant volume [7].

The significant properties of an asphalt mixture's creep curve are the time or number of loading cycles at which the secondary creep region begins, the constant strain rate in the secondary area, and the number of flows. Determination of these characteristics may be useful in investigating asphaltic paving rutting [8].

Figure 1 shows the strain behavior with time under loading and unloading conditions. The strain initially starts as elastic deformation, then it changes gradually to elastoplastic deformation partially elastic and partially plastic, and finally to plastic deformation. The visco-plastic and the visco-elastic phases are also typical in the viscoelastic material, such as asphalt mixtures. The accumulative deformation resulting from these phases is responsible for the rutting distress. The components of the total strain are expressed in Equation 2 [9].

\[
\varepsilon = \varepsilon_c + \varepsilon_p + \varepsilon_{vp} + \varepsilon_{ve}
\]

Where
\(\varepsilon_c\) = creep strain,
\(\varepsilon_e\) = elastic strain (Recoverable and independent of time ),
\(\varepsilon_p\) = plastic strain (Irrecoverable and independent of time),
\(\varepsilon_{ve}\) = viscoelastic strain (Recoverable and dependent of time),
\(\varepsilon_{vp}\) = viscoplastic strain (Irrecoverable and dependent of time).

The research aims to investigate the properties of the asphalt mixture after the addition of bentonite and reduce the strain produced when applied load. The sample behaves as an elastic material at the loading period and viscoelastic at the unloading period. Over time the pavement loses the ability to behaves as elastic or visco-elastic materials; after removing the load, it became plastic material. The purpose of bentonite to decrease the deformation.
2. Materials

2.1. Asphalt cement

One type of asphalt cement (40-50) penetration graded produced from Dourah refinery southwest of Baghdad was used in this research because of its local availability and most commonly used in paving roads in Iraq. The physical properties of the asphalt cement are presented in Table 1.

| Property                        | ASTM Designation [11] | Penetration Grade40-50 Test Results | SCRB Specification (R/9, 2003) |
|---------------------------------|------------------------|------------------------------------|--------------------------------|
| Specific gravity                | D70-2009e1             | 1.04                               | —                               |
| Flash Point, (°C)               | D-92/2016b             | 276                                | >232                            |
| Softening Point. (°C)           | D-36/D36M-2014         | 51                                 | 50-60                           |
| Penetration at 25°C,100g ,5 sec (0.1mm) | D-5/D5M - 13          | 45                                 | 40-50                           |
| Ductility at 25°C 5cm/min (cm)  | D-113/2007             | 112                                | ≥ 100 mm                        |

It can be concluded from the experimental result shown in Table 1, the properties of asphalt cement used are suitable with the requirement of SCRP 2003.

2.2. Aggregate

The coarse aggregate used in this work were crushed quartz aggregate from Al-Nibaie quarry; it is more widely used for asphaltic mixtures in Baghdad city. The aggregate was sieved to meet the requirement of the specification limits (SCRB R/9, 2003) [12] for the surface course layer type IIIA and also was checked with the requirement of Superpave gradation limit, The gradation of coarse aggregates ranges from nominal maximum sieve size ¾ in. (12.5 mm) to sieve size No.4 (4.75 mm).

The fine aggregate used was the crushed aggregate from al-Nibaie quarry, and also used the river sand. The gradation of fine aggregate is passing form sieve No.4 (4.75mm) and retaining on sieve No.200. The physical properties of aggregate and the chemical composition of coarse and fine aggregate are shown in Table 2 and Table 3, respectively. These tests were carried out by the National Center for Laboratories and Research in Construction.

2.3. Mineral filler

Mineral filler influences the properties and consistency of asphalt mixtures. Based on cost and quality, there are different types of mineral fillers. Limestone dust is a kind of mineral filler which passes from sieve No.200 (0.075mm). The chemical compositions and physical properties of the used filler are described respectively in Table 4 and Table 5. These tests were carried out by the National Center for Laboratories and Research in Construction.
Table 2. The physical properties of the used aggregate.

| Property                          | Result  | ASTM designation | Specification limits |
|----------------------------------|---------|------------------|----------------------|
| Bulk Specific Gravity (gm/cm³)   | 2.62    | ASTM C-127/15    | ……                   |
| Apparent Specific Gravity (gm/cm³) | 2.642   | ASTM C-127/15    | ……                   |
| Water absorption %               | 0.421   | ASTM C-127/15    | ……                   |
| Percent Wear (Loss Angeles Abrasion) | 18      | ASTM C 131/C131M – 14 | 35-45% Max.         |
| Angularity for Coarse aggregate  | 98%     | ASTM D5821       | Min 95%              |

Table 3. The chemical composition of the used aggregate.

| Chemical Compound                  | Content % |
|------------------------------------|-----------|
| Silica (SiO2)                      | 83.57     |
| Lime (CaO)                         | 4.39      |
| Sulfuric anhydride (SO3)           | 2.7       |
| Magnesia (MgO)                     | 0.76      |
| Ferric Oxide (Fe2O3)               | 0.66      |
| Alumina (Al2O3)                    | 0.49      |
| Loss on Ignition                   | 6.5       |
| Total                              | 99.07     |

Table 4. The chemical composition of the used mineral filler.

| The Chemical Compound               | Content % |
|-------------------------------------|-----------|
| Loss on Ignition                    | 35.14     |
| Ferric Oxide (Fe2O3)                | 0.08      |
| Silica (SiO2)                       | 1.96      |
| Alumina (Al2O3)                     | 3.4       |
| Magnesia (MgO)                      | 7.2       |
| Lime (CaO)                          | 51.9      |
| Sulfuric Anhydride (SO3)            | 0.32      |
| Total                               | 100       |
Table 5. Physical Properties of the used mineral filler.

| Physical Properties                  | Test Result |
|--------------------------------------|-------------|
| Specific Gravity (gm/cm³)            | 2.76        |
| Passing Sieve No.200 (0.075mm)       | 97%         |
| Specific Surface Area (m²/kg)        | 315         |

2.4. Additive khawa clay (bentonite)

Bentonite is a type of clay available in Iraq in the western region and northern region, which is cheap and available in the market. This consists mainly of montmorillonite. It was named after the cretaceous Benton shale close to Rock River by Wilbur C. Knight in 1898 [13]. There are two types of bentonite white color and green color. In this study, the green color type was used because of its availability in the local market.

To prepare the bentonite-asphalt cement, bentonite was crushed and modified to finer size, like powder, passing from sieve #100. Asphalt was heated to 150°C, and gradually, the bentonite was added by different percentages, 3%, 6%, and 9% of the weight of the asphalt cement. The bentonite was blended with the asphalt cement at 160°C. The period of mixing was 45min and the rotational of the blender was 2300rpm. The chemical composition of bentonite is illustrated in Table 6. The mineral content of bentonite was determined by using X-ray diffraction (XRD) as shown in Table 7.

Table 6. The chemical composition of Bentonite.

| Chemical components | Percent content |
|---------------------|-----------------|
| SiO2                | 56.77           |
| Al2O3               | 24.8            |
| Fe2O3               | 8.83            |
| CaO                 | 4.18            |
| MgO                 | 3.67            |
| Na2O                | 1.53            |
| K2O                 | 0.6             |
| SO3                 | 0.65            |
| LOI                 | 0.43            |

Table 7. The mineral composition of Bentonite.

| Mineral composition | Percent content |
|---------------------|-----------------|
| Montmorillonite     | 78              |
| Plygorskite         | 8               |
| Apatite             | 6               |
| Calcite             | 4               |
| Gypsum              | 2               |
| Halite              | 1               |
| Quartz              | 1               |

3. Selection of design aggregate structure

The selection of aggregate gradation was according to the Specification Limits of SCRB and Superpave Specification. The Superpave system improves a new method to select gradation of aggregate. It depends on the 0.45 power gradation chart which has two properties, the first was restricted zone and the other controls point, to specify the gradation of combined aggregate. The maximum density gradation is a significant feature of the 0.45 power chart. This gradation plotted as a straight line through the origin of the maximum aggregate size. The maximum density gradation represents a gradation in which the aggregate particles fit together in their densest possible arrangement.
In this study, three trail blends were selected for wearing course and drawn under the restricted zone, use 12.5mm Nominal maximum size. The aggregate gradation is shown in Table 8 and the selection of aggregate is shown in Figure 2.

Table 8. The selected gradation of combined aggregate.

| Sieve no. | Sieve Opening (mm) | Gradation passing % | super pave specification 2007 (Max.) | Super pave specification 2007 (Min.) | SCRBR-9-2003 (Max.) | SCRBR-9-2003 (Min.) |
|-----------|-------------------|---------------------|--------------------------------------|--------------------------------------|----------------------|----------------------|
| 3/4 "     | 19                | 100                 | 100                                  | 100                                  | 100                  | 100                  |
| 1/2 "     | 12.5              | 93                  | 95                                   | 97                                   | 100                  | 90                   |
| 3/8 "     | 9.5               | 77                  | 85                                   | 89                                   | 90                   | 76                   |
| No.4      | 4.75              | 50                  | 56                                   | 72                                   | 74                   | 44                   |
| No.8      | 2.36              | 30                  | 35                                   | 38                                   | 58                   | 28                   |
| No.16     | 1.18              | 16                  | 17                                   | 19                                   | 31.6                 | 25.6                 |
| No.30     | 0.6               | 10                  | 15                                   | 18                                   | 23.1                 | 19.1                 |
| No.50     | 0.3               | 8                   | 10                                   | 14                                   | 15.5                 | 15.5                 |
| No.100    | 0.150             | 4                   | 6                                    | 8                                    | 21                   | 5                    |
| No.200    | 0.075             | 2                   | 4                                    | 6                                    | 10                   | 2                    |

Figure 2. Aggregate gradation chart for wearing course.
4. Test Methods

4.1. Rotational viscosity test
This test was conducted for the used asphalt cement, without modification and for the modified asphalt cement, with 3%, 6% and 9% of bentonite by the asphalt weight. The viscosity was measured at the temperature of the compaction and mixing which are 135°C and 165°C respectively. The rotational viscometer (RV) test was used to evaluate the variation in viscosity between the original and the modified asphalt. The result of rotational viscosity of asphalt cement with bentonite (BE) for different percentages shows an increase in viscosity with increasing of BE modifier content (from 3% to 9%) by the weight of asphalt. Each value of viscosity at each temperature represents the arithmetic mean of the last of three reading.

4.2. Marshall mix design
The Marshall method is used to calculate the optimum asphalt content (OAC) following the Iraqi's specification for Roads and Bridges SCRB (2003) [12]. According to this specification, the aggregate was sieved using sieve analysis, then it was washed and cleaned from dust. After that, the aggregate was dried using air blower, then heated to a temperature of 160°C. The asphalt cement was also heated to a temperature of 160°C, asphalt cement was heated to the temperature producing a kinematic viscosity of (170 ± 20) centistokes (up to 163 °C as an upper limit). Then, the aggregate was mixed with the asphalt cement until all aggregate were coated with asphalt. The prepared mixture was put in a preheated mold (101.6mm) diameter, 63.5mm height. In this study, five asphalt cement content was investigated to find the OAC (4.0, 4.5, 5.0, 5.5 and 6.0 %). Three specimens for each percent of asphalt content were prepared. Each specimen was compacted by 75 blows with a hammer of 4.536 kg. The specimens cooled at room temperature for 24 hours after that all specimen were put in a water bath for 30 min at 60°C. The prepared samples were tested to report Marshall stability and flow tests. The average of each three specimens was recorded. The bulk specific gravity, theoretical specific gravity tests at a laboratory, the volumetric properties of the asphaltic mixture as a percent of air voids %AV, percent voids fill with Asphalt %VFA and percent voids in mineral aggregate %VMA were calculated. The optimum asphalt content was chosen as 4.9% for the surface layer type IIIA as the average content for 4% air voids in the total mix maximum specific gravity and maximum stability, according to the limits of the Iraqi SCRB specification (2003) [12].

| Properties | Result |
|------------|--------|
| Specific gravity | 2.65 |
| Air voids% | 4 |
| VMA% | 15.7 |
| VFA% | 71 |

4.3. Uniaxial creep test
Once the optimum asphalt content had been specified, other Marshal specimens were prepared using the determined OAC. Twenty four specimens were prepared using net asphalt without additives and modified asphalt with three selected percentages of bentonite. These specimens were tested at two different temperatures, 40°C and 60°C, with uniaxial creep test ASTM D1074 [14].

In the uniaxial creep test, also known as unconfined or simple creep test, a static load is applied. In this study, the static load is 600 KPa. The test was conducted in 3600 sec. The first 30 minutes was for loading, and the second 30 minutes was for unloading. During the test, the cumulative strain values were recorded at a constant temperature.

The deformation of the specimen resulted from loading and unloading was measured using LVDT (Linearly Variable Differential Transformer). The LVDT diverts the mechanical to an electrical signal to observe the deformation (displacement).

The GEODATALOG 8 is an eight-channel multipurpose data logger that can be used for a wide variety of laboratory applications.
The unit is fully controlled and operated from a PC with the general-purpose software ‘DATACOMM 2’ installed. Data are acquired by the unit and transferred to the PC in real-time for monitoring tests [15].

Strain can be calculated as in Equation (3) [16].

\[ \varepsilon_{\text{mix}} = \frac{\Delta H}{D} \tag{3} \]

where:
\( \Delta H = \) The total measured deformation at a certain loading time (mm)
\( D = \) the original diameter of the specimen 101.6 (mm)

5. Results and discussion

5.1. Effect of bentonite on viscosity of asphalt binder

It can be concluded from the result of rotational viscosity as demonstrated in Figure 3:

- The rotational viscosity of asphalt cement modified by Bentonite (3%, 6% and 9%) increased to 12.97%, 147.33 % and 195% respectively at mixing temperature and to 6.82%, 75.5% and 126.10% respectively at compaction temperature.
- It is clearly shown that the addition of bentonite into asphalt cement increases the binder viscosity. It also indicates that the improvement in viscosity occurred when the percentages of Bentonite adding to the asphalt increases.
- The result indicated that the viscosity of the asphalt binder decreases when the temperature increases.
- It is also seen from the results of rotational viscosity that all the modified asphalt percentages at 135°C lower than 3Pa.s according to the standard specification on Superpave.

![Figure 3. Rotational viscosity of the modified asphalt cement.](image)

5.2. Effect of bentonite on accumulated deformation

The strain-dependent time resulting from the application of constant uniaxial stress, 600 KPa, was measured in the creep test. In the loading period, which was half an hour time of applying the load on the specimen, the strain was recorded. It was also recorded in the unloading period, which is the half-hour time after removing the load. Figure 4 shows the results of the accumulated deformation of Bentonite–asphalt mixture at 40°C. This figure demonstrates that the strain decrease when the percentage of the bentonite increases during the loading period. The strain of asphalt mixture without any additive at the same conditions (temperature, load) has higher values compared with the modified mixture. when using 3%, 6% and 9% of Bentonite by the weight of asphalt, the reduction percent is around (41%, 49.74, 53%) at 60°C and (20%, 29.4%, 30.7%) at 40°C.
Figure 4. Accumulated strain of mixture modified at 40°C.

Figure 5. Accumulated strain of mixture modified at 60°C.

5.3. Stiffness of asphalt mixture

The stiffness modulus of the Asphalt mixture $S(\text{mix})$ is a ratio of stress to strain at a loading time [17].

$$S(\text{mix}) = \frac{\sigma}{\varepsilon(\text{mix})} \quad \text{(N/mm}^2)$$

where:
- $S(\text{mix})$ = Stiffness modulus (N/mm²).
- $\sigma$ = Applied stress (N/mm²), and
- $\varepsilon(\text{mix})$ = Vertical strain in the mixture sample (mm/mm).

The stiffness modulus can be used to explain the mechanical properties of viscoelastic materials, where the strain is a function of the time of loading (t).

Figure 6 and Figure 7 present the values of stiffness modulus of the bentonite asphalt mixture during the loading time under the applied stress of 0.6 MPa and at 40°C and 60°C test temperature, respectively. The stiffness of the asphalt mixture increases with an increase in the bentonite percentage and has the maximum value at 9%. This increment in the stiffness resulted from the increase in the asphalt viscosity. Higher values of stiffness modulus mean that the asphalt mixtures have considerable resistance to permanent deformation.

The addition of 3% of bentonite has an insignificant effect on the asphalt mixture comparing with adding 6% and 9%. On the other hand, the stiffness modulus decreases as the loading time increases and as the temperature increases, as illustrated in Figure 6 and Figure 7. This is because of that viscosity decrease as temperature increase.
5.4. Creep compliance
Creep compliance, which is a ratio of strain to stress, can be used as a demonstration of the creep of the asphaltic material. It can be defined as a time-dependent deformation caused by applying constant stress [18].

\[ D(t) = \frac{\varepsilon(t)}{\sigma} \quad (1/ \text{KPa}) \]  

(5)

Where:
- D(t): the creep compliance in (1/ KPa).
- \( \varepsilon(t) \): vertical strain (mm/mm).
- \( \sigma \): applied stress in (KPa).

As shown in figures (8) and (9) were to plot the log creep compliances versus time, the creep compliance at 0% additive have the highest values as compared with the other bentonite-asphalt mixtures. Bentonite may improve the asphalt mixture by decreasing the creep compliance of mixtures.
Figure 9. Creep compliance result of modified asphalt mixture at 60°C.

6. Conclusion
Based on the experimental work and the results of this study, it can be concluded that:
1. The addition of bentonite (Khawa clay) increases the rotational viscosity of asphalt. Therefore, it increases the viscosity of the asphalt mixture and reduces the permanent deformation.
2. The increase in the percentage of bentonite content in the asphalt mixture will cause a decrease in accumulative deformation.
3. The strain of asphalt mixtures increases when the temperature increases at the same gradation, asphalt content, and also the same applied load.
4. As a result of the viscosity increase, the stiffness modulus increases with the increase in the percentage of the bentonite content at the same condition regarding the applied load. On the other hand, the stiffness modulus decreases with loading time.
5. The useful features of bentonite make the creep compliance decreases by increasing the additive content at the same temperature 40°C or 60°C at the loading period.

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