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Optimum Portland Cement-Ceramic Waste Powder Blend as Filler in Bituminous Macadam

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Abstract: Industrial and technological advancements have led to an increase in environmental waste. Natural sources of construction materials have depleted over time making access to quality materials difficult. Recurrent deterioration of asphalt pavements, especially those subjected to heavy truck traffic has also become prevalent recently. This paper aims to evaluate the strength properties of Bituminous Macadam Surfacing (BMS) prepared with blends of Portland cement (PC) /Ceramic Waste Powder (CWP) as filler; replacing PC with CWP in 20 % increments (20 %, 40 %, 60 %, 80 % and 100 %). The Marshall properties of the mixes were tested and the results were compared with standard specifications as stipulated in the Nigeria General Specification for Roads and Bridges. The results showed that CWP significantly improved the Marshall properties, especially stability. At 80 % CWP and 5 % bitumen content (optimum bitumen content), stability of 11.2 kN was observed compared to 9.84 kN at 0 % CWP (control sample); representing a 13.82 % increase in stability. Similar improvement was observed in Marshal flow and volumetric properties. An 80 % CWP (by weight of filler) gave optimum values for all Marshall parameters and obtained values fall within the limits adjudged by The Nigerian Federal ministry of works & housing. An 80 % CWP by weight of filler is therefore recommended for the construction of BMS.
Keywords: Bituminous macadam surfacing; mineral filler; Marshall mix design; waste management; ceramic waste powder.

1. Introduction

Bituminous Macadam Surfacing (BMS) is a special type of asphalt surface. Compared to conventional asphalt concrete, BMS contains coarser aggregates, has a lower bitumen content and lower laying temperature [1]. Similar to asphalt concrete, BMS is also composed of about 0-5 % filler. For a material to be used as filler, it is expected that the material will satisfy engineering conditions, be environmentally compliant and be non-biodegradable [2].

Technological and industrial advancements have led to an increase in environmental waste. However, natural resources and disposal areas for the wastes are on the decline. Hence, recycling and reuse of waste materials have become crucial in terms of environmental and economic sustainability. Additionally, there's a recurrent deterioration of asphalt pavements with time. This deterioration is more pronounced on pavements which serve higher axle loads. This has become a serious cause of concern with the growth of the Nigerian economy and the increase in the number of heavy trucks on Nigerian highways. This occurrence prompted the exploration of materials which will enhance the pavement structure. Hence, the choice of ceramic waste for this research.

There have been several studies into the use of industrial and agricultural wastes in road construction. Murana *et al.* [3] replaced stone dust with cow bone Ash in Hot Mix Asphalt and obtained a higher stability value and lower flow value at an optimum bone ash content of 20 %. Otuoze *et al*. [4] explored the replacement of corn cob ash in hot mix asphalt and found all replacements at 20 %, 40 %, 60 %, 80 % and 100 % to meet the requirements of the Nigerian specification. Nwaobakata and Agwunwamba [5] used periwinkle shell ash (PSA) to replace limestone dust in hot mix asphalt and found a 3 % replacement to produce optimum results.

On the use of ceramic waste in asphalt concrete, Electricwala *et al.*, [6] explored its use in semi-dense bituminous macadam. Satisfactory results were obtained with stability values of 13.93 kN and 15.92 kN at 3% and 5% ceramic waste respectively.

Kara and Karacasu [7] investigated the replacement of natural aggregates with crushed ceramic waste in Hot Mix Asphalt. Acceptable values of Marshall properties were obtained for all samples prepared at 10, 20, 30 and 40 % replacement by weight. At high ceramic waste contents, optimum bitumen content was found to be high. 30 % ceramic waste content gave the best combination of stability and optimum bitumen values of 1545.5 kg and 6.99 % respectively. Mishra *et al.* [8] explored ceramic waste in the bituminous mix by introducing ceramic waste in 10, 15 and 20 % replacements and obtained strength parameters within the acceptable code limits.

This research work focuses on the use of ceramic waste obtained from used water closets (WC) to replace cement (at various replacement levels) as filler in the construction of Bituminous Macadam Surfacing.

The rest of the paper is structured as follows. Section 2 presents materials sourcing, processing, characterization and Marshall mix design to obtain optimum bitumen content. Section 3 follows up with the discussion on the performance of BMS prepared at selected replacement levels and section 4 ends the paper with conclusions and recommendations.

2. Materials and Methods

2.1 Materials

Materials used in the production of BMS for this research are: bitumen, aggregates (coarse and fine), cement (base filler) and Ceramic Waste Powder (CWP). This sub-section presents a description of their sourcing, characterization (according to relevant standards) and properties.

2.1.1 Bitumen

The bitumen used in this research was obtained from Mothercat Nig. Ltd in Zaria. Table 1 shows its physical and chemical properties. Based on the results in Table 1, the bitumen can be characterized as 60/70 penetration grade bitumen. The results showed that the physical properties of the bitumen fall within the specifications of the FMW&H [1] and can be used for the production of BMS.

Table 1. Physical and Chemical Properties of Bitumen

Property	Code/ Specification	Test value
Penetration (mm) @ 25ºC	ASTM D5 / D5M [9]	68.2
Ductility (cm) @ 25ºC	ASTM D113 [10]	115
Softening Point (ºC)	ASTM D36/D36M [11]	48.67
Flash Point (ºC)	ASTM D92 [12]	252
Fire Point (ºC)	ASTM D92 [12]	258
Specific Gravity	ASTM D70 [13]	1.03
Solubility (%)	ASTM D2042 [14]	100

2.1.2 Aggregates

Crushed granite obtained from Mothercat Nig. Ltd., Zaria was used for this research as coarse aggregate. Quarry fines obtained from the same granite source was used as fine aggregate in this research. Table 2 shows the physical properties of the aggregates. The results obtained on aggregates fall within the limits set by FMW&H [1] and can be used for the construction of BMS.

On aggregate proportioning, FMW&H [1] requires that an all-in-aggregate satisfying a gradation requirement, shown in Figure 1 is obtained. The three materials (coarse aggregates, fine aggregates and filler) are proportioned using trial and error until an all-in-aggregate satisfying the gradation requirement is obtained (Figure 1).

2.1.3 Filler material

Portland cement (PC) is used as base filler in the mix. The ceramic waste obtained was ground into powder using a jaw crusher and a ball mill. The powder was sieved using BS sieve No. 200 to obtain the ceramic waste powder (CWP) used as cement replacement in the mix – which is the material passing BS sieve No. 200. A composite filler obtained by replacing PC with CWP was prepared at replacement levels between 0 % (for control mix) and 100 % in increments of 20 % for use in the mix. Table 4 shows the physical properties of the filler materials.

The result of an oxide composition test on a sample of the CWP (Table 3) revealed CWP to have significant pozzolanic properties. This is evident with its total SiO_2, Al_2O_3 and Fe_2O_3 (86.6 %) being in excess of 70 % and can be classified as a class N pozzolana according to ASTM C-618 [21].

Table 2. Physical Properties of Aggregates

Property	Code/Specification	Test Value
Specific Gravity (Fine Aggregate)	ASTM C128 [15]	2.65
Specific Gravity (Coarse Aggregate)	ASTM C127 [16]	2.63
Flakiness Index	BS 812-105.1. [17]	19.45
Elongation Index	BS 812 105.2 [18]	24.6
Aggregate Crushing Value (%)	BS 812-110 [19]	22.46
Aggregate Impact value (%)	BS 812-112 [20]	17.94

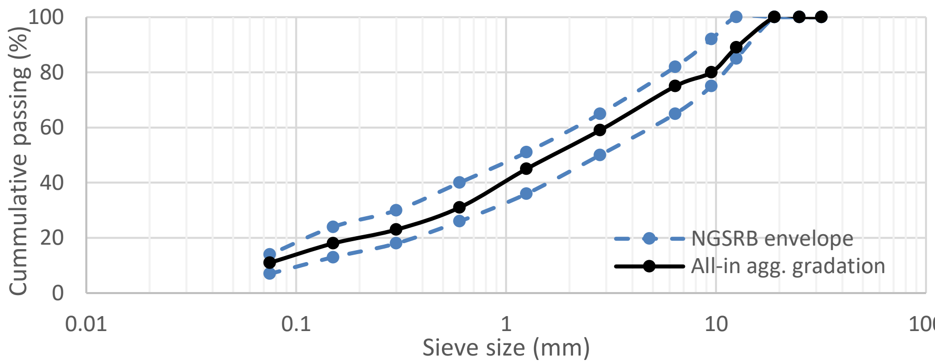

Figure 1. Gradation curves showing the NGSRB gradation envelope and fine aggregate gradation curve

2.2 Mix Design and Sample Preparation

Marshall mix design method [24] was used to determine the optimum bitumen content (OBC) in the hot mix asphalt. Since two parameters are varied (bitumen content and composition of composite filler), at each composite filler composition (e.g., 80 % PC and 20 % CWP) three samples of asphalt concrete were prepared using bitumen content ranging from 4.0 % - 7.0 % in increments of 0.5 %. Marshall stability, flow and volumetric properties were determined for each sample following ASTM D6927 [25]. From test results obtained, the OBC is evaluated as the average of the bitumen contents which give maximum stability, maximum bulk density and the median percent of air voids.

Table 3. Oxide composition of CWP

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	ZrO_2	K_2O	TiO_2	LOI
Composition (%)	66.31	19.31	1.00	1.09	3.21	3.30	2.20	1.67	0.70	1.18

Table 4. Physical properties of filler materials

Property	Code/Specification	Test Value
Initial setting time of cement (min)	BS EN 196-3 [22]	125

Final setting time of cement (min)	BS EN 196-3 [22]	205
Soundness of cement (mm)	BS EN 196-3 [22]	1.0
Specific gravity of cement	ASTM C188 [23]	3.15
Specific gravity of CWP	ASTM C188 [23]	2.95

3. Results and Discussion

3.1 Effect of CWP on Marshall Properties

The experiment was first carried out for the control mix (100 % PC as filler), then mixes with different compositions of the composite filler (as detailed in section 2.1.3). As CWP was added to the mix in various quantities, different properties exhibited different patterns.

3.1.1 Stability

The stability of a bituminous mix generally refers to its ability to resist deformation and distortion under traffic loading. The general trend observed with the stability of the mixture is shown in Figure 3.

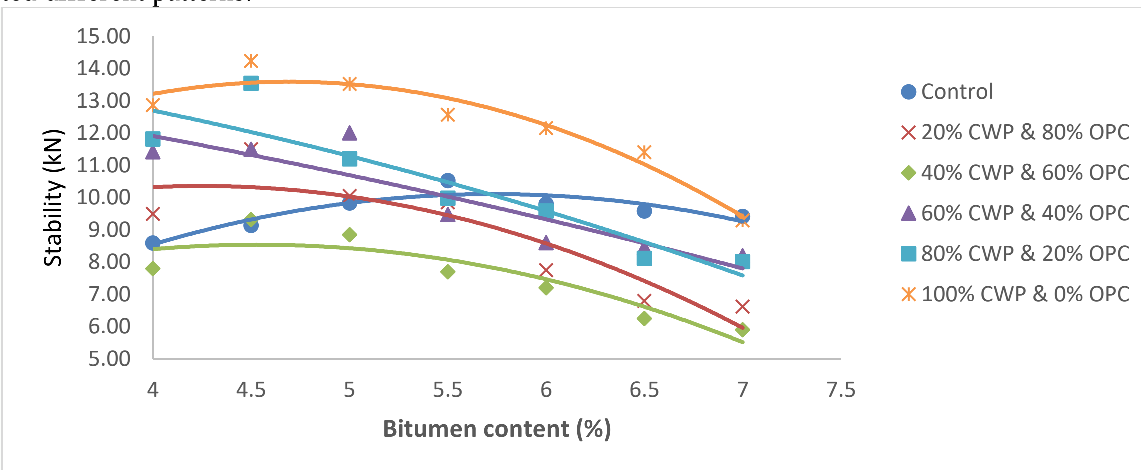

Figure 3. Variation of stability with bitumen and CWP contents

Figure 3 shows that; increase in the CWP contents is proportional to increased stability at lower bitumen contents. Between 4-5 % bitumen contents, asphalt mixes prepared using all filler proportions (except 40 % CWP replacement level) exhibited higher stability values when compared to the control sample. This trend could be attributed to the presence of high silica in CWP. Silica is mainly responsible for the strength of cement concrete (and invariably, asphalt concrete containing cement as filler). This trend of the result was consistent with the works of Electricwala *et al*. [6]. At each replacement level, stability is observed to decrease with increasing bitumen content. It is well known that; bituminous mixes derive their stability from aggregate interlocking and cementation (from bitumen-filler mastic). An excess amount of bitumen in the mix (beyond the optimum content) will result in a too wet mix. The high free-bitumen content of such mixes leads to the weakening of the asphalt concrete's stiffness and stability. This explains the decrease in stability as the bitumen content increases.

3.1.2 Flow

The flow of a bituminous mix is a measure of its deformation during the Marshall test. This property depends largely on the consistency of the filler(s) – bitumen mastic. As PC is replaced with CWP, an increase in the flow of the resulting mixes is observed (Figure 4). it is a fact that; asphalt mixtures are largely composed of mastic-coated aggregates than purely bitumen-coated aggregates [26]. As such, this increase could be largely due to the higher absorption property of PC compared to CWP. This increase could also be related to the particle sizes of the two fillers. Generally, larger particles will require more bitumen to be coated. CWP particles are smaller than PC particles (as only CWP particles passing B.S. sieve No. 200 were used in this experiment), therefore, require less amount of bitumen to be coated (and absorb even less). This means that; CWP filler will produce filler-bitumen mastic of higher consistency than PC filler and ultimately, mixes with higher flow values. A similar trend was observed in Mishra *et al*. [8]; Kara and Karacasu [7].

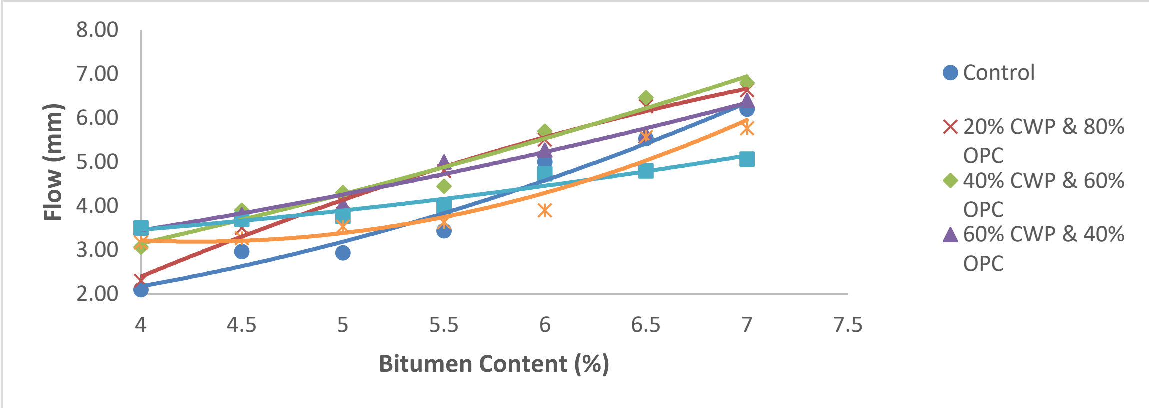

Figure 4. Variation of flow with bitumen and CWP contents

3.1.3 Unit Weight

Figure 5 shows a rise in the unit weight of the mixture with increasing bitumen content up to optimum value, then further addition of bitumen led to a decrease in unit weight. The increase in bitumen content also leads to improved bonding between the particles. This leads to greater densification which reflects in greater unit weight values. With the addition of CWP, unit weight decreases. This is a result of the difference in the specific gravity of cement and CWP. CWP has a lower specific gravity compared to cement. As the amount of CWP in the mix increases, it affects the density of the total mix and leads to a reduction in the unit weight of the mix. A similar result was obtained by Kara and Karacasu [7]; Electricwala *et al.* [6].

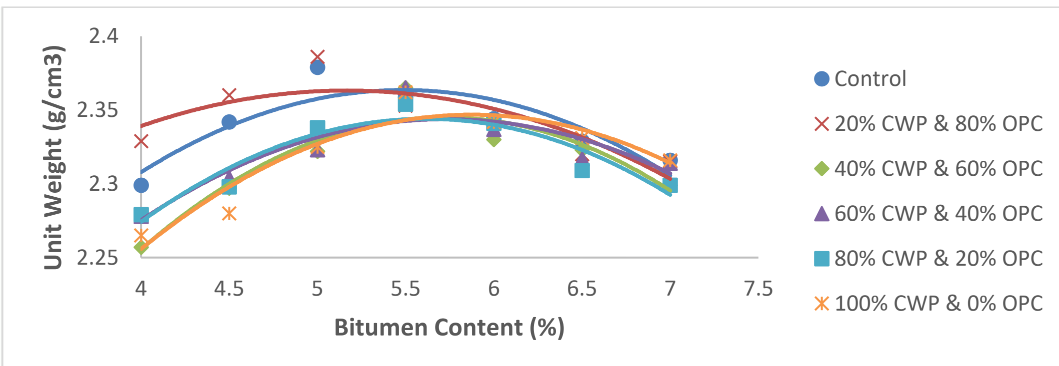

Figure 5. Variation of Unit Weight with bitumen and CWP contents

3.1.4 Percent Air voids (PA)

Figure 6 shows how PA varies with changes in bitumen and CWP contents. The increase in PA with increasing CWP content could be attributed to the higher ability of CWP to convert free bitumen to structural bitumen than PC. The reduction in the amount of free bitumen (which is responsible for filling intergranular voids) will lead to an increase in the total voids in the compacted asphalt concrete. The reverse is the case when a plot of PA against bitumen content is considered (at a particular CWP content) as shown in Figure 6. PA is observed to decrease with an increase in bitumen content. This trend could be attributed to the increase in the amount of free bitumen (which fills the existing voids) in the mix. A similar result was obtained by Electricwala *et al.* [6].

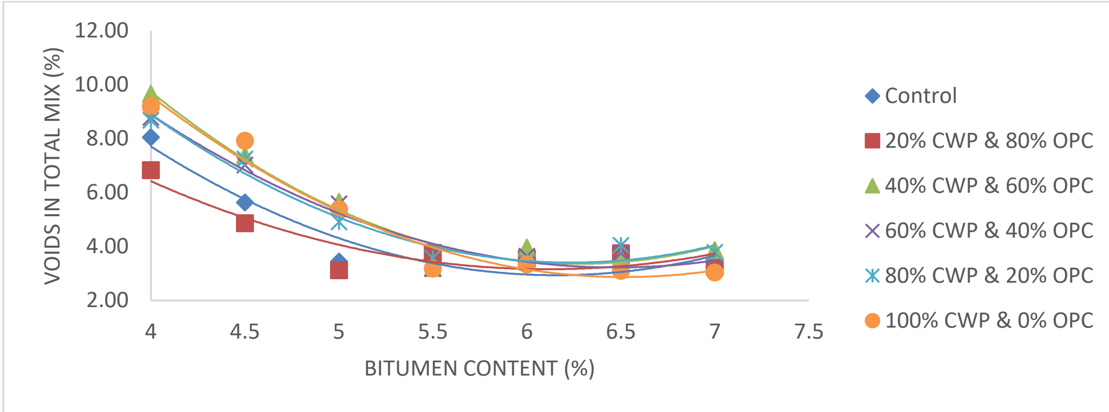

Figure 6. Variation of PA with bitumen content and CWP

3.1.5 Voids in Mineral Aggregate (VMA)

VMA is an important asphalt concrete design parameter. Design codes specify the minimum value of this parameter to ensure that adequate void spaces are provided in the concrete to avoid durability problems in the long – run. Figure 7 shows how this parameter varies with an increase in CWP and bitumen contents in the mix. With the increasing replacement of PC with CWP, VMA is observed to increase. This is because; VMA is largely defined by PA. As such, plots of the two parameters usually follow the same trend.

Mathematically, VMA could be defined as the sum of volumes of PA and unabsorbed bitumen. As such, when bitumen content increases, the amount of unabsorbed bitumen in the mix will increase – which explains the increase of VMA with increasing bitumen content. Also, PC has a higher surface area than CWP. Therefore, PC is much more able to fill voids in mineral aggregates than CWP. Therefore, as CWP increases, VMA increases. A similar trend was obtained by Murana *et al*. [3].

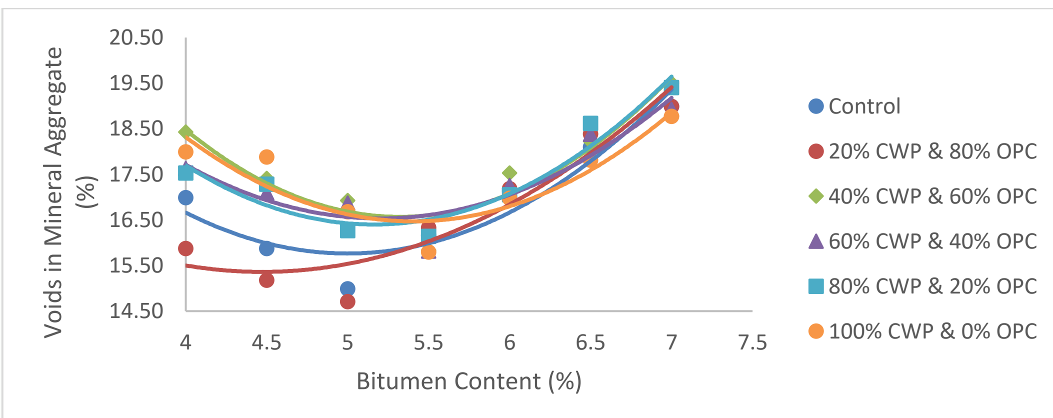

Figure 7. Variation of VMA with bitumen content and CWP

3.1.6 Voids filled with Bitumen (VFB)

VFB loosely translates to the part of VMA filled with bitumen. Figure 8 shows that VFB increases with increasing bitumen content. This is as expected; since when more bitumen is introduced into the mix, it is going to occupy the voids between mineral aggregates (increase in unabsorbed bitumen observed from VMA plots in Figure 7). For the lower bitumen contents (4 % - 5 %), VFB values were observed to rise sharply with increasing CWP content and then fall with further addition of CWP. As seen from VMA plots (Figure 7), as VMA increases, the voids filled with bitumen also increase. A similar trend was obtained by Nwaobakaba and Agwunwamba [5].

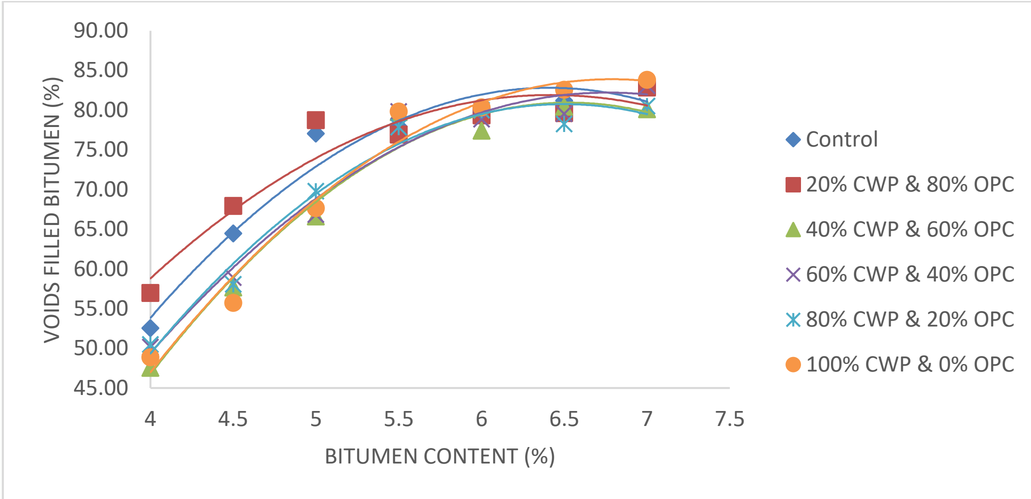

Figure 8: Variation of VFB with bitumen content and CWP

3.2 Optimum Bitumen Content

At each replacement level (replacement of PC with CWP) during the Marshall mix design, the optimum bitumen content (OBC) was obtained. The OBC is taken as the average of bitumen contents at which maximum stability, maximum bulk density and the median percent of air voids were recorded [24]. The values of the various Marshall parameters corresponding to the respective optimum bitumen content are shown in Table 5.

Table 5 shows the variation of OBC with different CWP contents. The various parameters obtained from this experiment were compared with those of the specification. Some percentage replacements had some parameters not meeting the specifications. 80 % CWP content gave the best set of values for the various parameters considered.

Table 5. Optimum bitumen content at different CWP contents with specifications according to [1].

Marshall Parameters	Specifications	CWP variations					
		0 %	20 %	40 %	60 %	80 %	100 %
OBC (%)	-	5.5	5.0	5.5	5.0	5.0	5.0
Unit Weight (g/cm^3)	-	2.364	2.362	2.34	2.33	2.362	2.345
Stability (kN)	Minimum 3.5	8.9	10.2	8.25	10.7	11.6	13.5
Flow (mm)	2 – 4	3.9	4.2	4.5	4.25	3.8	3.4
VMA (%)	Minimum 13	16.0	15.6	16.6	16.6	15.2	16.5
PA (%)	3 – 5	3.5	4.8	4.5	5	4	5
VFB (%)	75 – 85	78	75	73	70	75	70

3.3 Morphological Characteristics

Morphological characteristics were studied by subjecting the control sample and the optimum sample to Scanning Electron Microscopy, SEM. The results obtained are shown in Figures 9 and 10.

The SEM analysis was done on the sample using a magnification of x1000 for control and optimum blend sample (80% CWP) as shown in Figures 9 and 10. From the microstructure analysis of the control sample, one can observe a dark spot which shows the voids and a light surface area as shown in Figure 9. The void and less dense (light) structure could be responsible for the lower strength and stability as shown in the experimental results.

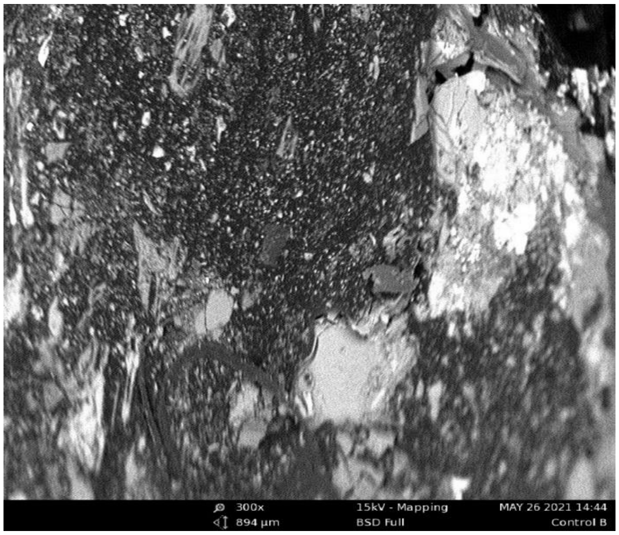

Figure 9. SEM for Control Sample

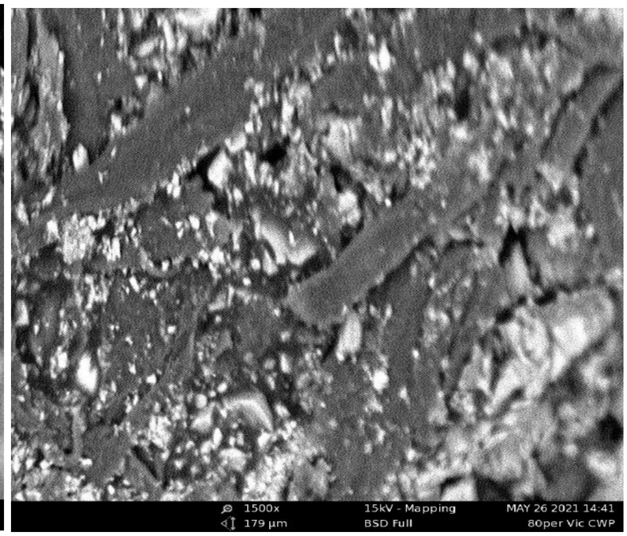

Figure 10. SEM for Optimum sample

In Figure 10, it can be seen from the SEM image that the addition of 80 % CWP to the mix results in a fibrous and denser matrix, which appears homogenous and of compact structure. This could be a result of a chemical reaction between CWP and PC which leads to the production of a fibrous and denser matrix and ultimately, higher stability as seen in the experimental result.

4. Conclusions and Recommendations

4.1 Conclusions

The conclusions drawn from this research are outlined as follows:

i. The optimum bitumen content for the control sample of BMS was found to be 5.5 %.
ii. The Marshall parameters and volumetric properties of the BMS prepared using CWP satisfy the minimum requirements specified by FMW&H [1].
iii. The BMS sample with 80 % CWP content performed best among other replacement levels (considered in this experiment) in terms of Marshall parameters and volumetric properties.

4.2 Recommendations

Based on conclusions drawn, up to 80 % CWP (by weight of filler material in the asphalt concrete) and 5 % bitumen (by weight of asphalt concrete) could be used in the production of BMS.

Conflict of Interest

There is no conflict of interest associated with this work.

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