Performance evaluation of asphalt concrete mixture incorporating calcite powder as filler substitute for sustainable pavement construction

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Abstract: The increasing cost and paucity of conventional pavement construction materials has in recent times become very worrisome and a serious challenge in the road construction industry. This has spurred the search for a less expensive and environmentally friendly material, readily available and suitable for the purpose of constructing sustainable pavements both in the rural and urban areas of developing countries. In this research, the suitability of calcite powder in asphalt as filler in substituted proportions was investigated through tests on the modified samples for enhanced engineering properties. This was achieved by partially replacing conventional filler with calcite in proportion of “10%, 20%, 30%, 40% and 50%” respectively. After the production of the modified bituminous concrete at the various proportions, the samples produced were placed in a water bath for 30 minutes at a temperature of 60ºC before conducting the Marshall stability test and flow. Marshall stability values of 37.7 kN, 37.9 kN, 34.0 kN, 35.0 kN, 28.9 kN and corresponding flow values of 12.0 mm, 11.3 mm, 10.5 mm, 9.60 mm, 10.3 mm, were obtained for the modification proportions respectively. The stability values were observed to be higher than the control mix and likewise satisfy the minimum requirement of 3.33 kN or 340 kg according to the Marshal mix design specification for wearing course surfacing. Similarly, the flow values obtained where found to be within the specified range of 8 – 17 mm at 0.25mm units. Percentage air voids (Vv) values of 3.7%, 5.2%, 4.7%, 3.0%, and 5.9% obtained where also found to satisfy the required range of 3-5% according to the specification. Voids filled with bitumen (VFB) values of 78.58%, 69.56%, 69.73%, 76.63%, and 58.93% derived where also within specified range 75 – 85 % of the specification. The X-Ray diffraction (XRD) micrograph showed the distinct presence of calcium and oxygen in the hot mix asphalt modified with calcite, while the scanning electron microscope (SEM) provided an in-depth perspective of the concrete grains in the hot mix matrix and the improved bonding of the aggregates, bitumen and calcite due the presence of calcium. The results have shown the possibility of calcite utilization in bituminous mixes, towards reducing cost of construction and best suitable for medium trafficked roads, parking lots and walkways.

Keywords: Pavement Engineering, Calcite Powder, Marshall Stability, Flow, Optimum Bitumen Content, Sustainable Transportation
1. Introduction

Recently, there has been an increase in the demand for the construction of more sustainable roads in developing countries taking advantage of innovative and substitute materials [1]. This is as a result of the increasing and worrisome high cost of conventional pavement construction materials [2]. This has motivated a lot of researchers to begin to look into this challenge, hence their search for a sustainable and alternative material with the similitude of the properties of the conventional mineral aggregates especially fillers in bituminous pavement mixes [3]. The wearing surfaces of flexible pavements comprise of coarse aggregates, fine aggregates, mineral filler and binder (bitumen), forming a complete compact composite [4]. The filler material in particular performs an important function in the mix as it forms a mastic with bitumen, filling all the cavities of the mixture and technically seals all the voids, hence resulting into a dense and stiff mix, resistant to the impacts of heavy loads [5]. Several investigations have been made on the substitution of conventional fillers with alternative materials from different sources for sustainable pavement works. For instance materials such as carbon powder [6], periwinkle shells [7], fly ash [8], rice husk ash [9], waste plastics [10], polymer [11], milled egg shells [12], brake pad waste [13], steel slag [14], date seed ash [15], coal gangue [16], recycled brick powder [17], oil shale [18], oyster shell powder [19], and cow-bone ash [20] have been investigated. A promising material with similar properties with the conventional is calcite, which is the focus of this paper. The use of calcite in asphalt as filler in substituted proportions poses a very economical move as this is a product that is abundant. Calcite is a rock forming crystalline mineral with a chemical formula of CaCO₃ [21]. It is usually found in sedimentary, igneous and metamorphic rocks. It is a mineral constituent of Limestone and Marble and is extremely common [22]. Calcite has more uses than any other mineral. This material is relatively cheap and can be found in most developing countries and if put to use, will make the production of asphalt cheaper [23]. Research has shown that the fatigue cracking resistance was enhanced by the addition of CaCO₃ in asphalt mixtures [24]. Such modifications will therefore increase the performance characteristics of the hot mix asphalt such as fatigue life, resistance to rutting and thermal cracking. Furthermore and according to [25] it was found that the complex shear modulus of asphalt was improved as a result of using sludge waste containing calcite in asphaltic concrete. Ameliorating the mechanical properties of asphaltic concrete has shown to improve the road service performance in the light of constant usage [22]. As a result of the search for cheaper and more environmentally friendly materials in road construction, the use of calcite as a partial replacement for filler in asphaltic concrete was conceived.

2. Materials used and Methodology

2.1 Materials

2.1.1 Aggregates

The aggregates used in this work are conventional and were sourced from an on-going construction site in Landmark University, Omu Aran, Nigeria. Coarse aggregates (granite chippings) with sizes larger than 2.36 mm were used, while aggregates whose particle sizes were less than 2.36 mm were used as fine aggregates (river bed sand). Prior to the laboratory experiments and tests, they were washed and subsequently sun dried.

2.1.2 Bitumen

Bitumen of 60/70 Penetration Grade (PG) [26] was used in the production the samples to be tested, both the calcite powder modified and control. It was sourced from Landmark University Omu-Aran, Nigeria.
2.1.3 Filler
Sieved particles of the calcite powder retained on the number 200 mesh were utilized in this investigation. Likewise, particles of the virgin or base mineral filler (quarry dust), passing sieve number 200 and retained on the pan were used. Calcite rocks for the study were sourced from the geophysics laboratory, Geophysics Department, Landmark University, Omu Aran, Nigeria. They were grinded to a powdery form and filtered with the 75 μm sieve. The base filler was blended with other aggregates and bitumen to obtain the control samples while the calcite powder for the samples [20].

![Calcite Powder](image1.jpg)

*Figure 1. Calcite Powder*

2.2 Method
In order to determine the appropriateness of materials sourced for this research, they were subjected to various tests in the laboratory. The suitability of these materials in terms of expected desirable properties to produce the control samples, and in accordance with the standard was verified by the tests.

2.2.1 Tests on Mineral Aggregates
Physical tests such as specific gravity [32], voids percentage [40], test for water retention [33], test on Abrasion [34], bulk density test [32], flakiness index test [36], aggregate impact test[37], test on elongation [36] and moisture content [38] tests were carried out on materials.

2.2.2 Test for Water Content
Empty cans were branded and their weights were determined. Representative wet soil samples were placed in the can, weighed transferred into the oven at 105°C for 20 to 24 hours. Water content for the experiment was thereafter calculated using equation 1

\[
\text{Water Content} = \left(\frac{W_2 - W_3}{W_3 - W_1}\right) \times 100
\]

Where; 
- \(W_1\) = can weight
- \(W_2\) = can + wet soil weight
- \(W_3\) = can + dry soil weight
2.3 Tests on Bitumen
2.3.1 Ductility test
The 60/70 Pen bitumen was softened to temperature of 75°C to 100°C greater than the nearest softening point until it was almost liquid. It was strained with the aid of IS sieve 30, transferred into a mold assembly and placed on a brass plate and afterwards a glycerin solution was applied over all the surfaces of the mold exposed to bitumen. Later the sample was transferred into the molds, the plate assembly along with the sample were placed in a water bath and kept at 27°C for 30 minutes. The sample and mold assembly were then removed from the water bath and excess bitumen material was cut off through leveling the surface with a hot knife. After trimming the specimen, the mold assembly in which the sample was poured was replaced in water bath and maintained at 27°C for 85 to 95 minutes. The slides of the mold were then removed and the clips were carefully hooked on the machine without causing any initial strain. The pointer was set to read zero. The distance at which the bitumen thread broke was recorded (in cm) and reported as the ductility value.

2.3.2 Flash and Fire Point Test
Using the Pensky-Martens Closed Tester method [28], the flash and fire point tests were carried out. The require temperature at which it would be safe to heat the specimens was determined.

2.4 Blending of aggregates
For the purpose of achieving a mix that would meet the requirements for gradation of bituminous mixtures, coupled with aid of a trial method, an integration of the mineral aggregates was done. Calculation of the various aggregate size percentages was carried out and benchmarked with the expected requirement. Repeated trials were done until the proportions were within acceptable limits.

2.5 Optimum Bitumen Content (OBC) Determination
To determine the OBC, mean values of three of bitumen contents at the highest values of stability and bulk density, and the bitumen content corresponding to the median value of air voids [27], were determined. The three values were determined through Marshall plots.

\[
\text{Optimum Bitumen Content} = \frac{\text{Stability} + \text{Bulk Density} + \text{Voids}}{3}
\]

Volumetric properties for asphalt mixes usually obtained from OBC such as VMA, VFB, stability, flow, volume of voids (Vv) and bulk density were determined and varied with the design requirements of medium traversed roads shown in Table 1.

2.6 Marshall test
In this research, it became necessary to calculate the optimum bitumen content required to be mixed with the mineral aggregates through the Marshall mix design method. In compliance with standard (ASTM D 1559-89), ten samples weighing 1200gm were produced. They were given 75-blows and maintained at varied bitumen contents (i.e between 4.45 – 6.45% with 0.5% augmentation). Average values each of Marshall flow and bulk density were obtained for one out of two samples prepared separately. OBC was determined for each of the Marshall properties determined viz stability, flow Voids in Total Mix (VTM), Voids Filled with Bitumen (VFB), air voids (Vv), and density (Gm). The standard plots of each of these properties against bitumen content were done to obtain the optimum bitumen content which was benchmarked with the standard Marshall requirement for wearing courses as shown in Table 1.
Table 1. Standard Marshall Requirements for Wearing Courses

| Properties                      | Type of Mix               | Standard Values |
|---------------------------------|---------------------------|-----------------|
| Air voids (%)                   | DG wearing course         | 3 – 5           |
| Voids filled with bitumen VFB (%) | DG wearing course         | 75 – 85         |
| Stability (KN)                  | DG wearing course         | Not less than 7.5 |
| Flow (mm)                       | DG wearing course         | 8 – 17          |
| Optimum bitumen content (%)     | DG wearing course         | 5.0 – 8.0       |

Source: AASHTO T245

2.7 Preparation of Calcite Modified Asphalt

Cylindrical samples containing calcite powder as shown in Figure 2, were prepared for testing to determine their Marshall and volumetric properties. A total of five samples weighing 1200gm each were prepared to assess the influence of mixing calcite powder to the asphalt mixture samples using five proportions of the calcite powder (10%, 20%, 30%, 40% and 50%) by the weight of OBC. Calcite rock was crushed to powdery form and sieved to size 0.075mm. The resultant powder was mixed with the base filler at the specified proportions and heated to about 150-170°C, as well as the mineral aggregates. Bitumen was also heated to about 150-165°C and thereafter mixed with the calcite powder – quarry dust mixture and with both the fine and coarse aggregates OBC. At 165°C, after a vigorous mixing of all the materials, a homogeneous mix was achieved. Mixes were put in cylindrical molds and given 75blows each according to ASTM D1559[30] for adequate compaction.

Figure 2. Calcite Modified Samples

3. Results and Discussion

Control sample test results, and of the samples partially modified are as presented below. Others such as Marshall stability test, SEM and XRF are also presented. All tests except SEM and XRF were conducted at Landmark University. The SEM test was carried out at the college of agriculture, University of Ibadan,
Oyo State while X-RAY Florescence test and analysis of materials was conducted at the Engineering Materials Development Institute (EMDI), km 4, Ondo road, Akure, Ondo State, Nigeria.

3.1 Combined Particle Size Distribution Graph

The combined graph of sieve analysis for the mineral aggregates and calcite powder used in the preparation of the asphalt is as shown in Figure 3.

![Combined Particle Size Distribution Curves](image_url)

Figure 3. Combined Particle Size Distribution Curves (PSDCs) for coarse, fine, mineral filler aggregates and Calcite Powder

From the combined particle size distribution graph of the aggregates above, the values of $D_{10}$, $D_{30}$ and $D_{60}$ on the fine aggregate curve in orange were obtained as 0.32, 0.54 and 0.96 respectively. The values of $Cu$ and $Cc$ were calculated using equations 3 and 4 as follow:

$$Cu = \frac{D_{60}}{D_{10}} = \frac{0.96}{0.32} = 3.0$$  \hspace{1cm} (3)

$$Cc = \frac{D_{10}^2}{D_{60} \times D_{10}} = \frac{0.54^2}{0.96 \times 0.32} = 0.95$$  \hspace{1cm} (4)

From ASTMD-2487 soil classification it can be said that the fine aggregate soil is a fairly graded soil sample because $Cu < 6$. Similarly, the values of $D_{10}$, $D_{10}$ and $D_{60}$ on the coarse aggregate curve in blue were 0.11, 0.30 and 0.85 respectively. The value of $Cu$ and $Cc$ were using equations 5 and 6 as follow:

$$Cu = \frac{D_{60}}{D_{10}} = \frac{0.85}{0.11} = 7.72$$  \hspace{1cm} (5)
\[ C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{0.30^2}{0.85 \times 0.11} = 0.96 \] (6)

From ASTMD-2487 soil classification, it can be said that the particles of the coarse aggregates are well graded as \( 1 \leq C_c \leq 3 \). The results in Table 2 are indicators of the suitability of the materials for use in construction having met the required standard and specification.

**Table 2. Coarse Aggregates Mechanical Test Results**

| Properties                        | Results  | Standard        |
|-----------------------------------|----------|-----------------|
| Aggregate Impact Test             | 19.20%   | 30% Max         |
| Aggregate Crushing Test           | 42.40%   | 45% Max         |
| Los Angeles Abrasion Test         | 48.92    | 60% Max         |
| Flakiness Index                   | 27.73    | 30% Max         |
| Elongation Index                  | 28.42    | 30% Max         |
| Density                           | 1500.20 kg/m³ |
| Specific Gravity                  | 3        | 3               |

Source: ASTM D2419 [29] – for Aggregates’ Soundness

### 3.2 Bitumen

The summary of the properties of bitumen investigated are shown in Table 3. These properties were compared with the values stipulated in the specification.

**Table 3. Standard Engineering Test Results on Bitumen**

| Parameters Tested     | Test Values | Expected Standard Values (in ranges if possible) | Standard |
|-----------------------|-------------|--------------------------------------------------|----------|
| Penetration (mm)      | 72          | 60-70 IS Standard                                | ASTM D-5 |
| Softening (°C)        | 58          | 45-60 IS Standard                                | ASTM D-36|
| Ductility (cm)        | 82          | 75 Minimum IS Standard                           | ASTM D-113|
| Viscosity (secs)      | 77          | Nil                                              | ASTM D-3381|
| Flash Point (°C)      | 275.7       | 175 Minimum BIS Standard                         | ASTM D-92 |
| Fire Point (°C)       | 307.7       | Nil                                              | ASTM D-92 |
| Specific gravity      | 0.96        | 0.97-1.02                                       | ASTM D-70 |
| Loss on heating       | 0.86        | 1.00% max                                        | ASTM D-6  |
| Moisture Content      | 0.0022      | Nil                                              | ASTM D-41 |

### 3.3 Results for Marshall Stability of Control Samples

Table 4 shows the result from the carried-out Marshall test on the control sample. It also shows the uncorrected and corrected Marshall stability.
Table 4. Results of Marshall Properties for the Control Samples

| Test No | % BC | Weight in air | Weight in H₂O | Gt  | Gm  | Vol. of void (vv) | % Vol of bitumen (vfb) | Vma (%) | Vfb | Uncorrected stability (kN) | Corrected stability (kN) | Flow (mm) |
|---------|------|---------------|---------------|-----|-----|------------------|------------------------|---------|-----|----------------------------|-------------------------|----------|
| 1       | 5.5  | 1017          | 578           | 2.404 | 2.317 | 3.619           | 13.274              | 16.893  | 78.577 | 37.7                        | 1.000                   | 37.7     | 12|
| 2       | 5    | 1025          | 579           | 2.425 | 2.298 | 5.237           | 11.969              | 17.206  | 69.563 | 37.9                        | 1.000                   | 37.9     | 11.3|
| 3       | 4.5  | 1002          | 572           | 2.446 | 2.330 | 4.742           | 10.922              | 15.664  | 69.727 | 34                          | 1.000                   | 34       | 10.5|
| 4       | 4    | 897           | 522           | 2.467 | 2.392 | 3.040           | 9.967               | 13.007  | 76.628 | 35                          | 1.000                   | 35       | 9.6|
| 5       | 3.5  | 995           | 570           | 2.489 | 2.341 | 5.946           | 8.535               | 14.481  | 58.939 | 28.9                        | 1.000                   | 28.9     | 10.3|

3.4 Optimum Bitumen Content (OBC)

It is necessary to obtain the Optimum Bitumen Content (OBC) in order to produced asphalt concrete modifier with an alternative filler material. The OBC was determined based on Marshall mix design and analysis technique which ranges from 4.5% to 6.5% of bitumen by standard. A total of 5 samples were tested representing the control mix in this research. As shown in figure 5, The plots each of density, stability, flow, stiffness, void fill with bitumen and void in total mix against % of bitumen were used to determine the OBC.
Figure 4. Marshall Plots for the determination of OBC

3.5 Marshall Properties Results of the Calcite Powder Modification as filler
The Marshall properties of the calcite powder modified asphalt mixture were compared with the control mix and checked with standard expectations for sustainable highway construction purposes. The Marshall experiment on the samples modified using the OBC was conducted and the resulting parameters of the asphalt concrete mix with calcite powder and without calcite powder were compared. The required Marshall parameters of the calcite modified mix were same as the control mix. Table 5 shows the summary of the Marshall properties of the calcite modification.

Table 5. Marshall properties of the calcite modification

| CALCITE POWDER | VB    | STABILITY (kN) | Vv (%) | VMA | VFB | OBC | FLOW | GM    |
|----------------|-------|----------------|--------|-----|-----|-----|------|-------|
| 0%             | 10.93 | 34.7           | 4.517  | 15.45 | 70.7 | 4.27 | 10.74 | 2.36  |
| 10%            | 10.36 | 17.91          | 8.07   | 12.76 | 100.61 | 4.03 | 16.8  | 2.56  |
| 20%            | 9.45  | 16.45          | 6.82   | 16.28 | 57.84 | 3.15 | 14.74 | 2.34  |
| 30%            | 9.27  | 16.77          | 6.57   | 15.84 | 59.06 | 3.3  | 19.83 | 2.35  |
| 40%            | 9.41  | 30.64          | 3.68   | 12.87 | 78.34 | 3.68 | 12.85 | 2.43  |
| 50%            | 44.74 | 19.77          | 3.89   | 41.79 | 46.63 | 3.73 | 18.63 | 13.12 |

4. Scanning Electron Microscopy (SEM) and X-Ray Fluorescence (XRF) Test Results
4.1 SEM Analysis Test Results
Figure 5 shows the SEM micrograph of the control and calcite powder modified samples using SEM machine at different magnifications. The micrograph of the modified samples at the different
magnifications (b), (c), and (d) show proper interaction between the particles of the conventional aggregates and the calcite powder compared to the voids observed in the SEM micrographs of the control sample.

Figure 5: SEM Micrographs of the Control and Calcite Powder Modified Samples at (a) 5000x mag, (b) 5500x mag (9.2mmWD), (c) 5500x mag (7.2mmWD), and (d) 6000x mag.

Figure 6 shows the X-Ray Florescence results, displaying the level and intensity of the elements present in calcite. It was observed to contain Calcium in high proportion which contributes to adhesion in bituminous mixtures.
Figure 6. X-Ray Florescence
4.2 Energy-Dispersive Spectroscopy (EDS)

Figure 7 shows the level and intensity of elements present in calcite powder. It can be observed that the calcite powder is filled with high intensity of calcium, which is responsible for the pozzolanic characteristic of the material.

![Energy-Dispersive Spectroscopy (EDS)](image)

From the above readings, a high proportion of Calcium (65.13%) by weight of other elements present in the calcite powder was observed. This further strengthens the bond between the constituent materials in the mix.

5. CONCLUSION

Findings from this study have shown that calcite powder can be incorporated into asphaltic concrete mixtures with the intention of improving its Marshall properties due to its similarities in terms of aggregate shape, size and texture with the conventional filler. Calcite is readily available and can be explored for sustainable pavement construction or rehabilitation. According to the results from the calcite powder modified proportions viz 10%, 20%, 30%, 40%, 50% as substitute for the conventional filler, it was found suitable for the construction of medium trafficked roads at 10%, 20%, 30%, 40% and 50%, which corresponds to stability values 17.91 kN, 16.45 kN, 16.77 kN, 30.64 kN and 19.77 kN respectively, having satisfied the minimum standard requirement for stability (not less than 7.5 kN). Furthermore, the XRF, SEM, stability and the flow results obtained from the experimental work show that the physical and chemical properties of the asphaltic concrete had a significant improvement to them.

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