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Optimum Portland Cement-Guinea Corn Husk Ash Blend as Filler in Hot Mix Asphalt

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Abstract- Dwindling natural resources and the negative environmental impact that comes with the industrial processing of construction materials are the driving forces to man's quest for cleaner (green) and cheaper alternative construction materials. Among such alternatives include agricultural wastes. Guinea corn husk ash (GCHA), an agricultural waste obtained from the incineration of Guinea corn husk, has shown potentials of been used as filler material in hot mix asphalt due to its pozzolanic properties. Thus, this research aims to assess the strength and durability properties of hot mix asphalt with the incorporation of GCHA as a partial replacement for filler (cement). Marshal mix design method was used to determine the optimum bitumen content (OBC) at no GCHA content (control mix) within the bitumen content range prescribed by Nigerian general specifications for roads and bridges (NGSRB) for bituminous courses in flexible pavements. This OBC was used to determine the optimum GCHA by replacing the primary filler with GCHA up to 45% in increments of 5%. Marshal indices and volumetric properties of samples prepared at each replacement level were determined according to relevant standards. Mixtures containing up to 20% Portland cement replacement with GCHA were found to produce competitive results against the control mix (only cement as filler). Thus, Marshall indices and volumetric properties of mixtures containing up to 20% cement replacement GCHA satisfy the minimum requirements prescribed by NGSRB for hot mix asphalt to be used as binder course in flexible pavements.

Keywords: hot mix asphalt; mineral filler; Marshall mix design; waste management; guinea corn husk ash

1. INTRODUCTION

Generally, asphalt concrete is composed primarily of aggregates and asphalt binder. Hot mix asphalt (HMA) concrete or simply hot mix asphalt (HMA) is a type of asphalt concrete that requires heating the concrete constituents (to a specific temperature) prior to transport, placement, and compaction [1]. Apart from the two components mentioned above, a very fine material referred to as filler is present in HMA mixtures. Fillers contain particles passing B.S. sieve No. 200 (sieve aperture of 75 µm) and can occur naturally within the aggregates or are added from foreign materials. When added from foreign materials, fillers often participate in chemical processes within the hot mix asphalt. Hydrated lime, for example, is described as an "active filler" due to its ability to reduce chemical aging of bitumen and stiffen the mastic more than a conventional filler (one naturally occurring within the crushed aggregate) above room temperature [2].

Primarily, fillers are incorporated into HMA to fill voids in coarser aggregates, thereby increasing the density, stability, and toughness of a conventional bituminous paving mixture. Another function of fillers in HMA is filler-asphalt mastics, which serves as a cementing agent in HMA [3]. Hence, HMA is practically a mixture of aggregates and mastic coatings [4]. Also, fillers play an important role concerning stripping or moisture damage in HMA [5].

In Nigeria and some parts of the world, Portland cement (P.C.) is the most commonly used material as filler in HMA. High cost and environmental concerns associated with this material's production are primarily the reasons for growing interest in exploring suitable alternatives to P.C. as filler material in HMA. In Nigeria, for example, cement costs about 183% higher than the global average cost [6]. As such, researchers sought alternatives to P.C. from inexpensive materials. One such alternative comes from solid wastes. Since these materials are already byproducts of other processes (e.g., agricultural, industrial, municipal, etc.), it implies there are almost no costs and environmental concerns associated with their production. Rapid industrialization and other activities of man leave behind huge amounts of these wastes annually. This figure is as high as 42 million metric tons (MMT) in Nigeria [7]. Of the huge amount of waste generated annually in Nigeria, only a small percentage is recycled. The remaining finds its way to landfills or incineration plants. The limited capacity of landfills and alternative recycling means together with the carbon footprint from waste incineration present a serious challenge to the safe disposal of these wastes. For these reasons, researchers sought ways to expand the alternative means of recycling these wastes for sustainable waste management. One of such alternatives is incorporating them into the civil construction industry as construction materials. This, apart from saving the environment, will lessen the burden on excavating the ever-dwindling virgin resources for use in the construction industry.

Experimentally, several wastes from various sources have been investigated for use as an alternative filler in HMA. Industrial wastes such as fly ash and coal waste powder produce HMA with better flexibility behavior than HMA containing cement-based filler material [8, 9]. Other industrial wastes, when used as fillers at various percentages such as cement kiln dust [10], waste foundry sand [11], limestone dust [12], etcetera, are found to improve the performance of HMA.
Among agricultural wastes, up to 50% replacement of limestone dust with rice husk ash as filler improves the stability, volumetric properties, and long-term performance of HMA [13]. However, Arabani et al. [14] observed that HMA prepared with rice husk ash as filler tends to have larger air voids and is susceptible to moisture damage. The authors recommend its use as filler only in arid regions or regions where the probability of moisture damage is low. Sugarcane bagasse ash is another agricultural use that has shown promising results as filler material in HMA. Sugarcane bagasse ash is found to improve stability, flow, and resilient modulus of HMA by 0.6%, 4.9%, and 17.4%, respectively, compared to HMA prepared with P.C. as filler [15]. We refer readers interested in an extensive study on how various solid wastes perform as filler material in hot mix asphalt to a recent survey paper by Choudhary et al. [16].

Guinea corn, also known as Sorghum, is a staple food and livestock feed. It has been used to produce bioethanol in many parts of the world. Guinea corn is the fifth most produced grain globally [17] and, of the 57.3 MMT estimated global production of guinea corn in 2020, Nigeria accounts for about 6.9 MMT [18]. It is among the significant foods consumed, especially in Northern Nigeria [19]. As the production of Guinea corn soars, there is an equal increase in Guinea corn husk (GCH). GCH is inexpensive biomass that is obtained as a residue after the cut crop has been threshed. GCH has found applications in the textile industry as a source of Sorghum husk extract for dyeing [20] and amorphous silica for various industrial applications [21]. However, in Nigeria, this residue is mostly left in the threshing fields and incinerated in an open field or tilled into the soil in preparation for the next farming season. GCH, when incinerated to produce Guinea corn husk ash (GCHA), is rich in silica [21], therefore has the potential to be used as a pozzolana. Several researches have been conducted to ascertain the viability of using this material as a supplementary binder in cement concrete [19], lateritic concrete [22]; as a stabilizer in lateritic soil for road construction [23], and as an extender (additive) in oil-well cement slurries [24]. GCHA at various quantities is found to perform well in these experiments.

This research derives motivation from the performance of GCHA mentioned in the experiments above. It aims to determine the optimum blend of P.C. and GCHA as filler in

HMA for which the asphalt concrete can be used in pavement construction. The rest of the paper is structured as follows. Materials preliminary assessment according to relevant standards and mix design to obtain optimum bitumen content of HMA are presented in the next section. Experimental results on the performance of HMA at different proportions of the blended filler are discussed in section 3, and we end the paper with some conclusions in section 4.

2. MATERIALS AND METHODS

2.1. Materials

Materials used in the production of HMA include aggregates (coarse and fine), bitumen, and filler material (Portland cement and GCHA). A detailed description of material sourcing, processing, and properties is given below.

2.1.1. Bitumen

The bitumen used in this study was obtained from gidan kwalta Zaria, Kaduna state- Nigeria, and **Table 1** shows its physical characteristics and standard used for each test. Based on test results on the bitumen shown in **Table 1**, the bitumen can be classified as 85/100 penetration grade bitumen [25] and satisfies all standard requirements for use as a binder in HMA.

Table 1. Physical Characteristics of bitumen

Test conducted	Standard	Result
Penetration at 25^0C, 0.1mm	ASTM D5 [26]	87.2
Softening point (^{0}C)	ASTM D36 [27]	49.5
Flash-point (Cleveland open cup) ^{0}C	ASTM D92 [28]	248
Fire-point (Cleveland open cup) ^{0}C	ASTM D92 [28]	256
Ductility at 25^0C, cm	ASTM D113 [29]	116
Specific gravity at 25^0C, (g/cc)	ASTM D70 [30]	0.98
Solubility in trichloroethylene, %	ASTM D2042 [31]	99

2.1.2 Aggregates

Crushed aggregates (fine and coarse) obtained from a quarry site in Zaria-Nigeria were used in this research. **Table 2** shows the physical characteristics of the aggregates, standard specifications used for each test, and results obtained. The results obtained are within the specifications of NGSRB.

Table 2. Physical characteristics of aggregates

Test conducted	Standard	Result
Aggregate crushing value (%)	BS 812-110 [32]	20
Aggregate impact value (%)	BS 812-112[33]	22.2
Specific gravity	ASTM C127 & C128 [34, 35]	2.61 2.63^*
Water absorption (%)	ASTM C127 & C128 [34, 35]	0.48 8.62^*

Note: Values with an asterisk (*) are for fine aggregates others are for coarse aggregates.

2.1.2.1 Aggregate Proportioning and Blending

NGSRB requires that the all-in-aggregate gradation to be used in HMA must lie within the envelope shown in **Figure 1**. In this study, coarse aggregate (material retained on 4.75 mm sieve with a maximum aggregate size of 25 mm). Fine aggregate (material passing 4.75 mm sieve and retained on 200 µm sieve), and mineral filler (material passing 200 µm sieve) were proportioned by trial and error and blended until an all-in-aggregate satisfying NGRSB requirement is obtained. **Figure 1** shows the particle size distribution curve of the all-in-aggregate used in this study.

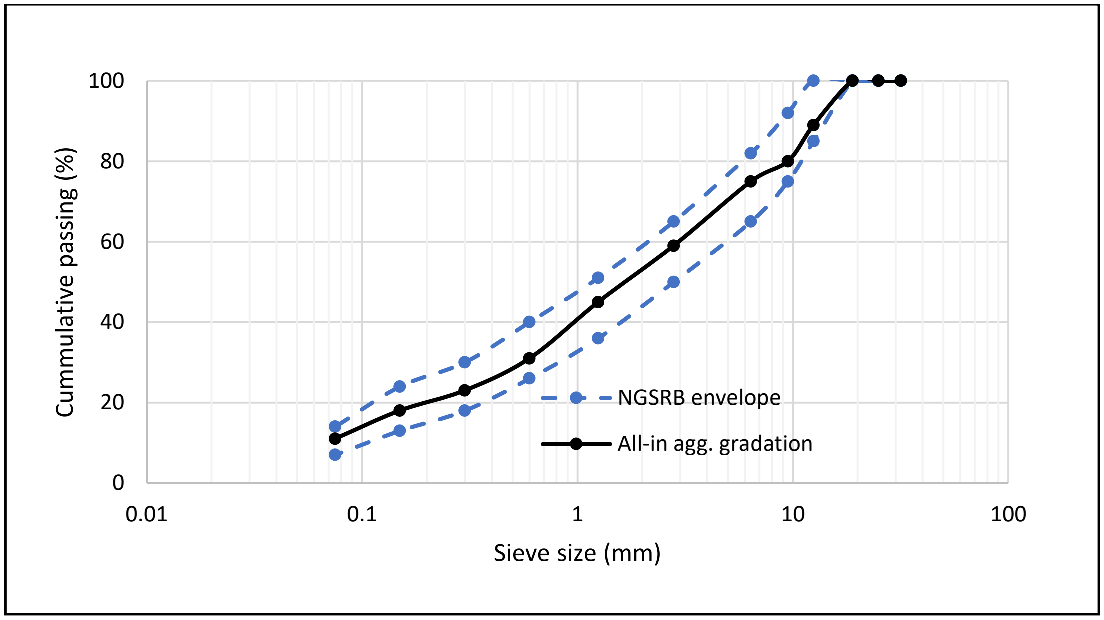

Figure 1. Gradation curve of all-in aggregates (According to BS 812-103.1 [36]).

2.1.3 Fillers

There are two materials used as fillers in this research; Portland cement and Guinea-corn husk ash (GCHA). Portland cement is the reference filler material and is partially replaced at various percentages with GCHA to obtain a blended filler material. The blended filler is obtained by partially replacing cement up to 45% in increments of 5%. The Dangote 3X cement brand used in this study was obtained from a cement depot in Samaru, Zaria-Nigeria. **Table 3** shows the physical properties of filler materials and the standard used for each test.

Table 3. Physical properties of filler materials

Test	Standard	Result
Initial setting time (min)	BS EN 196-3 [37]	125
Final setting time (min)	BS EN 196-3 [37]	205
Soundness (mm)	BS EN 196-3 [37]	1.0
Specific gravity	ASTM C188 [38]	3.10 2.17*

Note: Value with an asterisk (*) is for GCHA while others are for P.C.

Guinea corn husk was obtained from a farm in Zaria-Nigeria. Foreign materials in the sample were handpicked, and the clean sample was burnt in an electric furnace for 3 hours at 700ºC. This burning time and temperature are found to yield the optimum pozzolanic activity in GCHA [39]. The ash was collected from the furnace, allowed to cool, and sieved through B.S. sieve No. 200 to obtain a material that satisfies the particle size requirements. A chemical composition test on the GCHA (**Table 4**) was carried out according to ASTM C311 [40] to determine the pozzolanic activity of a random sample. The result showed that silica + alumina + iron oxide is above 70% (74.6%). Thus, it can be adjusted to a pozzolana of class N following ASTM C618 [41].

Table 4. Chemical composition of GCHA.

Composition	Concentration (%)	Composition	Concentration (%)
Na_2O	0.747	SO_3	1.772
MgO	4.052	Cl	1.620

Al_2O_3	2.365	K_2O	7.615
SiO_2	72.178	CaO	3.569
P_2O_5	4.857	TiO_2	4.857
Cr_2O_3	0.000	Mn_2O_3	0.054
Fe_2O_3	0.0831	ZnO	0.030

2.2. Optimum bitumen content

Marshall method was used to determine the optimum bitumen content (OBC) using HMA containing 100% P.C. filler as the reference (control) mix. For this, 15 samples of the reference mix (3 samples each at varying bitumen content ranging from 5%-7% at 0.5% increment) were prepared for the Marshall test, according to Asphalt Institute [42]. After sample preparation, Marshall stability, flow, and other volumetric properties of the samples were determined. 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 [42]. The OBC was found to be 5.8% (**Table 5**), approximated to 6%.

Table 5. Determination of OBC using control mix

Test property	Bitumen content (%)
Max. stability (kN)	6.0
Max. bulk density (g/cm^3)	6.0
Median % air voids	5.3
OBC = (6+6+5.3)/3 = 5.8%	

The OBC was used to prepare HMA samples at various percentage replacement of OPC filler with GCHA. Performance of the mixes were assessed according to Nigerian general specifications for roads and bridges [43], as shown in **Table 6**.

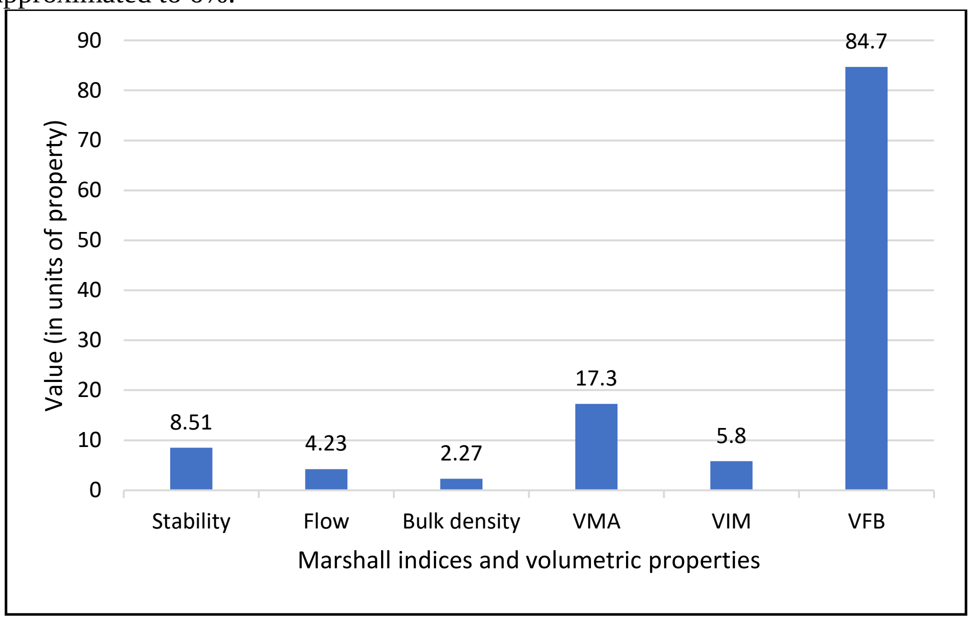

Figure 2. Marshall indices and volumetric properties of reference mix (100% P.C. filler)

3. Results and discussion

This section presents the results and discussion on Marshall stability, flow, and volumetric properties of HMA samples prepared at various percentage replacement of P.C. filler with GCHA. The replacement levels considered range from 5%-45% at 5% increment, and all HMA samples were prepared at the optimum bitumen content. At each replacement level, 3 samples were prepared, and the results of the three were averaged. The volumetric properties considered are; bulk density, voids filled with bitumen (VFB), void in mineral aggregate (VMA), and void in the mix (VIM).

Marshall stability is a measure of HMA resistance to deformation and distortion under traffic loading.

This resistance is mainly derived from cohesion (provided by the binder material) and internal friction (provided by interlocking and frictional resistance of aggregates). The increasing trend in Marshall stability seen in **Figure 3** (between 5% - 20% replacement levels) could not be attributed to the achievement of better cohesion because P.C. (being the primary filler) is a material with better cohesion properties, and its replacement (with a material with weaker cohesion properties) could not likely yield any better cohesion. This agrees with the assertion in Antunes et al. [44] that siliceous fillers (e.g., GCHA – having high silica content as shown in **Table 4**) form weaker bonds with bitumen compared to basic fillers (e.g. P.C., hydrated lime etc.).

However, this increase could be attributed to an improvement in aggregate gradation. GCHA being finer than P.C., occupies the tiny voids between cement particles yielding a more compact aggregate skeleton. The sudden decline in Marshall stability after the 20% replacement level could be attributed to the mix's saturation with finer particles. This problem is two-fold. First, it leads to the absorption of more bitumen (by filler material) required to coat aggregates for bonding. Second, the fine particles tend to push the larger particles apart, distorting the initially compact aggregate skeleton. Both scenarios lead to a decrease in the resistance of the HMA to deformation. However, Marshall stability values of HMA samples at all replacement levels considered in this experiment satisfy the minimum value prescribed by NGSRB (3.5%, **Table 6**) for use in the wearing course.

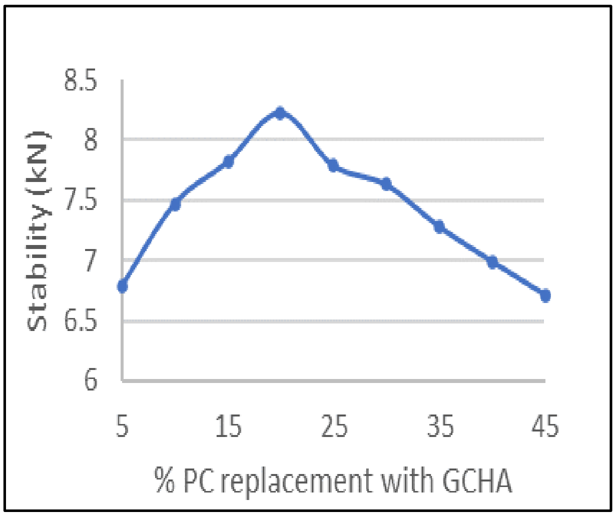

Figure 3. Stability of HMA containing filler blend

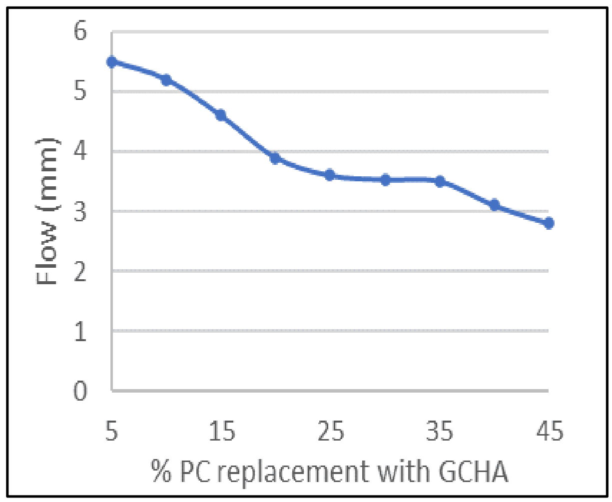

Figure 4. The flow of HMA containing filler blend

Marshall flow, on the other hand, is a measure of deformation (both elastic and plastic) of HMA during the stability test [45]. Allowable limits on the flow of an HMA define boundaries on plasticity or brittleness of the mix. . Large flow values indicate a plastic or unstable mix, and too low flow values signal a brittle mix. Both extremes are undesirable in HMA. The workability of filler-bitumen mastic (the cementing component of asphalt concrete) influences asphalt concrete flow. The gradual decrease in flow reported in **Figure** *3*. Stability of HMA containing filler blend Figure *4*. The flow of HMA containing filler blend

is due to the stiffening of the filler-bitumen mastic. The increase in mastic stiffening (and a decrease in the flow of the mix), which increases with P.C. replacement, could be due to GCHA having more absorption properties than P.C.

The bulk specific gravity or bulk density of asphalt concrete is crucial because it influences other volumetric properties and ultimately asphalt concrete strength. This density measurement, unlike the maximum specific gravity, is obtained with voids in the compacted mix. **Figure 5** presents how this asphalt concrete property varies with increasing GCHA content in the compacted mix. The decline in bulk density of the mix (between 5%-20% P.C. replacement levels) is as a result of the replacement of P.C. particles (having higher specific gravity) with GCHA particles (with lower specific gravity). The gradual rise in bulk density beyond 20% P.C. replacement could be attributed to forming a compact aggregate skeleton. GCHA particles are finer than P.C. particles. As such, the replacement of P.C. particles with finer GCHA particles will likely yield a better interlocking of aggregate particles. Although this replacement (at early stage) comes with a decrease in bulk density due to the difference in specific gravity between the two materials (as seen between 5%-20% replacement levels), a replacement-level is reached (around 20% in this experiment) where a more compact aggregate skeleton is formed (with lesser air voids) that leads to increase in bulk density.

Percent air voids or voids in the mix (VIM) defines the percentage of a compacted HMA sample occupied by air voids.

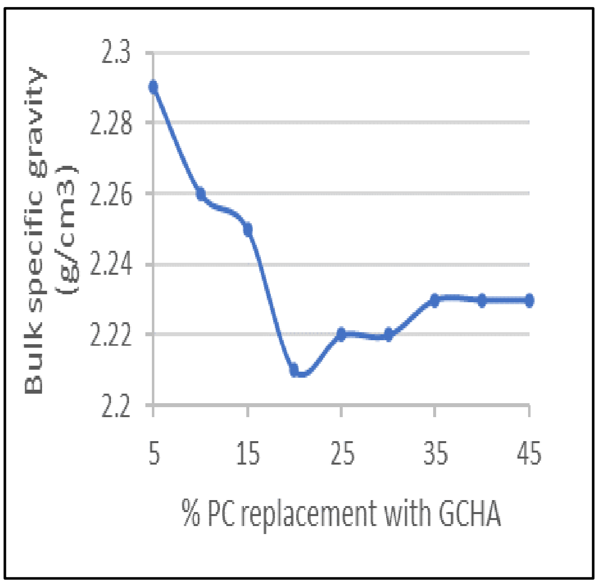

Figure 5. Bulk density of HMA containing filler

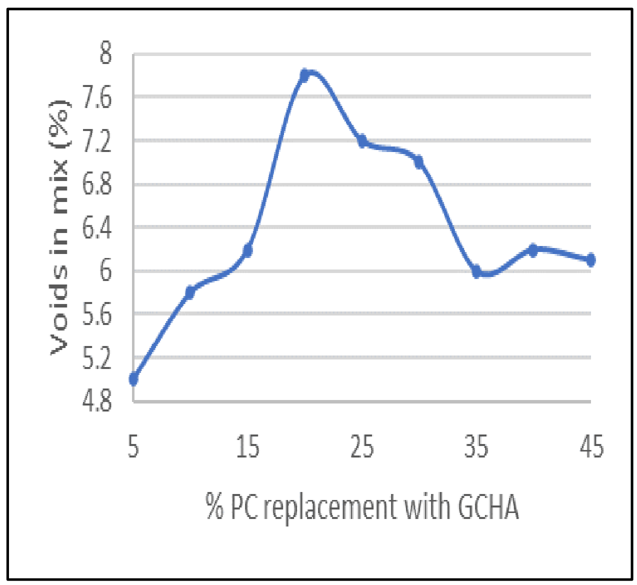

Figure 6. VIM of HMA containing filler blend

A certain percentage of voids is desirable in compacted HMA to allow for the movement of unabsorbed bitumen (through spaces created by the voids) during post-construction compaction of the pavement by traffic and weather-induced asphalt expansion. The durability of asphalt pavement is a function of this HMA property. The lower the air-void content, the denser the mix (less permeable). Too high air-void content will provide passageways for air and water and leads to durability problems. Too low air-void content is also undesirable as it leads to bleeding, where the unabsorbed bitumen bleeds out to the surface of the mix.

The introduction of GCHA into the asphalt concrete (up to 20%), causes a gradual increase in air voids in the compacted mix (**Figure** *6*). This increase could be attributed to GCHA particles' greater ability to convert free bitumen to structural bitumen than P.C. particles. Structural bitumen here refers to the bitumen that fills the voids among filler particles. This conversion reduces the amount of free bitumen required to lubricate aggregates and fill intergranular voids. The reduction in percent air voids beyond 20% of P.C. replacement with GCHA could be attributed to the achievement of a compact aggregate skeleton where the void spaces (in fine and coarse aggregates) not filled with bitumen are occupied by smaller but weaker GCHA particles. This trend correlates well with stability and bulk density plots of the compacted HMA (**Figure 3** and **Figure 5** respectively).

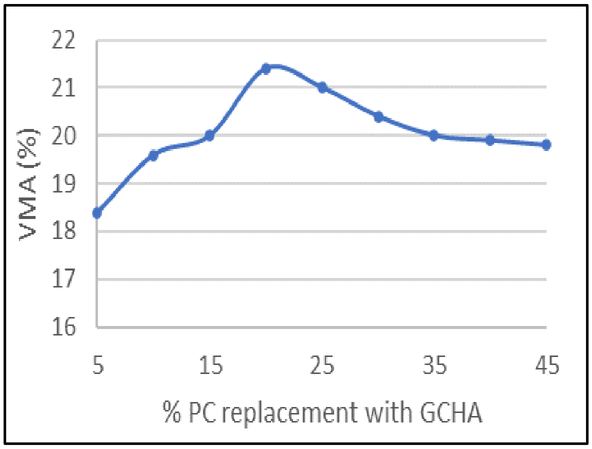

Figure 7: VMA of HMA containing filler blend

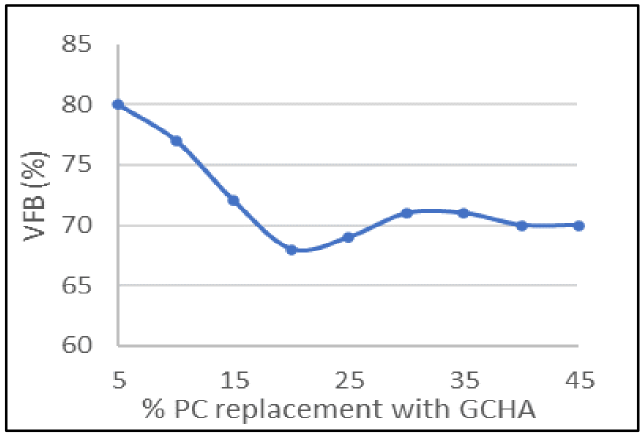

Figure 8: VFB of HMA containing filler blend

Voids in mineral aggregate (VMA) is an HMA design parameter that defines the sum of the volumes of air voids (voids in total mix) and the unabsorbed bitumen (effective binder content) in a compacted HMA sample. Minimum requirements on VMA are set to ensure that sufficient voids are present in the compacted mix to avoid durability problems. The VMA plot in **Figure 7** follows the trend of VIM plot (**Figure** *6*) largely because the driving factor in changes in VMA of the mix comes from changes in VIM.

Table 6. NGSRB minimum requirement of HMA for use in pavement surface course

Property	Binder course	Wearing course
OBC (%)	4.5 – 6.5	5.0 – 8.0
Stability (kN), not less Than	3.5	3.5
Flow (mm)	2 – 6	2 – 4
Voids in total Mixture (%)	3 – 8	3 – 5
Voids filled with Bitumen (%)	65 – 72	75 – 82

Voids filled with bitumen (VFB) refers to the portion of VMA filled with bitumen. It is synonymous with a bitumen-void ratio. It has a strong correlation with the bulk density of an HMA. The more the bulk density, the more voids will be filled with bitumen and vice versa. **Figure 8** shows how this HMA design parameter varies with GCHA content. The initial reduction in VFB (up to 20% P.C. replacement) in **Figure 8** could be due to GCHA particles having more voids in compacted dry-state (higher Rigden voids) than P.C. particles. Fillers with higher Rigden voids are known to produce stiffer mastics [46], increase air voids at constant binder content, and reduce intergranular voids filled with bitumen [47].

4. CONCLUSIONS

This study focused on determining the suitability of PC-GCHA blend for use as a filler material in HMA. Various HMA test samples were prepared according to the Marshall mix design method by varying the proportion of the two filler materials to determine their optimum content that satisfies relevant standards for use in flexible pavement construction.

Higher absorption and voids in compacted dry-state of GCHA are likely the driving factors for decreased flow. These, however, reduce the amount of free bitumen needed to coat and fill voids in the compacted HMA and produce weaker mixes with low VFB. Up to 20% P.C. replacement with GCHA as filler material produces HMA with satisfactory performance. Although mixes at all replacement percentages performed below the reference mix (except with decrease in flow achieved), Marshall indices and volumetric properties obtained with up to 20% PC replacement with GCHA satisfy the minimum requirement prescribed by NGSRB for use in binder course of flexible pavements.

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