Investigation of asphalt binder performance modified with ceramic waste powder

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Abstract. The widespread use of industrially produced ceramic in multiple uses around the world has resulted in large quantities of wastes dumped in landfills. Thus, the presence of these quantities of waste materials is a source of concern for environmental pollution. For the purposes of conservation and sustainable construction, recycle and reuse of ceramic wastes are a good and new attempt in this field. This study investigated the effect of various percentages of ceramic waste powder (CWP) on the physical and rheological properties of binders. Two different penetration grades of binder 60/70 and 80/100 were used in this research, and each one was blended with three different percentages of CWP content (3%, 6%, and 9% by weight of binder), to evaluate for such related properties of the ceramic waste powder modified binder (CWPMB). Laboratory tests undertaken included penetration, softening point, viscosity, storage stability, and Dynamic Shear Rheometer (DSR). To simulate the short-term aging, Rolling Thin Film Oven Test (RTFOT) was conducted after RTFO aging, whereas the long-term aging simulated by Pressure Aging Vessel (PAV) test which is used after (PAV) aging, then, evaluated for rutting \( \frac{G^*}{\sin \delta} \) and fatigue \( G^* \sin \delta \) factors by conducting the (DSR) test. It found that the addition of CWP enhances the physical properties of the asphalt binders, due to increased viscosity, storage stability, and softening point, as well as decreasing the penetration. The results observed that the high percentages of CWP content can increase \( \frac{G^*}{\sin \delta} \) before and after RTFO aging and decrease \( G^* \sin \delta \) after PAV aging, which is leading to higher resistance to permanent deformation (rutting and fatigue) of binders. Also, as compared to the 80/100 CWPMB, the results showed that the stiffer 60/70 CWPMB was more resistant to rutting and less resistant to fatigue cracking.

Keywords: Ceramic waste powder, Asphalt binder, Physical and Rheological properties.
1. Introduction
There are many distresses of the pavement that can occur gradually after construction especially of the flexible road, due to changes in the climate and heavy traffic loads lead to the accelerated appearance of defects. The perpetual defects in the flexible pavement caused by two major reasons that are rutting and fatigue cracking, which makes maintenance a necessity at specified intervals [1]. Generally, the properties of the asphalt binder responsible for the performance of the pavement. Properties of the conventional asphalt binder like rheological and durability need improvement to resist pavement distresses.

Many claims have been made about protecting the environment from pollution resulting from waste materials like ceramic wastes, fly ash, and silica fume [2], which helped researchers to investigate the use of these wastes in asphalt binder modification. Using these waste materials in modification will solve several problems like landfill problems and help to improve workability, durability, and strength of asphalt binder [3]. Making stiffer asphalt cement binder with high viscosity in the hot weather is one of the major goals of using a modification of asphalt binder to reduce rutting and shoving, as well as a less stiff binder in very cold weather to reduce transverse cracking. On the other hand, improving the adhesion of asphalt binder to aggregate during the presence of moisture to reduce stripping. Modifiers of asphalt binder provided in a variety of materials able to improve the performance of flexible pavements. Fillers and fibers are common modifiers found to reinforce the mixture [4]. Also, sulfur is another additive that can be used to modify the asphalt binder by a partial or complete replacement [5].

Other forms of additives have recently been discovered, such as polymers, elastomers, antistripping agents, and metal complexes to improve asphalt properties [6]. The solid or liquid form is available in abundance for these additives [7]. Ceramic is classified as an inorganic and non-metallic material resulting from the influence of heat and subsequent cooling. The use of this product was widely in this globe. However, ceramic uses lead to provide big quantities of waste materials, and instead of sending this amount of ceramic wastes to landfill, it can be recycled as aggregate and used for modification purposes or other application in civil engineering at the lowest cost [8-9]. The improvement of stiffness and rutting resistance was reported by Muniandy et al. [10] by replacing 10% of conventional limestone filler with ceramic waste filler. To enhance asphalt natural crack repair, some researchers have used waste cooking oil as a rejuvenator to aged bitumen in the presence of temperature [11-14].

Many studies and research conducted by scientists recently on the effectiveness of using waste powders and the possibility of replacing it with the mineral filler of asphalt mixtures, where researchers found that using ceramic waste dust can be totally replaced by limestone powder in asphalt paving mixtures [6,15–18]. Asphalt mixtures evaluated by using(as an effective filler in dense-graded wearing course) fly ash as a filler replacement [7]. In addition, the investigations about waste lime can use as mineral filler of asphalt mixtures to improve the permanent deformation characteristics [4]. The performance of asphalt pavement is greatly affected by temperature changes [19-20]. Most of the defects that appear in asphalt pavement are closely related to temperature changes, for example, rutting (high temperatures) and cracking (low temperatures) distresses. Researchers believe that using ceramic powder from waste material as an additive of asphalt binder can be a solution to reduce pavement distresses due to the low thermal conductivity of ceramic.

Based on the previous studies, the results referred that the use of ceramic powder from waste materials has a positive effect not just in modifying the base asphalt binder but also can improve its engineering characteristics. Therefore, investigation and evaluation of ceramic powder additive made from ceramic wastes on the physical and rheological changes of modified asphalt binders are representing the objective of this research. Also, knowing the effect of the ceramic waste powder additive in the modified binder on the extent of aging in the rheological properties and the extent of its effect on the properties of high temperatures (rutting) as well as intermediate temperatures (fatigue cracking), which is being by (RTFOT) for short-term aging and (PAV) test for long-term aging. Furthermore, investigation and evaluation of ceramic waste powder content on the modified asphalt binder performances had been conducted by using the softening point, penetration, viscosity, storage stability, and (DSR) tests.
2. Experimental and Materials

Two different conventional 60/70 and 80/100 penetration grades with 50°C and 49°C respectively as a softening point used in this research. The physical and rheological properties of the control binders are shown in Table 1. The CWP was used to modify the control binders. The ceramic waste was obtained from factories and construction waste. In order to get a smaller ceramic size, firstly, it was manually crushed by using a hammer, secondly, crushed into the jaw crusher so that it would be easier to sieve by using the 1.18 mm sieve size to extract the larger sizes, thirdly, it was ground into a fine powder using a Los Angeles abrasion machine for at least 9 hours, finally, the fine powder has been sieved, and fine particles that passed through the 40 μm sieve was used in this mixing [21-22]. Table 2 presents the chemical compounds in the CWP additive. Silicon oxide (SiO$_2$) (75.45%) was the most common compound and it occupies the largest part of CWP. Other elements were relatively inactive, such as sodium oxide (Na$_2$O) (3.71%), alumina (Al$_2$O$_3$) (12.22%), magnesia (MgO) (1.20%), potassium oxide (K$_2$O), and calcium oxide (CaO). The main focus of this analysis was the presence of a large amount of silica. These ceramic wastes were an incredibly useful modifier ideal as a binder due to the predominance of silica.

| Table 1. Physical and Rheological properties results of the control binders. |
|------------------|------------------|------------------|
| Test Properties  | 80/100           | 60/70            |
| Penetration at 25°C (d-mm) | 86              | 67               |
| Softening point (°C) | 49              | 50               |
| Viscosity at 135°C (Pa·s) | 0.45            | 0.54             |
| Ductility at 25°C (cm)  | >100            | >100             |
| G*/sin δ at 64°C (kPa) | 1.56            | 1.89             |
| G*/sin δ for RTFO aging at 64°C (kPa) | 3.1             | 4.22            |
| G*sin δ for PAV aging at 31°C (kPa) | 2900            | 3200            |

| Table 2. Chemical compounds of CWP modifier. |
|--------------------------------------------|
| Composition | Profusion (%) |
| SiO$_2$    | 75.45         |
| Al$_2$O$_3$| 12.22         |
| Na$_2$O    | 3.71          |
| Fe$_2$O$_3$| 3.00          |
| MgO        | 1.20          |
| CaO        | 1.48          |
| TiO$_2$    | 0.56          |
| K$_2$O     | 1.79          |
| LOI        | 0.11          |

Using a high shear mixer to mix the control binder and CWP modifier at 160°C temperature to prepare the samples. The mixing time is 60 minutes to ensure that the adequate mixing between the CWP and the control binder to produce a homogeneous binder [23], and a velocity of 1500 rpm to ensure that the CWP material was well dispersed in the asphalt binder. Physical tests conducted to investigate the effect of CWP content on the asphalt binder through; the penetration test (25°C) ASTM D-5 to measure the consistency of the binders [24], temperature susceptibility determined by using the softening point test (25°C) ASTM D-36 [25], the viscosity test (135°C) ASTM D-4402 [26] carried out to measure the resistance flow of the modified binders, and finally storage stability test to measure extent
stability of modified binders during storage at high temperatures in accordance with ASTM D-5976 [27]. The oxidative aging effect was investigated on rheological changes of modified binders due to age hardening that was evaluated by conducting the DSR test ASTM D-7175 [28]. RTFO test with ASTM D-2872 [29] used at 163°C for 85min for short-term aging, whereas the PAV test carried out in accordance with ASTM D-6521 at a temperature of 100°C for 20 hours for long-term aging [30] of binders. After that, the samples had been tested using the DSR test.

3. Discussion of Results

3.1 Physical properties

3.1.1 Penetration and Softening point. The results in Figure 1 refer that the penetration was decreased by 13%, 25%, and 39% in the 60/70 CWPMB, as well as 19%, 34%, and 44% in the 80/100 CWPMB for 3%, 6%, and 9% CWP samples, respectively. The penetration results for the modified binders were lower than the control samples. Moreover, due to this decrease in the penetration values, stiffness in the asphalt binders was increased after CWP added to the control samples. As a result, higher stiffness of the modified asphalt binder will help in resisting the deformation like rutting as mentioned by Liu et al. [31] compared to the control asphalt binder. A similar study was found by Shafabakhsh et al. [32]. Also, the softening point temperatures increased from 3 to 6°C in the 60/70 CWPMB also from 2 to 4°C in the 80/100 CWPMB when the CWP contents increased from 3% to 9%. Related to the 60/70 binder penetration lower than 80/100 binder in the two control and modified cases, the softening point values in the 60/70 binder are higher compared to the 80/100 binder. Therefore, the presence of silica in a high percentage of CWP can affect positively on improving the viscoelasticity properties of binders.

Figure 1. Penetration and Softening point results versus CWP content.

After the CWP addition of the asphalt binder, a penetration aging ratio is an alternate option for demonstrating the effects of aging on physical properties. The penetration aging ratio is the ratio of aged penetration value to the unaged penetration as in the equation (1):

\[
\text{Penetration Aging Ratio} = \frac{\text{Penetration after aging}}{\text{Penetration before aging}}
\]
The penetration aging ratio for the control and CWPMB after RTFOT and PAV test are shown in Figure 2. The findings showed that unmodified binder and CWPMB penetration decreased after the two different aging. In addition, the lower penetration aging ratio that contributed to a decrease in the degree of aging of CWPMB was the higher ceramic waste powder content. Thus, the addition of ceramic waste powder contributed to the enhancement of binder resistance to oxidative aging.

\[
\text{PAR} = \left( \frac{\text{Penetration/aged}}{\text{Penetration/unaged}} \right) \times 100
\]

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\]

3.1.2. Viscosity. The essential property of the asphalt binder and can be determined at a given temperature with a loading time. Furthermore, stiffness and resistance of asphalt pavement deformation are related to viscosity. The results of viscosity showed in Figure 3 at 135°C and 165°C for the two different asphalt binders. The binder’s ability to pump through the asphalt plant is an important indicator, that is related to viscosity at high temperatures [33]. It can be seen that the CWPMB viscosities were increased compared to the control binder due to the effect of CWP modifier that enhanced properties of the asphalt binders. As expected, the higher percentages of CWP lead to the higher viscosity of the asphalt binders. Since the 60/70 binder is stiffer than the 80/100 binder, the viscosity of the 60/70 binder is higher than the viscosity of the 80/100 binder. At 135 °C compared to 165 °C, the viscosity increase was apparent.
3.1.3. Storage stability. In accordance with ASTM D5976, the results of the storage stability test for the modified binders passed a specification of less than 2.2 °C, as shown in Table 3. This suggested that in the asphalt matrix, the ceramic waste powder content was well dispersed. Also in high-temperature conditions, the modified asphalt binder remains homogenous and stable. In addition, the CWP is probably homogeneously distributed in the asphalt to ensure that the asphalt is in a safe condition during storage and transportation [23]. Thus, the results suggest that the compatibility and stability of the modified binders has been improved. However, the variations in the softening point in the 80/100 CWPMB were inconsistent with the same percentages of CWP content in comparison with the 60/70 CWPMB. This may be a return to the differences in the asphalt particles' molecular size distribution.

Table 3. Differences in softening point between top and bottom parts.

| CWP (%) | Softening point differences (°C) | Specification < 2.2(°C) |
|---------|---------------------------------|-------------------------|
| 3       | 0.7 0.4                         | Pass                    |
| 6       | 1.0 0.8                         | Pass                    |
| 9       | 0.6 1.0                         | Pass                    |

3.2 Rheological properties

3.2.1 Rutting factor (G*/sinδ). In this analysis, the dynamic shear rheometer test at 70°C calculated the rutting resistance parameter (G*/sinδ) of the unmodified and modified binders. The results are shown in Figure 4, with the higher CWP content leading to a higher rutting factor (G*/sinδ) value. As expected, G*/sinδ was enhanced when percentages of CWP content increased after RTFO aging. Moreover, for 80/100 unaged binder, the increasing of percentages in G*/sinδ ranged between 9% and 15%, and for RTFO between 15% and 32% for CWP content ranging from 3% to 9%. Also, the percentage increase in G*/sinδ for 60-70 unaged binder was ranging between 22% and 27%, and for RTFO between 22% and 29% for CWP contents ranging between 3% and 9%. The increase in CWP content increases the resistance to rutting (G*/sinδ) with better correlation coefficients. From the findings, all rutting factor values with a specification of at least 1.0 kPa and 2.2 kPa at 70°C showed that the susceptibility to
rutting deformation can be lower when $G^*/\sin\delta$ values are higher at high temperatures [34-35]. The 60/70 CWPMB rutting factor values were higher because they were stiffer compared to the 80/100 CWPMB.

Figure 4. $G^*/\sin\delta$ results versus CWP content.

Figure 5 illustrates the aging index of $(G^*/\sin\delta)$ of the control and ceramic waste powder modified binders at 70°C. As calculated by equation (2).

$$AIRF = \frac{(G^*/\sin\delta)_{aged}}{(G^*/\sin\delta)_{unaged}}$$

The results indicated that the AIRF values of the control binders were higher which will lead to greater susceptibility to aging. Whereas, CWPMB reported lower AIRF, leading to lower susceptibility to aging especially after increasing the percentage of ceramic waste powder content.
3.2.2 Fatigue factor ($G\sin\delta$). In accordance with the Strategic Highway Research Program (SHRP), the maximum value of $G\sin\delta$ is 5000 kPa. Therefore, any reduction in the values of these parameters is a good indicator against fatigue cracking. [33]. In this research, the fatigue factor ($G\sin\delta$) results for unaged and modified binders after PAV aging were measured by a DSR test at a temperature range of 22°C-37°C. The results of the two different types of 60/70 and 80/100 asphalt binders for the different percentages of ceramic waste powder content are shown in Figure 6 at 31°C. In the modified binders, $G\sin\delta$ values are lower than unmodified binders at 31°C, and this relates to improving fatigue resistance due to the quality of ceramic waste powder in asphalt binders. In general, the high percentage of CWP content has a positive effect on improving fatigue resistance. After PAV, for 60/70 CWPMB, the $G\sin\delta$ decrease percentages were 30%, 31%, and 32%, with correlation coefficient $R^2 = 0.9027$, and for 80/100 CWPMB, the $G\sin\delta$ decrease percentages were 28%, 30%, and 38% with correlation coefficient $R^2 = 0.9425$ for CWP contents 3%, 6%, and 9% respectively. It has been observed from the results that the lower $G\sin\delta$ values have a positive effect of decreasing shear energy loss and increasing fatigue resistance ability. At the same percentage of ceramic waste powder content, the $G\sin\delta$ results of 80/100 CWPMB were lower than 60/70 CWPMB, suggesting more resistance to fatigue cracking. 

![Figure 5. Aging index of rutting factor results.](image-url)
4. Conclusions
It has been found from the experiments and thorough review that many conclusions can be drawn as follows:

- Using the ceramic powder from ceramic wastes as an asphalt binder modifier consider part of sustainability and has positive effects to improve the physical properties like penetration, softening point, viscosity, and storage stability. Due to decreasing penetration, the improvement of temperature susceptibility resistant characteristics was expected. Moreover, the CWP modifier increases viscosity and stiffness of asphalt binder and make them more workable. In addition, this modifier makes the asphalt binder more stable during storage and transport.

- Rutting resistance of the modified binder was enhanced by CWP addition which affects positively of rutting factor $G^*\sin \delta$ of the asphalt binders.

- Increasing the addition of CWP leads to improved fatigue resistance. Therefore, the higher percentage of CWP content contributes to a lower fatigue factor of $G^*\sin \delta$.

- In this study, as compared to 80/100 CWPMB, rutting resistance in 60/70 CWPMB was higher. However, in the 60/70 CWPMB, the fatigue resistance is lower than in the 80/100 CWPMB.

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