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The Effect of Crumb Rubber and Ceramic Waste Filler on the Performance of Hot Mix Asphalt

Reuben Ayodeji Bolaji, and **Olugbenga Joseph Oyedepo**

Civil and Environmental Engineering Department, Federal University of Technology, Akure, Nigeria

Corresponding author's Email: bolajira@futa.edu.ng

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ABSTRACT

In curtailing the effects of scrap tires and ceramic waste in the environment, this study evaluates the effect of crumb rubber as bitumen modifier and ceramic waste as filler on the performance of hot mix asphalt. Bitumen was modified with crumb rubber in increasing percentages of 0%, 6%, 9%, 12% and 15%, by the weight of bitumen, while limestone filler was replaced with ceramic filler at 0%, 25%, 50%, 75%, and 100% proportions by the weight of total filler. Five asphalt mix types were produced and evaluated, based on Marshall mix design method for heavy traffic. The physical and chemical characterization of crumb rubber and ceramic filler showed that their properties were within the specified range and could be potentially applied in hot mix asphalt. In comparison to other variations, the modified mix which contained 6% crumb rubber and 25% replacement of limestone filler with ceramic filler, gave better resistance to deformation and rutting, cracking and moisture susceptibility, from the obtained Marshall flow of 2.92 mm, stability of 32.57 KN, Marshall quotient of 11.15 KN/mm, indirect tensile strength (dry) of 884.2 KN and tensile strength ratio of 90.36 % KN/m^2. The combination of 6% crumb rubber and 25% ceramic filler effectively enhanced the performance of hot mix asphalt, thereby offering as a sustainable approach for recycling these waste materials.

Keywords: Crumb rubber, Ceramic filler, Hot mix asphalt, Marshall properties, Indirect tensile strength, Waste

INTRODUCTION

Hot Mix Asphalt (HMA) is a composite mixture of aggregates, filler, bitumen and sometimes additives, that are mixed and laid while hot, to resist the impacts of traffic and environmentally induced stresses. However, asphalt pavement is susceptible to major distresses such as deformation (rutting), moisture damage, fatigue cracks and thermal cracks, resulting from poor performance attributed to pavement materials, traffic loading, temperature change, rainfall, among others (Kodippily et al., 2020; Wang et al., 2021). Globally, there is a rising research interest in the use of waste materials in HMA, as a means of mitigating the negative effects of generated waste in the environment, as well as improving performance of asphalt pavements against distresses (Victory, 2022).

The growth in the use of automobiles in the world leads to the yearly accumulation of over 1 billion scrap tires that can no longer be used on vehicles or for their primary purpose of production. It therefore forms part of solid waste in landfills because they are non-biodegradable, thereby contributing to pollution of the environment when stockpiled, burnt or dumped (Mohajerani et al., 2020; El Naggar et al., 2023). Scrap tires as a whole or its derivatives can be applied in lightweight constructions, embankments, insulations and fillings. However, scrap tires have been commonly ground into crumb rubber for other applications, especially in asphalt pavement, practically and through research (Lamour and Cecchin, 2021). Crumb rubber (CR) is generated in many sizes and shapes from scrap tires in a recycling facility through the devulcanization process and a mechanical grinding process, free of fiber and steel. The source, sizes, surface texture, production process, blending time, blending temperature, quantity, method of application and composition are important factors that contribute to it effect in asphalt mixtures (Nanjegowda and Biligiri, 2020; Jamal and Giustozzi, 2022; Zakerzadeh et al., 2024).

The two common methods of adding CR to asphalt mixes are through the dry process or wet process. In the wet process, Crumb rubber is mixed with bitumen before preparing the asphalt mixture, while CR is added to the aggregate or filler when adopting the dry process. In comparison to the dry process, the direct interaction between bitumen and CR result in superior performance thereby making the wet process preferable, even though the dry process is easier and helps to utilize more CR (Alfayez et al., 2020; Riekstins et al., 2021; Victory, 2022).

However, CR is often considered as modifier in asphalt pavement in mitigating its negative environmental impacts and improving upon the performance of asphalt pavement (Guerrero-Bustamante et al., 2024). Incorporating CR in HMA had been reported to have benefits such as resistance to rutting, moisture resistance, fatigue resistance, cracking, reduced traffic noise, greater stability, reduced service life, reduced cost, reduced pollution, general performance, sustainability and energy optimization (Sun et al., 2022). On stressing the potential of applying CR-modified asphalt for heavy traffic, Haroon and Ahmad (2024) reported enhanced overall performance at 10% CR content. Also, White et al. (2022) investigated low CR contents in dense graded asphalt, and 5 to 10% was reported to have better resistance to cracking and deformation under low traffic. Similarly, 5 to 15% CR content in HMA gave enhanced stability, better resistance to moisture damage and permanent deformation under high temperature (Khaled et al., 2020). More so, CR-modified pavement for low traffic roads improved stability, cracking resistance and reduced water penetration at 7% content (Okonta et al., 2024). Additionally, 10% of CR was recommended as it gave optimal rutting and skid resistance, on investigating 5 to 15% CR contents (Kerni and Tangri, 2024).

On the other hand, significant quantity of waste ceramics is being generated during production, use and transportation. Generated waste ceramics form around 15% to 30% of its total production (Meena et al., 2022; Kiran et al., 2024; Pathak and Baldania, 2024). Following concrete and bricks, ceramic waste formed the third highest construction waste generated from building sites in the European union for the year 2020. Ceramics are tough, strong and non-degradable, making it a suitable material for hot mix asphalt. Several research focused on utilizing ceramic waste as coarse, fine or filler materials in HMA, which helps to manage ceramic waste and promote sustainability in road construction (Llopis-Castelló et al., 2022; Al-kheetan, 2023; Caro et al., 2024). However, drawbacks such as brittleness, weak impact and crushing resistance, flakiness and elongation have been reported, which makes it to be preferably used as fine aggregate or filler replacement.

Fillers in HMA are finely ground minerals or rocks that are generally less than 0.075 mm (sieve No. 200), primarily used to stabilize asphalt mixtures, reinforce the bonding, enhance mechanical properties and durability, and fill in voids in the granular skeleton, depending on properties of the filler. Several studies investigated the effect of ceramic filler (CF) on the performance of HMA. On investigating bituminous concrete using CF, Adarsh et al. (2023) reported 22.2% increase in stability at 75% CF content. The study by Shamsaei et al. (2020) reported maximum stability, peak resistance to moisture, reduced thermal conductivity, enhanced fatigue life and resistance to deformation at full replacement of limestone filler with CF, with increasing performance as the CF content increased from 25% to 100% at 25% intervals. Also, 5% reduction in stability and 12% increase in flow value for HMA containing CF in comparison to HMA containing stone dust were highlighted, as the CF contents increased with 2% from 4% to 8% content (Fard et al., 2022). More so, Ali (2022) investigated HMA with CF at 3% intervals, 0 to 9% by weight of total aggregates, compared to HMA with limestone filler, better stability, resistance to rutting and cracking was achieved at 6% CF content. Additionally, the study by Khedaywi et al. (2023) replaced limestone filler with CF in HMA from 0% to 100% by total weight of filler, at 25% intervals. The results indicated the highest rutting resistance at 100% CF content, and the highest cracking resistance at 5 °C and 40 °C to be at 25% and 50% CF content, respectively.

While existing research works have explored the use of CR and CF independently for low traffic asphaltic roads, this research investigates the combined effect of CR and CF on HMA under heavy traffic loading, for wider applications. This research investigates their distinct properties that could contribute to meeting the need of better performing roads. Since asphaltic roads are widely used in developing countries and in the world, this research contributes to the 9th sustainable development goal (SDG 9, target 9.1: develop sustainable, resilient and inclusive infrastructures) as it explores the effect of these waste materials in view of enhancing the performance of asphaltic road at no extra cost for economic development. In line with SDG 11.2, the investigation of the effect of CR and CF in developing resilient asphaltic roads that are long lasting and less susceptible to distresses, contributes to achieving safer roads and more accessible transport infrastructure for all types of users. The use of CF and CR in HMA contributes to reducing the dumping of non-biodegradable wastes in the environment and promoting good air quality by preventing the indiscriminate burning of CR, thereby achieving environmental sustainability in line with SDG 11.6.

The aim of this research is to evaluate the effect of CR and CF on the performance of HMA, under heavy traffic loading. Bitumen was modified with CR in increasing percentages of 0%, 6%, 9%, 12% and 15%, by the weight of bitumen, while limestone filler was replaced with CF at 0%, 25%, 50%, 75%, and 100% proportions by the weight of total filler. The properties of CR and CF were determined and the mechanical and durability properties of HMA specimens were evaluated from Marshall and indirect tensile strength tests. The objective is to characterize CR, bitumen, CF, determine mechanical and durability properties of specimens produced using Marshall method at evaluated optimum bitumen contents, and conduct comparative analysis of the test results with the standard values and existing research. The findings of this research will contribute to the development of resilient asphaltic roads that can withstand varying environmental and traffic conditions, through the incorporation of balanced contents of CR and CF. The explored effect of CR and CF in HMA will further advance innovation in HMA modification techniques.

MATERIALS AND METHODS

Materials

Materials for this research work include bitumen, aggregates, ceramics and crumb rubber.

- *Bitumen*: Bitumen of grade 60/70 which comformed with the grade of straight-run bitumen specified in the general specifications for roads and bridges (GSRB) by federal ministry of power, works and housing (FMPWH) of Nigeria (2016), was sourced locally from Ondo state asphalt company.
- *Aggregates*: Crushed Limestone was procured from Stoneworks industries limited, Obaile, Akure, Nigeria. It was fractionated into three; coarse aggregate (19 mm to 4.75 mm), fine aggregate (4.75 mm to 75 μm) and limestone filler (< 75 μm).
- *Waste ceramics*: Waste ceramic tiles were locally sourced from a building construction site in Akure, Nigeria. The waste ceramic tiles were grinded into CF using a machine as shown in Figure 1, at the mechanical workshop of the federal university of technology, Akure, and sieved through 75 μm (sieve No. 200).
- *Crumb rubber*: CR shown in Figure 2 with sizes less than 425 μm was procured from Freee recycle limited, a recycling company in Ibadan, Nigeria.

Figure 1. Ceramic filler processed from waste ceramic tiles.

Figure 2. Crumb rubber

Material Tests

The physical properties of bitumen, limestone aggregates, CR and CF were investigated according to ASTM, AASHTO and FMPWH standards. The chemical oxides of the CF were determined using an Energy Dispersive X-ray fluorescence spectrometry (ED-XRF), a Skyray instrument with model EDX3600B detects elements between magnesium and Uranium with high resolution and fast analysis. Moreso, CR was characterized according to ASTM D6114-19 specification for textile content, metal content, particle size and specific gravity.

Specimen Preparation

As recommended by Asphalt Institute (2014), Marshall mix design method according to ASTM D6926-20 was adopted to prepare HMA specimens according to the mix design presented in Table 1. Compacted cylindrical specimens weighing 1200 g, with approximate diameter of 101.6 mm, height of 63.5 mm at trial bitumen content of (5.0%, 5.5%, 6.0%, 6.5%, 7.0%), were prepared in compliance with FMPWH GSRB (2016). The Marshall moulds and associated apparatus were pre-conditioned in the oven at 130 ˚C as shown in Fig. 5. Asphalt rubber was produced through the wet process by mixing varying proportion of CR and bitumen at 150 ˚C for 2 hours, then immediately mixed uniformly in 1 minute with hot aggregate combination, already conditioned at 145 ˚C. Hot mix asphalt specimens were produced by applying 75 blows (heavy traffic) at a free fall distance of 500 mm. The Compaction was done at 135 ˚C and all working temperatures fell between 130 ˚C and 163 ˚C as specified by FMPWH (2016), which is below 177 ˚C as specified by Asphalt Institute (2014). Compacted specimens were allowed to cool and hardened before extrusion to avoid deformation. Seventy-five cylindrical specimens were prepared for the determination of volumetric and Marshall properties as shown in Figure 3, in order to evaluate the OBC, after which while forty-five specimens were produced at OBC for performance tests. The prepared specimens were labelled with codes to signify the proportion of CR, CF and bitumen that they contain. For instance, the mix labelled “R9-C50” signify a mix containing 9% CR by weight of bitumen and 50% CF by weight of total filler.

Table 1. The mix design of specimens

Specimen mixture	Coarse aggregate (by weight of total aggregate) %	Fine aggregate (by weight of total aggregate) %	Limestone filler (by weight of total aggregate) %	Crumb rubber (by weight of Bitumen) %	Ceramic filler (by weight of total aggregate) %
R0-C0 (Control)	55	35	10	0	0
R6-C25	55	35	7.5	6	2.5
R9-C50	55	35	5	9	5
R12-C75	55	35	2.5	12	7.5
R15-C100	55	35	0	15	10

Figure 3. Hot mix asphalt specimens.

Volumetric tests

The volumetric properties of HMA were considered in the mix design at each trial bitumen contents of 5.0%, 5.5%, 6.0%, 6.5%, 7.0%, to evaluate the OBC and to produce HMA with satisfactory performance under traffic loading and exposure to the environment. Volumetric properties include various specific gravity and air voids which significantly contribute to the performance of HMA. The specific gravity values are critical in determining the air voids of compacted asphalt specimens. The various specific gravity that was considered included bulk specific gravity of compacted mix (G_{mb}) (ASTM D2726-21), theoretical maximum specific gravity (G_{mm}) and the bulk specific gravity of combined aggegate present in the compacted mix (G_{sb}). Voids in the HMA include voids in total mix (VTM) (ASTM D3203-22), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB). In addition, the values of Marshall stability and flow of the HMA were determined at each trial bitumen content according to ASTM D6927-22. The OBC for each asphalt mix type were finally calculated as the average bitumen content values that correspond to peak stability, peak bulk specific gravity of compacted mix (G_{mb}) and 4% air voids (median of 3% to 5% VTM).

Performance tests

The performance of HMA against distresses was evaluated by determining parameters such as Marshall stability, flow, Marshall quotient, indirect tensile strength and tensile strength ratio.

- *Marshall stability*: Measures the maximum load capacity of HMA in Kilonewton (KN) at failure, as the resistance of HMA to instability rutting under repeated and heavy traffic loading. Marshall stability evaluates the cohesion and durability behavior of the pavement material (Asphalt Institute, 2014). The Marshall stability was determined according to ASTM D6927-22 and AASHTO T245-22, using an automatic Marshall stability tester shown in Figure 4, which has a 50 KN capacity for stability and a capacity of 15 mm for flow values, and could measure stability to a resolution of 0.01 KN, and measure Marshall flow to a resolution of 0.01 mm. Three specimens from each mix type were immersed in water bath for 30 minutes at 60 ˚C, and compressed laterally on the digital Marshall stability tester at a constant loading rate of 50 ± 5 mm per minute, until the specimen failed. Thereafter, the maximum average stability and flow values were recorded.

- *Marshall flow*: Marshall flow is a parameter that measures the permanent strain at failure when an asphalt mixture is tested for Marshall stability. Flow indicates the pavement resistance to plastic flow under traffic loading (Asphalt Institute, 2014). Every Marshall stability value has a corresponding flow value in millimeter (mm), which is measured at specimen failure.

- *Marshall quotient*: Marshall quotient (MQ) is the ratio of Marshall stability (KN) to flow (mm), as a measure of the ability of HMA to resist plastic deformation, rutting, shear stresses and creep deformation. Marshall quotient further combines Marshall stability and flow as a single parameter measured in KN/mm, using Equation 1.

$$\text{Marshall quotient} = \frac{\text{Stability}}{\text{Flow}} \qquad (1)$$

Figure 4. Marshall stability and flow test.

- *Indirect tensile strength (ITS)*: ITS measures the internal bonding of HMA and its resistance to cracking. The ITS measures the number of repeated load in KiloPascal (KPa), that HMA can sustain before cracking (Asphalt Institute, 2014). The procedures for the determination of ITS was according to AASHTO T283-21 and ASTM D4867-22. Six (6) asphalt specimens were selected from the same mix type and separated into two subsets of uncondtioned (dry) test specimen and conditioned (dry) test specimen. One subset was tested when dry, while the other subset was tested after conditioning in water for 24 hours at 60 ºC. However, both subsets of HMA specimens were immersed in a water bath for two hours at 25 °C before loading on the machine.

The ITS of both subset was determined using a multispeed compression tester as shown in Figure 5, by loading the specimens at a uniform rate of 50 mm per minute until fracture occurred. The ITS of these asphalt specimens was calculated from the specimens dimension and the attained maximum load at fracture using Equation 2.

$$\text{ITS} = \frac{2000 \times \text{Pmax}}{\pi \text{Dt}} \qquad (2)$$

Where ITS is the indirect tensile strength (KN/m^2); t is specimen height; D is specimen diameter; and $\pi = \frac{22}{7}$, P_{max} is maximum load at failure (N).

Figure 5. Indirect tensile strength test.

- *Tensile strength ratio:* The vulnerability of HMA to water penetration is commonly evaluated from the tensile strength ratio (TSR), which is a function of ITS. AASHTO T 283-21 and ASTM D4867-22 standards were adopted to evaluate the moisture resistance of HMA specimens. The TSR expressed in percentage, is the ratio of the indirect tensile strength of wet HMA specimens (ITS wet), to the indirect tensile strength of unconditioned HMA specimens (ITS dry) (Asphalt Institute, 2014). The TSR was evaluated using Equation 3.

$$\text{TSR} = \frac{\text{ITS wet}}{\text{ITS dry}} \times 100 \qquad (3)$$

Where TSR is the tensile strength ratio (%); ITS is indirect tensile strength (KN/m^2).

RESULTS AND DISCUSSION

Material properties

The properties of bitumen and crushed limestone presented in Table 2, satisfied the requirements of relevant codes for wearing course. The selected bitumen demonstrated well-rounded properties for long-term performance of HMA pavements. This bitumen exhibits good blend of binding properties, resilience and adaptability to varying traffic and environmental conditions. The properties of aggregates showed good resistance to disintegration when exposed to traffic and the environment. Aggregates display moderate absorption of bitumen required for coating, which if excess can negatively impact the performance of HMA. The particle size distribution of the CF in Table 3 comformed with the particle size requirement in the FMPWH-16 general specifications for roads and bridges, which specified up to 100 % passing on sieve No. 200 (75 μm). The well graded aggregates enhance stability and minimize voids in HMA for long lasting performance. From the chemical concentrations in Table 4, the major compounds in the CF were slilicon, aluminium and iron oxides. The concentration of acidic oxides (SiO_2 + Al_2O_3 + Fe_2O_3) amounted to (59.807%) which is greater than minimum percentage requirement of (50%) for category “C” pozzolan as highlighted in ASTM C618-15. The concentration of SO_3 of the CF was also less than the maximum allowable concentration of 5% for class C pozzolan. These results are in line with the reported results by Shamsaei et al. (2020), having acidic oxides concentration of (SiO_2 + Fe_2O_3 + Al_2O_3) above 50%. The pozzolanic properties of the CF contributed to the durability of modified HMA, by increasing bonding and reducing absorption and porosity. The spectrum plot shown in Figure 6 further indicated the high intensity of silicon oxide, iron oxide compounds, among others, signifying their high concentration level in the CF. Also, compounds with low intensity were displayed, such as silver oxide, manganese oxide, among others, signifying low concentration level in the CF.

Table 2. Properties of bitumen and aggregates.

Tests	Results	Specification	Standard
Bitumen			
Penetration	64	60 — 70	ASTM D5-20
Ductility (cm)	105	Min. 100	ASTM D113-17
Flash point (˚C)	332	Min. 250	ASTM D92-18
Fire Point (˚C)	372	—	ASTM D92-18
Softening Point (˚C)	54.6	49 — 56	ASTM D36-14
Specific Gravity (g/cm^3)	1.018	0.97 — 1.06	ASTM D70-18a
Coarse Aggregate			
AIV (%)	17	Max. 30	BS 812 – 112, FMPWH-16
ACV (%)	20	Max. 30	BS 812 – 110, FMPWH-16
Bulk (dry) Specific gravity	2.661	—	AASHTO T85-22
Apparent Specific gravity	2.698	—	AASHTO T85-22
Water Absorption %	0.48	Max. 0.5	AASHTO T85-22, FMPWH-16
Fine Aggregate			
Bulk (dry) Specific gravity	2.673	—	AASHTO T84-22
Apparent Specific gravity	2.721	—	AASHTO T84-22
Water Absorption %	0.68	—	AASHTO T84-22
Limestone Filler			
Specific Gravity	2.774	-	ASTM D854-23
% Passing Sieve 75 μm	100	85 - 100	FPMWH-16, ASTM D242-19

Table 3. Physical properties of ceramic filler

Properties	Results	Standards
Specific Gravity	2.651	ASTM C188-17
% Passing Sieve No. 200 (0.075 mm)	100	FMPWH-16

Table 4. Chemical composition of ceramic filler

Oxides	**Al_2O_3**	**SiO_2**	**Fe_2O_3**	**SO_3**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**
Content (%)	11.945	33.577	14.285	0.639	2.850	1.141	1.269	0.048	0.020	0.144	0.585
Oxides	**ZnO**	**PbO**	**WO_3**	**Ag_2O**	**Rb_2O**	**MoO_3**	**CdO**	**SnO_2**	**Sb_2O_5**	**CuO**	**P_2O_5**
Content (%)	1.072	0.166	1.428	0.058	0.142	2.850	0.708	14.713	14.04	0.689	0.479

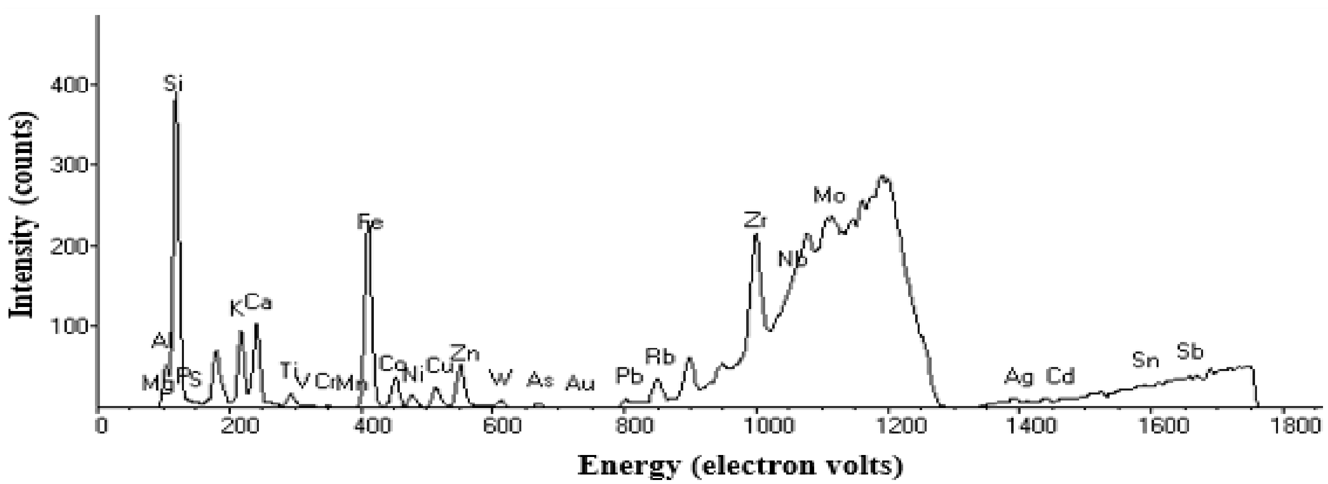

Figure 6. ED-XRD spectrum plot of ceramic filler

- *Crumb rubber***:** The physical properties of crumb rubber and the particle size distribution are presented in Tables 5 and 6 respectively. The crumb rubber was neat and contained neglible metal, textile or foreign materials, which could compromise the performance of the asphalt pavement. The sizes of CR particles were below 425 μm and well graded.
- *Particle size distribution*: Figure 7 shows the gradation curve of the blended materials in relation to the set boundaries in the GSRB by FMPWH-16. This combination of aggregates and filler comply with the gradation requirement for wearing course in the GSRB of Nigeria. The aggregate proportions (55% of coarse aggregate, 35% of fine aggregate and 10% of filler) by percentage of total aggregate weight, produced a well graded aggregate blend in conformity with the FMPWH-16 and the nominal maximum aggregate size (NMAS) was obtained as 12.5 mm.

Table 5. Properties of crumb rubber

Physical Properties	Results	Specifications	Standards
Color and form	Black fine	-	-
Max. Size	< 425 μm	Max. 2.36 mm	ASTM D6114-19
Specific gravity	1.161	1.15 ± 0.05	-
Metal content	None	Max. 0.01%	ASTM D5603-19a
Textile Content	0.15%	Max. 0.5 %	ASTM D5603-19a
Foreign Material	0.1%	Max. 0.25 %	-

Table 6. Particle size distribution of crumb rubber

Sieve (mm)	2.36	0.425	0.3	0.15	0.075
% Passing	100	100	65.7	18.5	-

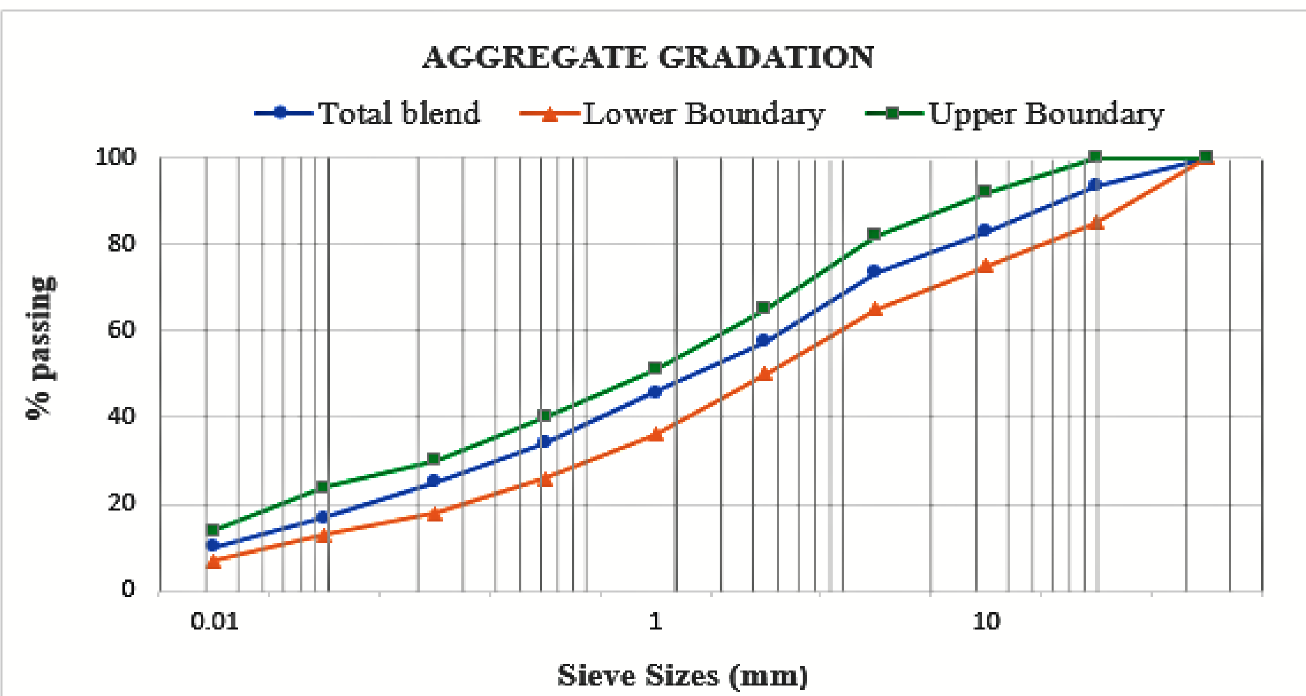

Figure 7. Gradation curves of the blended materials.

Volumetric Results

- *Bulk specific gravity*: Figure 8 shows the bulk specific gravity (Gmb) of the mix types at trial bitumen contents. The Gmb of modified specimens were generally less than that of the control specimen at each bitumen content, with observed reducing trend with increasing content of CR and CF. Modified samples become less dense due to the elasticity property of CR which is in line with the results of Almusawı et al. (2020). The lesser specific gravity of CF in comparison to the specific gravity of limestone filler is also responsible for the reduction in density. Denser mixes with higher Gmb values demonstrate better compaction and stability against distresses, while less dense mixes with lower Gmb values portray poor strength and stiffness.
- *Voids in total mix*: As presented in Figure 9, the VTM across all mix types is less than 10%, therefore, the asphalt mixes are dense graded according to ASTM D3203-22. The VTM for all mix types generally reduced with increasing bitumen content, because more binder filled the voids. Consequently, porosity of all compacted asphalt mixes steadily reduced with increasing bitumen content due to bitumen occupying the voids between aggregate. It was observed that R0-C0, R6-C25, R9-C50 had 3% to 5% VTM at all trial bitumen contents, as specified by the FMPWH GSRB for asphalt wearing course. This reduces the possibility of bleeding in that sufficient space for bitumen expansion is provided by balancing compaction and adaptability to temperature changes. But R12-C75 and R15-C100 exceeded 5% VTM at 5% bitumen content, indicating high permeability and poor performance in terms of stability and moisture penetration.
- *Voids in mineral aggregate:* Figure 10 shows that the obtained VMA across all mix types were above the minimum specified VMA of 14 %, as specified by Asphalt Institute (2014) for 12.5 mm NMAS at 4% VTM. The steady increase in VMA across mix types indicated sufficient bitumen coating around aggregates and the presence of CR particles creating thicker binder films between the aggregate. Due to this increase, VMA increases the binder space around aggregates thereby reducing its susceptibility to cracking. However, too high VMA compromises the strength of HMA due to lack of contact between HMA particles.
- *Voids filled with bitumen:* From Figure 11, it can be observed that the voids filled with bitumen for all mix types generally increased with subsequent addition of bitumen. Only R6-C25 fell within the specified range of 72% to 85% VFB as stated by the FMPWH GSRB for asphalt wearing course, while other mix types were out of range. This demonstrates optimized bitumen content in HMA, which is necessary for the long-term performance of HMA under heavy traffic and extreme weather condition. The low VFB portrayed at 5% bitumen content by R9-C50, R12-C75 and R15-C100, contributes to a more brittle HMA that is prone to cracking, increased permeability and low durability.

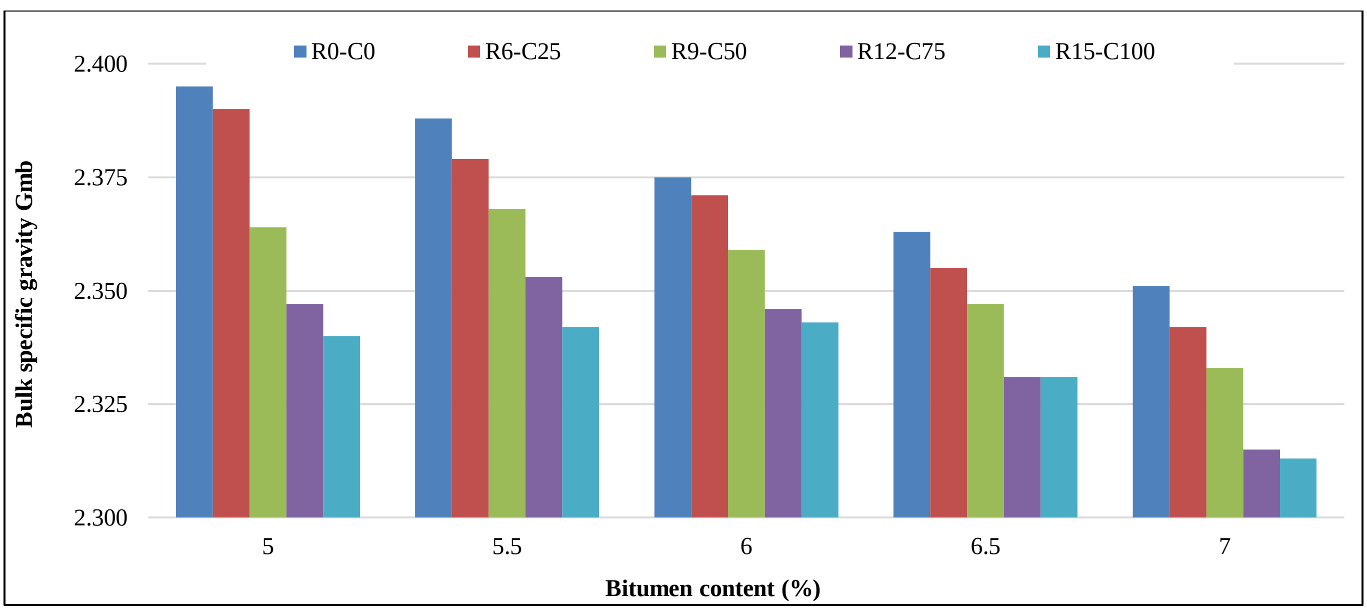

Figure 8. Bulk specific gravity of compacted mixes.

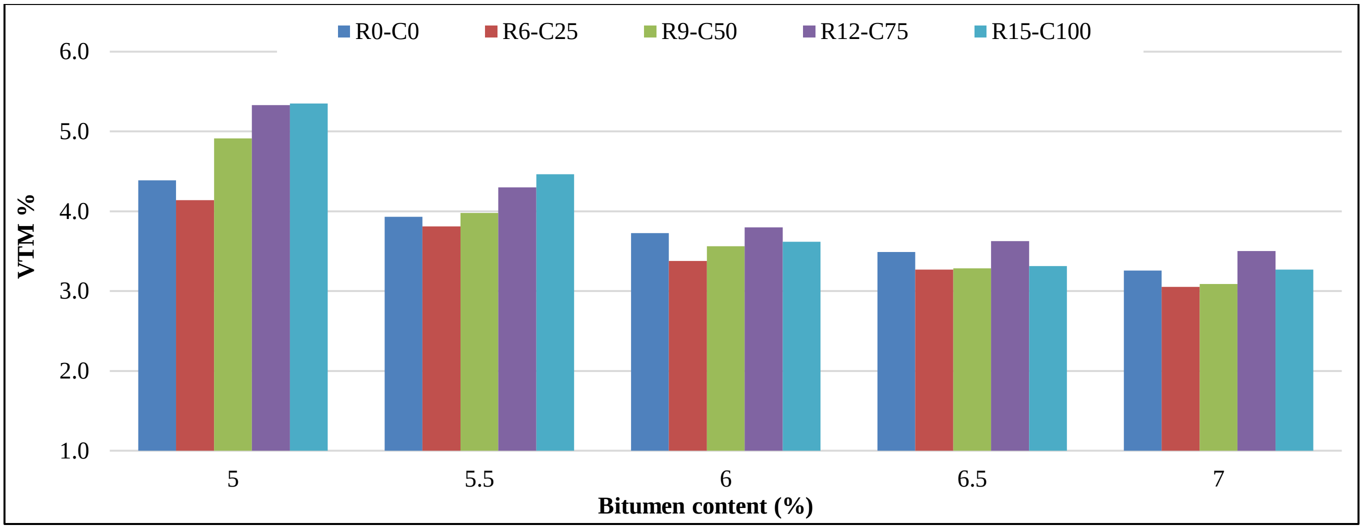

Figure 9. Voids in total mix

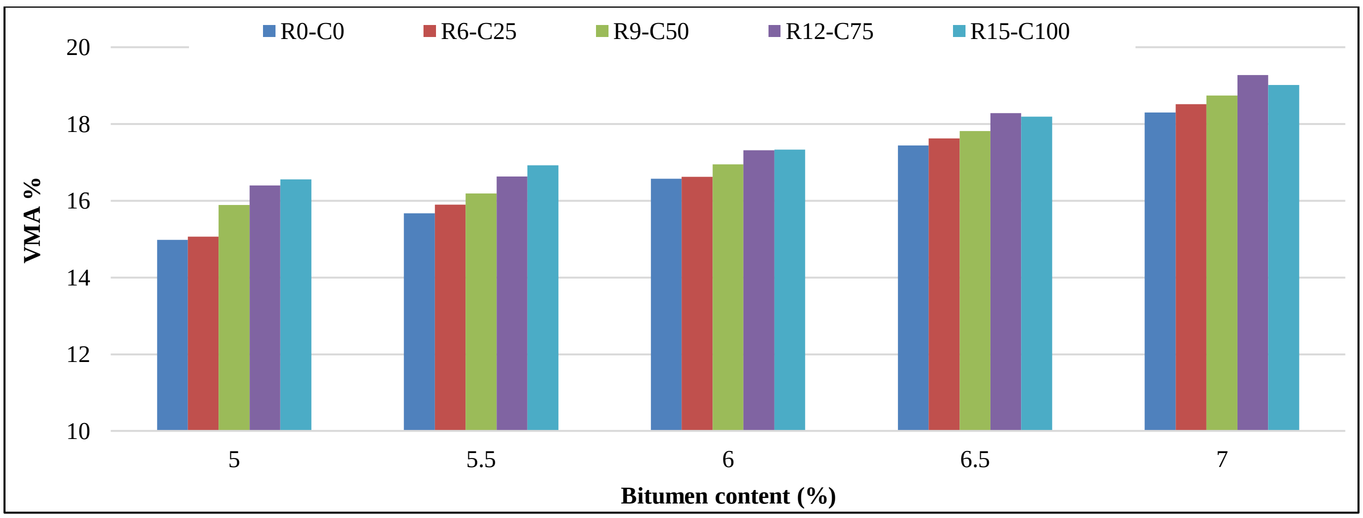

Figure 10. Voids in mineral aggregate

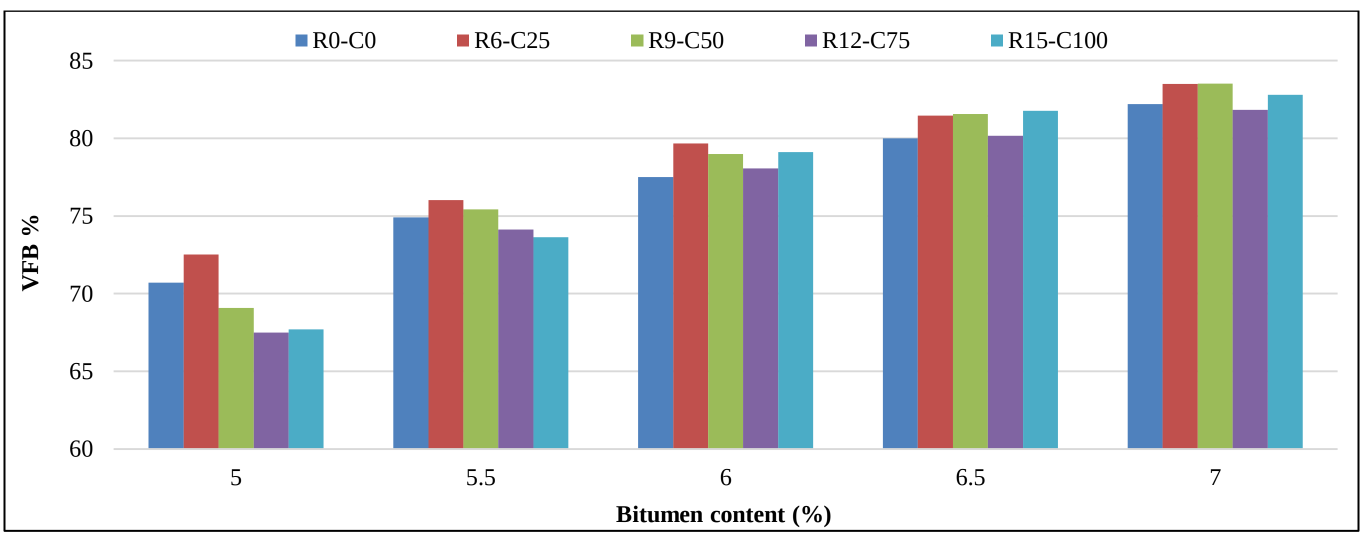

Figure 11. Voids filled with bitumen

Optimum bitumen content

The evaluated optimum bitumen content (OBC) of each mix type is presented in Table 7. The values of Marshall stability and flow of the HMA were determined at each trial bitumen content according to ASTM D6927-22 and the peak values are also presented in Table 6. The evaluated OBC for mixes R0-C0, R6-C25, R9-C50, R12-C75 and R15-C100, were 5.0%, 5.3%, 5.5%, 5.6% and 5.9%, respectively. The OBC progressively increased with increasing content of CR and CF. The increasing trend is as a result of the demand of more bitumen to sufficiently coat the increasing CR content and to accommodate the increasing absorption of bitumen by the CR and CF. The pozzolanic property of the CF also contributed to the absorption of more bitumen as the content of CF increased, while bitumen is also absorbed from the direct interaction of CR and bitumen.

Table 7. Optimum bitumen content of asphalt specimens

Mix Types	Peak Stability (KN)	Bitumen Content at Peak Stability (%)	Peak Bulk Density	Bitumen Content at Peak Bulk specific Density (%)	Bitumen Content at 4% VTM	Optimum Bitumen Content (OBC)
R0-C0	32.46	5.0	2.404	5.0	5.1	5.0
R6-C25	32.58	5.5	2.390	5.0	5.2	5.3
R9-C50	31.21	5.5	2.368	5.5	5.5	5.5
R12-C75	31.03	5.5	2.353	5.5	5.7	5.6
R15-C100	30.54	6.0	2.343	6.0	5.7	5.9

Performance results

- *Marshall Stability:* From Figure 12, Marshall stability was slightly higher for the modified sample (R6-C25) with 6% CR content and 25% CF content, when compared to other mix types. Similar slight increase in stability was also reported by Haroon and Ahmad (2024). The increase in stability is attributed to compaction and enhanced adhesion within the mix structure, as a result of slightly replacing limestone filler with 25% CF which adequately filled voids, and the moderate addition of 6% CR which improved the adhesion of the binder with aggregate. Also, the lower specific gravity of CF in comparison with that of limestone filler could have contributed to having a greater but moderate volume fines in the HMA specimen. The absorption of more bitumen by the introduction of CF and CF contributed to filling air voids (Shamsaei et al., 2020). Therefore, more voids are filled with CF and the stability of HMA is enhanced when subjected to heavy traffic loading. However, the stability of the subsequent mixes were lesser due to the increasing content of CF and CR, which reduced the degree of contact between aggregates and lowered internal adhesion through the formation of excess binder thickness film (Khaled et al., 2020). More compaction tends to increase the density and recover the HMA adhesion from the elastic property of CR, as the excess of it tends to lower stability (Almusawı et al., 2020). Moreover, the HMA with 6% CR and 25% CF showcased the highest load bearing capacity and durability properties, having the ability to withstand heavy traffic loading when used on roads.
- *Marshall flow:* Marshall flow values presented in Figure 13 showed that all mix types had flow values which were within the specified limits of (2 to 4 mm) in line with the FMPWH GSRB for compacted wearing course. However, R6-C25 showed the highest resistance to plastic flow, corresponding to the mix with the maximum stability and lowest flow. The enhanced stiffness can be attributed to the CF content in the specimen, in that the CF absorbed bitumen and increased the bonding within the internal structure (Shamsaei et al., 2020). Similarly, Khaled et al. (2020) reported improvement in stability and reduction in plastic flow due to enhanced stiffness. On the other hand, the mix with the highest content of CR and CF (R15-C100) gave the highest flow value. As the content of CR and CF for mixes R12-C75 and R15-C100, the flow values also increased but stayed within the specified limits, which agree with the findings of Haroon and Ahmad (2024).
- *Marshall quotient (Stiffness)*: Modified mix containing 6% CR and 25% CF displayed maximum Marshall quotient in the result presented in Figure 14. This improved performance is attributed to the moderate addition of crumb rubber (CR) and partial replacement of filler with CF, which is in support of the results reported by Shamsaei et al. (2020). Heavy traffic road demands for high Marshall quotient value, of wich mix R6-C25 offers enhanced resistance to permanent deformation and shear

stresses. This justifies the high stability value and its corresponding flow value compared to other mix types.

- *Indirect Tensile Strength*: The ITS of unconditioned (dry) HMA specimens and conditioned (wet) HMA specimens are presented in Figure 15. The presence of CR and CF in modified mixes significantly increased the ITS under wet and dry conditions. In comparison with the control mix, the modified samples exhibited significant enhanced ITS under wet condition, as a result of the stronger bond produced by the modified binder, the poor thermal conductivity of CF and reduced permeability when conditioned at 60 ºC for 24 hours, supporting the findings by Khaled et al. (2020) and Kashesh et al. (2023). The pozzolanic property CF contributed to the strength of modified mixes by forming Cementous compounds in the presence of water. Also, the ITS values of the mixes showed peak strength at 6% crumb rubber and 25% CF under both conditioning, after which the ITS of subsequent samples decreased with increasing CR and CF content. Under wet conditions, the ITS of the modified mix (R6-C25) increased significantly by 25% from 639.2 KN/m^2 to 799 KN/m^2, in comparison with the control sample. This is the resultant effect of partially filled voids and enhanced bonding provided by the joint action of CR and CF. However other modified mixes R12-C75 and R15-C100 displayed lesser ITS in comparison with the control sample when unconditioned, because excess CR reduced the adhesive properties by providing excess thickness of binder film between aggregate (Almusawı et al., 2020). Though having the potential of resisting water penetration, this mix is weaker in stability and could result in short-lived pavements. The modified specimens generally gave enhanced resistance to cracking distresses arising from heavy traffic loading and temperature change.

- *Tensile Strength Ratio:* The TSR for modified mixes were significantly higher compared to the TSR of the control mix as presented in Figure 16. Generally, TSR of all mix types were above the minimum required value of 80% which is also in line with the results reported by Shamsaei et al. (2020) and Okonta et al. (2024). Due to the enhanced coating of aggregate provided by CR, the stripping potential of HMA is also reduced Haroon and Ahmad (2024). Also, the bond within the internal structure of modified asphalt mixes is strengthened as a result of the increase in viscosity of binder by CR, thereby reducing water penetration (Khaled et al., 2020; Kashesh et al., 2023). More so, the highest resistance to moisture was observed when the CR content and replacement percentage of CF were increased to 15% and 100%, respectively. However, the same mix exhibited the least ITS value among the modified mix types due to the reduction of adhesion within the mix structure by excess binder film thickness between aggregates, thereby cracking easily. The modified samples showcased enhanced resistance to moisture, with observed progression in increasing content of CR and CF, highlighting suitability of application in heavily traffic roads that are susceptible to moisture damage. The ability of CF to withstand heat also contributed to low thermal conductivity within the mix.

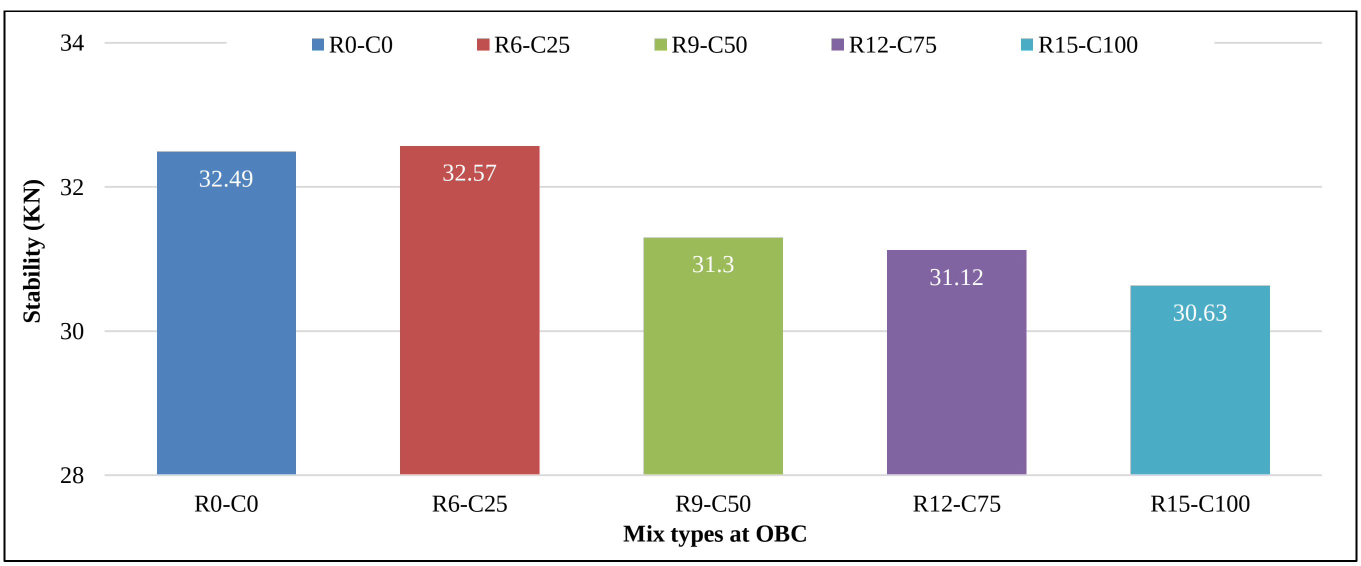

Figure 12. Marshall stability of mixes

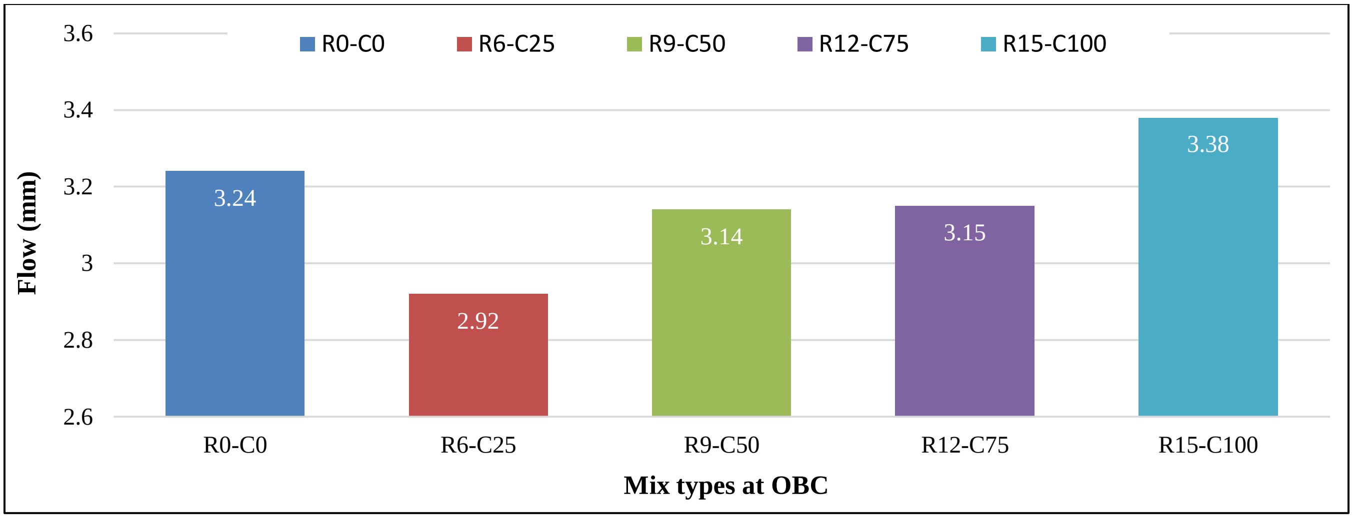

Fig. 13 Marshall flow values of mix types

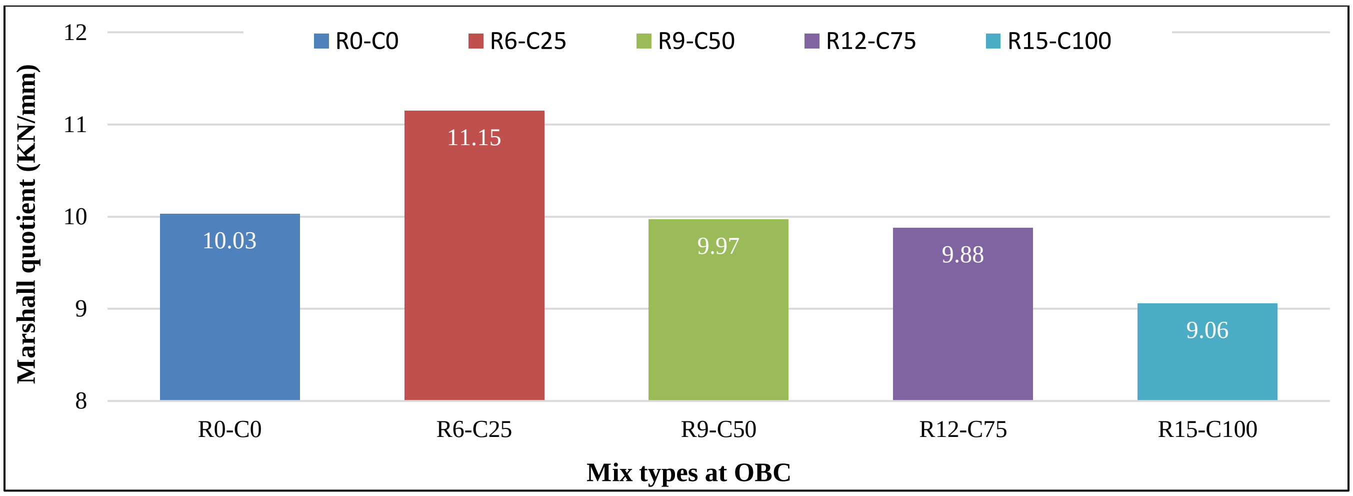

Figure 14. Marshall quotient of mixes

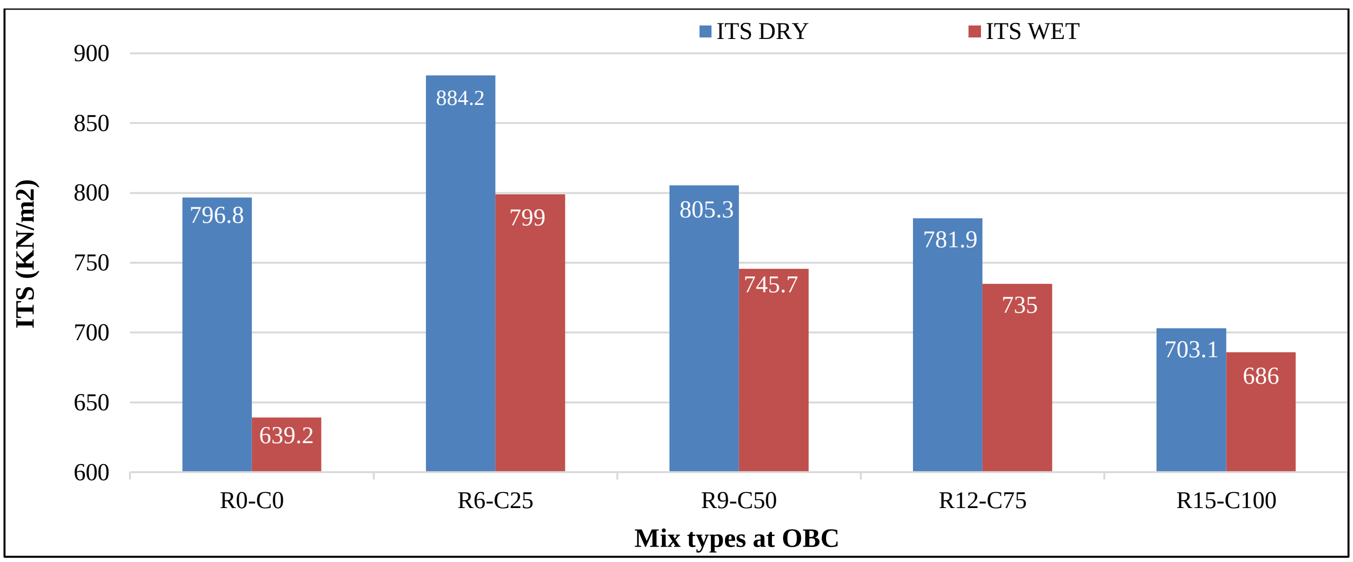

Figure 15. Indirect tensile strength of wet and dry HMA

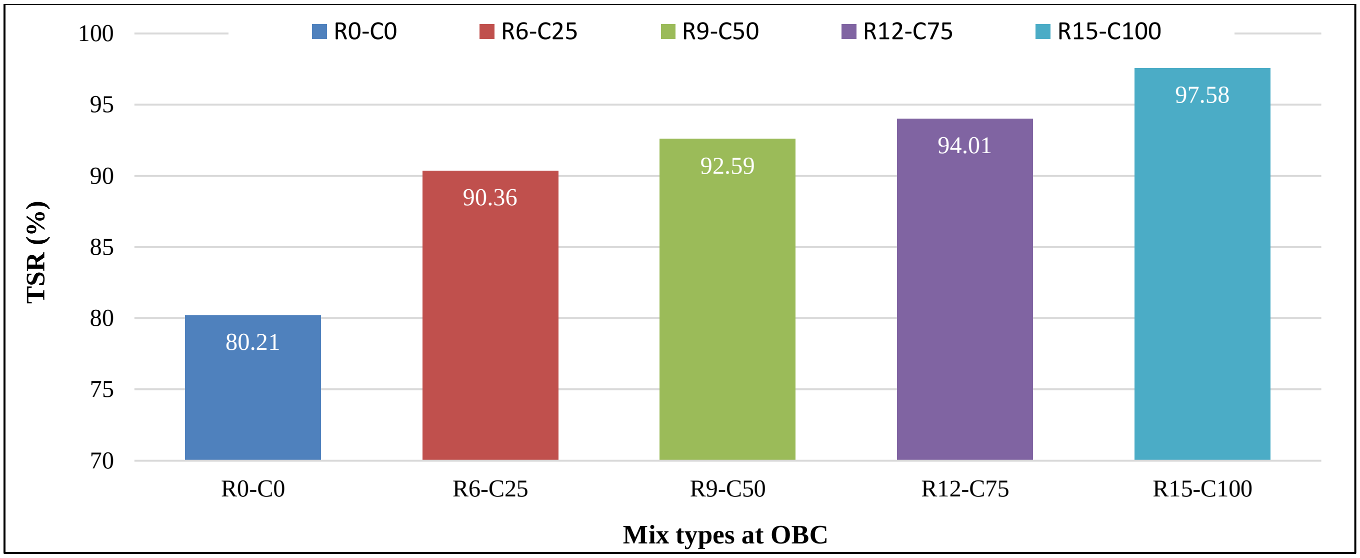

Figure 16. Tensile strength ratio of mixes

CONCLUSION

The investigation of the effect of crumb rubber and ceramic waste filler on the performance of HMA under heavy traffic loading revealed that the combination of 6% crumb rubber and 25% ceramic filler satisfied all requirements of relevant codes and Marshall criteria in terms of volumetric properties, stability, flow, stiffness, indirect tensile strength and tensile strength ratio.

Key findings

1. The chemical properties of ceramic filler revealed good pozzolanic properties which enhanced the adhesion of hot mix asphalt when applied up to 25% as partial replacement for conventional fillers, increasing the internal bond against cracking and rutting when exposed to varying temperature and heavy traffic loading.
2. The ITS value of 799 KN/m^2 and TSR value of over 90% revealed that 25% ceramic filler content and 6% crumb rubber adequately filled the voids in HMA, thereby reducing susceptibility of asphaltic roads to moisture damage in water prone environment. Modified specimens conditioned in water at 60 ºC for 24 hours exhibited poor thermal conductivity due to CF presence and increase in binder viscosity due to the action of CR, resulting in enhanced cracking resistance.
3. Due to enhanced stiffness, modified HMA mix with 6% crumb rubber and 25% ceramic filler exhibited the strongest stability with the ability to withstand the deformation and shear stresses that is induced on heavily trafficked roads.
4. The drawbacks of other modified asphalt mixes could be because of the limited voids in the asphalt mix, being dense graded, limiting the accommodation of more CR and CF. The effect of higher percentages of crumb rubber and ceramic filler on gap graded aggregates and its long-term aging is recommended for further research.

DECLARATIONS

Corresponding author

Correspondence and requests for materials should be addressed to Reuben Ayodeji Bolaji; E-mail: bolajira@futa.edu.ng; ORCID: https://orcid.org/0009-0001-5539-4516

Availability of data and materials

All data generated during this study are available and can be shared upon request

Authors' contributions

Both authors contributed equally to this work. Prof. OJO: conceptualization, methodology design, project administration, resources, supervision, review and editing. RAB: laboratory investigations, analysis, original draft, review and editing. Both authors read and approved the final manuscript.

Authors’ information

Reuben Ayodeji Bolaji holds a master’s degree in transportation engineering and a bachelor’s degree in civil engineering from the federal university of technology, Akure (FUTA), Nigeria. Olugbenga Joseph Oyedepo is a professor of transportation engineering and head of department, civil and environmental engineering, federal university of technology, Akure, Nigeria.

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Competing interests

The authors declare that they have no competing interests

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