Research Article

Assessment of Reclaimed Asphalt Pavement as Recycled Aggregates for Green Roads

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Abstract

The construction of road pavements requires large amount of aggregates, which contributes to the depletion of natural resources, greenhouse gas emissions, and high cost. The use of reclaimed asphalt pavement (RAP) contributes to achieving green roads by reducing aggregate exploitation, haulage, cost, emissions and dumping. However, the presence of aged binder in RAP had limited the incorporation of RAP to a small amount in asphalt pavement. In order to achieve sustainable high content utilization of RAP, this research provides an assessment of extracted RAP aggregates with an emphasis on characterization, strength, durability, and performance. RAP samples were found to contain 6.5% aged binder and 93.5% aggregates, which were separated using a centrifuge extraction process with 100% of aggregates recovered. The gradation of RAP aggregates was sufficient for asphalt production without outsourcing virgin aggregates to complement for meeting with standards. The bulk of extracted RAP aggregates showed good physical properties, gradation and hardened qualities from the obtained aggregate impact value of 17.4% and aggregate crushing value of 19.5%, making them an effective replacement for natural aggregates in asphalt. The asphalt mixtures demonstrated acceptable volumetric properties and performance with a peak stability of 31.91 KN at 5.3% optimum bitumen content. It was observed that extracted RAP aggregate contained absorbed bitumen that contributed to higher weight, higher specific gravity and lower water absorption, which could also reduce the consumption and demand of fresh bitumen in large road projects.

Keywords: Reclaimed Asphalt Pavement, Recycled Aggregates, Green Roads, Greenhouse Gas Emissions, Eco-friendly Materials, Environmental Footprint

Introduction

The road pavement plays important role in providing safe and efficient surface for transportation. Asphalt pavement is a composite mixture of aggregates, filler, bitumen, and sometimes additives. Asphalt pavement is widely adopted due to its comfortable driving surface, exceptional performance and ease of maintenance [1]. However, non-renewable natural aggregate is heavily impacted by the construction of asphalt pavement. The increasing need for natural aggregates used in asphalt pavement construction had resulted in expensive extraction, depleted natural deposit and scarcity, leading to higher haulage costs, harmful emissions and negative environmental impacts [2,3]. Meanwhile, flexible pavement top layer known as the surface course requires maintenance during its service life, coupled with scrapped asphalt materials during reconstruction contributes to the yearly generation of reclaimed asphalt pavement (RAP) [4]. Reusing RAP for new asphalt surface course or unbound lower layers of the pavement play critical roles in achieving green roads by managing and consuming generated waste RAP materials in protecting the environment and preserving natural resource deposits [2]. For instance, the use of RAP prevented the exploitation of 82.1 million tons of bitumen and natural aggregate in the United States in 2018 [4]. However, there are no official figures on the amount of RAP created and recycled in Nigeria each year [5]. Also, RAP consist of useful aggregates and bitumen that contribute to reducing aggregate exploitation, cost, emissions, depletions, dumping, landfills, pollutions and haulage [6,7].

However, aged bitumen in RAP had loss properties from volatilization, thixotropy, oxidation, degradation, and polymerization due to the effect of temperature, oxygen, climate, light and traffic during its service life. The lighter components of bitumen had partially evaporated, causing the asphalt binder to become hard, brittle, more rigid and viscous, less ductile, and prone to cracking [8,9]. These had limited the incorporation of RAP in asphalt mixtures between 10 to 30% in several countries, to avoid poor performance [10]. Rejuvenators sometimes referred to as recycling agent, softening, or reclamation agent, is added to the aged bitumen in RAP to restore the characteristics that had been lost over time and return it to its original qualities [11]. Even at that, recovered bitumen may not be totally clean of residual RAP mineral and the dissolving solvent, that was repeatedly applied in the centrifuge extraction process, thereby leading to an impure recovered binder [12,13].

However, controlled mixture designs and adherence to state specifications can potentially increase allowable RAP content to 40 to 100% [14]. By incorporating rejuvenators or modifiers to improve performance, some studies have explored the use of higher RAP contents. The study by Khan [15] investigated RAP content in percentages of 0%, 30%, 50%, 70%, and 100%, modified with CR and waste engine oil (WEO). As the RAP percentage increased, the overall performance of all modified samples increased by 7.4% on an arbitrary scale. Likewise, mixtures with up to 100% RAP have shown satisfactory performance. Up to 2% epoxy asphalt applied to 100% RAP mixture significantly enhanced the low temperature cracking resistance at 8 °C and moisture resistance [16]. The research work of Antunes [17] evaluated the use of a high RAP inclusion rate of 75% and 25% virgin aggregate in wearing course, based on both short and long-term evaluation, with the inclusion of a crude tall oil for rejuvenation. The high RAP combinations presented comparable and better long-term by attaining an indirect tensile strength ratio value higher than 80%. Moreso, 6% improvement in overall performance was noted when RAP was partially used to replaced virgin aggregate in hot mix asphalt (HMA) containing high density polyethylene - modified bitumen [18].

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To further accommodate higher inclusion of RAP in asphalt pavement, the focus of this research is to separate useful RAP aggregates from the aged binder, and investigate the properties of RAP aggregate. The properties of RAP aggregates are investigated with the intent of application without rejuvenators or other materials. This research contributes to preserving natural aggregate resources by optimizing RAP in roads and reducing quarrying activities, thereby strengthening efforts in preserving natural heritage in line with sustainable development goal (SDG) 11.4. Also, reducing dumped RAP in the environment by recycling RAP contributes to reducing environmental pollution and degradation while promoting efficient use of resources in line with SDG 11.6. Adopting RAP as sustainable materials in road projects contributes to SDG 11.2 by reducing reliance on virgin aggregates which could make transportation more affordable, accessible and sustainable.

The findings of this research will advance knowledge of the characteristics of RAP in road construction. In particular, it will lessen reliance on virgin materials, encourage the use of circular economy concepts in the transportation industry, and stimulate the development of more environmentally friendly pavement design techniques. The study may also offer evidence-based recommendations to contractors, engineers, and legislators for maximizing RAP utilization, improving the long-term viability, economic efficiency, and environmental effects of roadway infrastructure.

Materials and Methods

Materials

The materials for this research are RAP, solvent and bitumen.

- Reclaimed Asphalt Pavement: RAP was obtained from Oda-Road construction site (Latitude 7º 12’ 18.3” N) and Longitude 5º 13’ 34.5” E) in Akure, Nigeria, shown in Figure 1.
- Solvent: 50 litres of petrol used as solvent was procured from Glofes filling station Akure, Ondo state, Nigeria.
- Bitumen: Bitumen of grade 60/70 was procured from Ondo state asphalt company limited, and the properties were determined.

Figure 1. Discarded RAP at Oda Road construction site

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RAP Characterization

The characterization of RAP samples involved cleaning, physical characterization, aggregate extraction and aggregate tests.

Cleaning: Sampled RAP from the road site were washed in water to discard unwanted materials around the RAP samples as shown in Figure 2.

(a) (b)

Figure 2. RAP samples: (a) unwashed sample (b) cleaned RAP samples

Physical characterization: RAP samples were examined physically and visually sectioned into wearing course and binder course in Figure 3. The yellow dash lines in Figure 3 points to the joint (tack coat) between the upper layer (wearing course) and the lower layer (binder course) of the RAP samples, which was necessary to separately characterize the aggregates in both layers. The total depth of each RAP sample ranged between 200 mm and 550 mm.

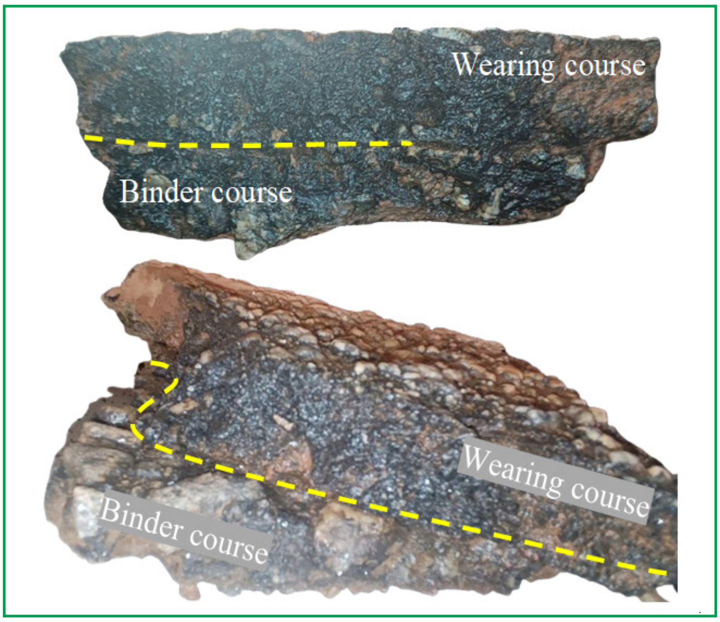

Figure 3. Visual characterization of RAP samples

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Aggregate extraction: Aggregate extraction from RAP samples included heating and solvent extraction processes as illustrated in Figure 4. In order to pass the RAP sample through the extraction process, RAP samples were disintegrated to smaller loose sizes by heating in the oven or hot plate (Figure 5). RAP samples softened within 15 minutes of heating at a temperature greater than the softening point of the aged bitumen in the RAP. Loose RAP materials were cooled at room temperature and passed through the centrifuge extraction process in accordance with ASTM D2172/D2172M-17e1 and AASHTO T164-22, by using a cold non-chlorinated and flammable solvent known as petrol (Figure 6). Through the centrifuge extraction process, aged bitumen from RAP was extracted and disposed, leaving behind the aggregates that was oven dried for further characterization.

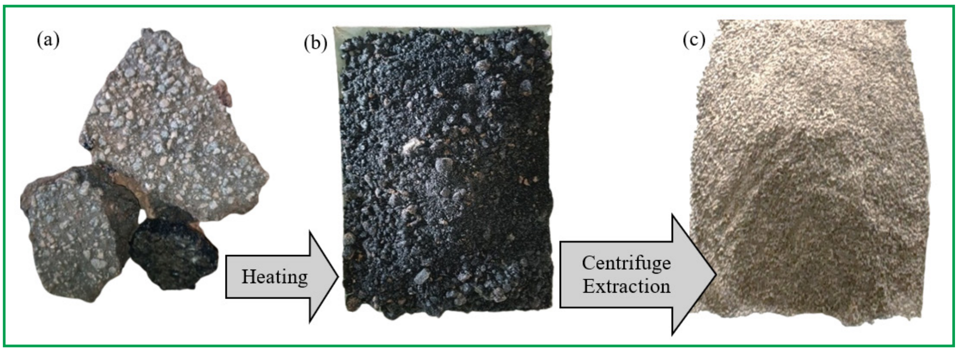

Figure 4. Summary of aggregate extraction process: (a) RAP samples (b) heated RAP (c) extracted aggregates

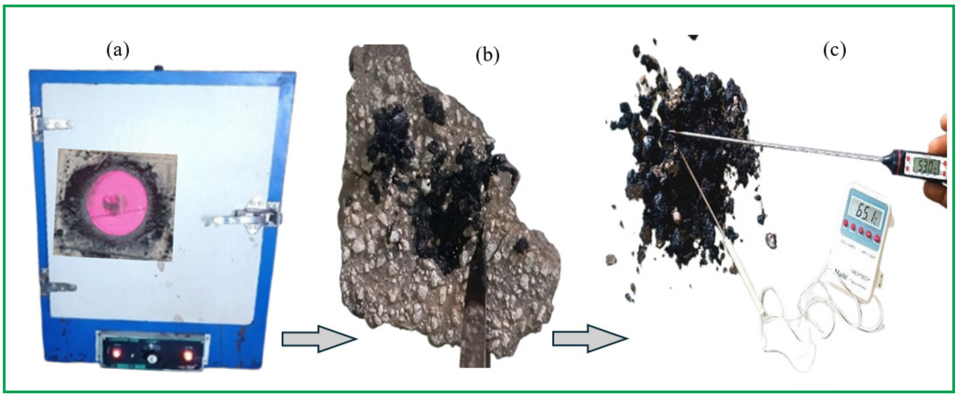

Figure 5. Heating process of RAP samples: (a) oven and hot plate (b) disintegrating RAP (c) disintegrated RAP

Aggregate Characterization

Oven dried RAP aggregate was characterized in terms of physical properties and mechanical properties. The particle size distribution was separately carried out for the extracted wearing course and binder coarse aggregates in accordance with ASTM D5444-23 and the General Specifications for Roads and Bridges (GSRB) by the Nigerian Federal ministry of power, works and housing (FMPWH) [19]. Other tests were carried out, including aggregate impact value (AIV), aggregate crushing value (ACV), Bulk (dry) specific gravity, apparent specific gravity, and water absorption.

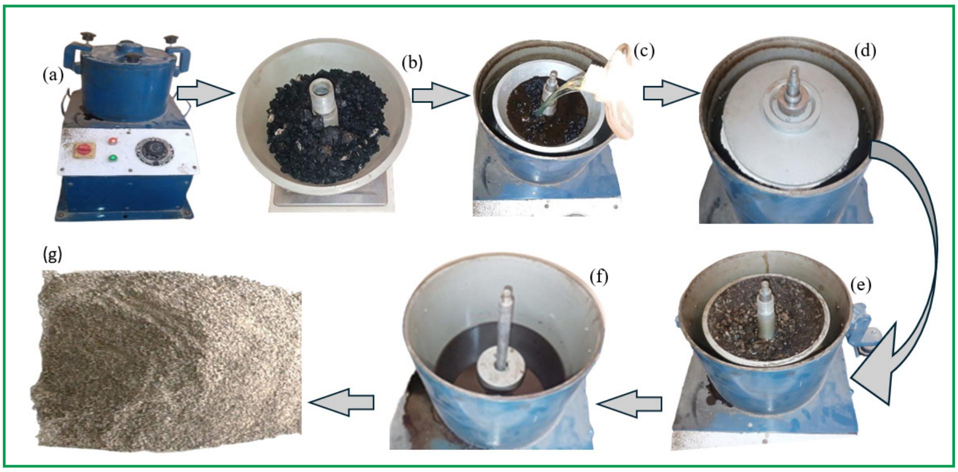

Figure 6. Centrifuge extraction process: (a) centrifuge (b) weighed RAP (c) solvent in RAP (d) covered RAP in test (e) aggregates in extraction (f) extracted bitumen plus solvent (g) final aggregates

Asphalt Production

The procedures for asphalt production encompasses blending of RAP aggregates, mix design, and specimen preparation. The exact blending of aggregates was obtained through trial mixes that was based on the particle size distribution of each aggregate fraction. The suitable percentages of each aggregate fraction which met the design range set by FMPWH GSRB [19] were determined by setting target values for each sieve and performing trial blending percentages. The mix design in Table 1 was prepared for five groups of HMA specimens at trial bitumen contents of 5.0%, 5.5%, 6.0%, 6.5%, 7.0%, in compliance with [19]. The Marshall mix design method, as outlined in ASTM D6926-20, was implemented in accordance with the mix design outlined in Table 1 to produce HMA specimens.

Table 1. Specimen mix design

Specimen	Bitumen Content		Coarse Aggregate		Fine Aggregate		RAP Filler		Total Weight
	%	(g)	%	(g)	%	(g)	%	(g)	(g)
S1	5.0	60	55	627.0	35	399.0	10	114.0	1200
S2	5.5	66	55	623.7	35	396.9	10	113.4	1200
S3	6.0	72	55	620.4	35	394.8	10	112.8	1200
S4	6.5	78	55	617.1	35	392.7	10	112.2	1200
S5	7.0	84	55	613.8	35	390.6	10	111.6	1200

Volumetric Properties of Specimens

The volumetric properties of asphalt pavement particularly specific gravity and voids, contribute significantly to the performance. These parameters are considered in the mix design at each trial bitumen content, in determining the

OBC and to produce asphalt paving mixtures that perform satisfactorily when subjected to environmental conditions and traffic loads [20].

Specific Gravity of Asphalt Mix

The specific gravity of asphalt mixtures is the ratio of its density to the density of water and are critical in determining the air voids of compacted asphalt specimens [20]. These includes bulk specific gravity (density) of compacted mix (G_{mb}) according to ASTM D2726-21 and AASHTO T166-22, theoretical maximum specific gravity (G_{mm}), and bulk specific gravity of combined aggregate (G_{sb}).

Voids

Appropriate percentage of voids are necessary in asphalt mixtures to contain extra compression from repetitive axle load without causing bleeding or instability. Too much voids paves way for more water infiltration, while too less voids leads to bleeding or flushing. Thus, the percentage of voids in asphalt pavement determines how long it lasts [20]. These includes voids in total mix (VTM) in line with ASTM D3203-22 and AASHTO T 269, voids in mineral aggregate (VMA) and voids filled with bitumen (VFB).

Marshall Stability and Flow of Specimens

Marshall stability assesses the resistance of asphalt mixtures to deformation under load, which is critical for maintaining the lifetime and performance of pavements. The corresponding flow is a parameter that measures the permanent strain and pavement resistance to plastic deformation [20]. In accordance with ASTM D6927-22 and AASHTO T245-22, the Marshall stability and flow at trial bitumen contents were assessed with a digital Marshall stability tester shown in Figure 7.

Figure 7. Marshall stability test

Optimum Bitumen Content

The Optimal Bitumen Content (OBC) is the amount of bitumen in an asphalt mix that makes the road surface last the longest, stay stable, and easy to work on. The OBC for the each asphalt mix was calculated using Equation 1, according

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to Asphalt Institute [20]. Where β,γ,φ are the bitumen content at peak stability, peak G_{mb}, and 4% VTM, respectively.

$$OBC\ (\%) = \frac{\beta + \gamma + \varphi}{3} \quad (1)$$

Results and Discussion

Properties of Fresh Bitumen

The bitumen characteristics in Table 2 achieved the requirements of ASTM standards as required for good pavement performance. It demonstrates a good combination of binding qualities, durability, and flexibility to changing environmental and traffic circumstances. The bitumen properties indicated good adhesion, elongation, sufficient fluidity, good workability, less susceptibility to change in tempertature and safe working temperature when heated.

Table 2. Properties of Bitumen

Tests	Units	Results	Test Method	Spesifications
Penetration	0.1 mm	65	ASTM D5-20	60 –– 70
Ductility	cm	106	ASTM D113-17	Min. 100
Flash point	˚C	334	ASTM D92-18	Min. 250
Fire Point	˚C	375	ASTM D92-18	-
Softening Point	˚C	55.4	ASTM D36-14	49 –– 56
Specific Gravity	g/cm^3	1.017	ASTM D70-18a	0.97 –– 1.06

Aggregates Extraction

The proportion of extracted aggregates is presented in Figure 8. The wearing course and the binder course contained 6.5% aged binder content by weight of total mix which was within the specifications of FMPWH GSRB [19]. A sample test showed that 1269.9 g of dry aggregates was recovered from 1358.1 g of RAP. This indicated one hundred percentage (100%) aggregate recovery from RAP samples, as the aggregates occupied 93.5% of the total weight and the aged binder took 6.5% of the total RAP weight.

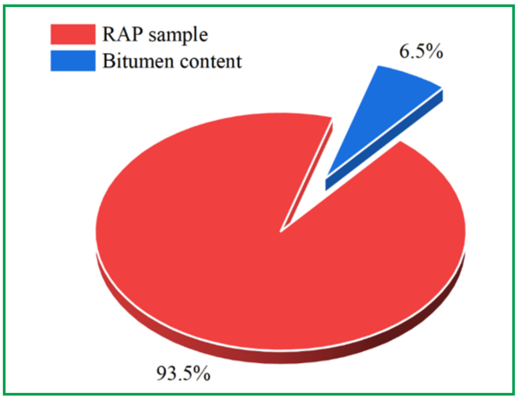

Figure 8. Aggregate and binder proportion in RAP

RAP Aggregates Gradation

The gradation curves for the wearing course and binder course are presented in Figure 9 and Figure 10 respectively. The nominal maximum aggregate size for RAP wearing course was ⅜ ″ (9.5 mm) and the maximum aggregate size was ¾ ″ (19 mm). Wearing course aggregates were well graded, containing aggregate which retained on each sieve within the limits of the Nigerian FMPWH GSRB [19]. On the other hand, nominal maximum aggregate size of the binder course was 1″ (25 mm), while the maximum aggregate size was 1″ (25 mm). Although, the RAP binder course contained aggregate retaining on each sieve, it however had more coarse aggregates above the specified limits. The aggregates in the RAP layers contained distributed aggregates across different sieve sizes in larger or lower proportion, with outlier aggregate sizes which were excluded and discarded. This is necessary to ensure that the right aggregate sizes were utilized in accordance to the set specifications of the layer which these aggregates were to be applied to in construction.

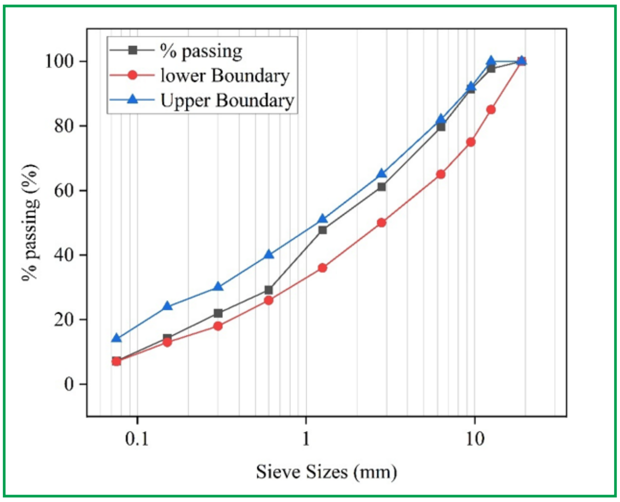

Figure 9. Gradation curve for RAP wearing course

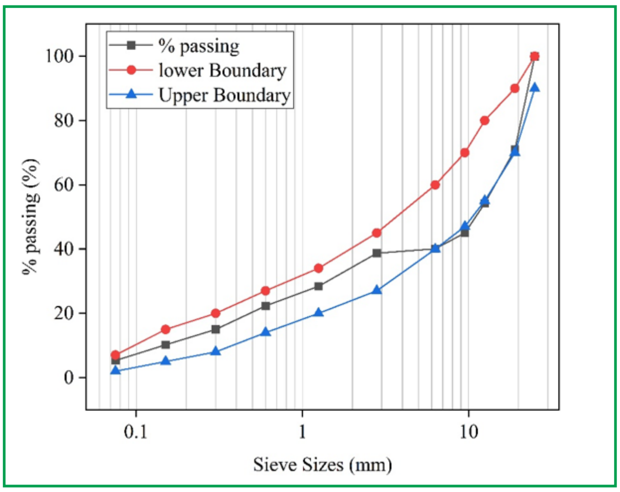

Figure 10. Gradation curve for RAP binder course

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RAP Aggregate Properties

The qualities of aggregate in Table 3 demonstrated potential resilience to breaking in the presence of environmental factors and traffic. RAP coarse aggregate remained strong and tough for reuse in road construction as ACV and AIV were less than 30 % as required by FMPWH GSRB [19]. This further showed that repetitive wheel load which RAP coarse aggregates had been subjected during its service life had no effect on the hardness of the RAP aggregate. The mechanical properties of these aggregates are unaffected by the aging of the binder, of which the retained strength of these aggregates qualified them for reapplication for both bound and unbound layers in asphalt pavement. After extraction, the aggregate appeared darker with strands and spots of aged bitumen permanently sticked to the surface. Also, extracted aggregate consist of aged bitumen that was absorbed during its former mixing process and cannot be accessed during extraction. These occupied part of the voids in aggregate and protected the aggregates from chemical weathering and water infiltration. These characteristics makes RAP aggregate more durable or comparable to virgin aggregates when reused. Additionally, the absorbed bitumen in aggregate contributed more to higher weight, higher specific gravity and lower water absorption. The specific gravities and rates of absorption of aggregates seem to produce a balanced asphalt mix free from the possibility of bleeding or brittleness.

Table 3. Properties of RAP aggregates

Properties	Values	Limits	Standards
RAP coarse aggregates			
AIV (%)	17.4	Max. 30	BS 812 – 112
ACV (%)	19.5	Max. 30	BS 812 – 110
Bulk (dry) specific gravity	2.658	-	AASHTO T85-22
Apparent specific gravity	2.692	-	AASHTO T85-22
Water absorption (%)	0.5	Max. 0.5	AASHTO T85-22
RAP fine aggregates			
Bulk (dry) specific gravity	2.669	-	AASHTO T84-22
Apparent specific gravity	2.718	-	AASHTO T84-22
Water absorption (%)	0.57	-	AASHTO T84-22
RAP filler			
Specific gravity	2.769	-	AASHTO T84-22
% Passing 75 µm	100	85 - 100	ASTM D242-19

Blended Aggregates

The gradation curve of the blended materials in respect to the limits established by FMPWH GSRB [19]. is presented in Figure 11. The proportions of RAP coarse aggregates, fine aggregates and filler that produced the closest match with the target values were respectively 55%, 35% and 10% (by weight of dry aggregates). The blend of aggregates produced a balanced distribution of sizes that are adequate for good load carrying capacity, design voids, and stability under traffic. The gradation of RAP samples was sufficient for asphalt production without outsourcing virgin aggregates to complement for meeting with standards. This showed that RAP aggregates are adequate for use in road layers with little or no addition of virgin aggregates.

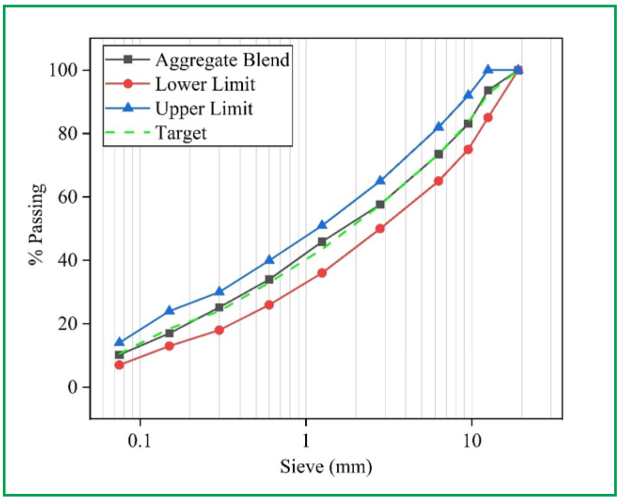

Figure 11. Blended aggregates

Volumetric Properties of Asphalt

Specific Gravities

The G_{mb} of compacted asphalt mixture is the ratio of the total mix density (including aggregate, binder and air voids) to the density of water. It ratios aggregate and bitumen mass, to the volume occupied by aggregate, bitumen and air voids [20]. On the other hand, G_{mm} is the specific gravity of the total materials in the total mix that are coated with binder (without air voids). It is the ratio aggregate and binder mass, to the volume occupied by the aggregate and binder (excluding air voids) [20]. Meanwhile, the bulk specific gravity of combined aggregate present in the total mix (G_{sb}), is the ratio of the density of asphalt mixture (excluding binder) to the density of water under constant temperature [20]. The bulk specific gravity (density) of compacted mix (G_{mb}) and theoretical maximum specific gravity (G_{mm}) are presented in Figure 12. Also, bulk specific gravity of combined aggregate (G_sb) was 2.676 at all bitumen contents. The asphalt mixes were denser due to the inherent absorbed binder in the aggregate pores. As the bitumen percentage in an asphalt mixture increased, the G_{mb} and G_{mm} decreased because bitumen has a lower specific gravity than aggregates. Consequently, a reduced G_{mb} and G_{mm} results from the decreasing density of asphalt specimens when lighter constituents (bitumen) replaced denser constituents (aggregates).

Voids

VTM, VMA and VFB of produced asphalt mixes at each trial bitumen contents are presented in Figure 13. Voids in Total Mix (VTM): The VTM of asphalt mixtures are the percent volume of air voids between filmed aggregate, in respect to the volume of the total mix [20]. The voids within the asphalt mixture decreased as the percentage of bitumen increased, because more binder filled

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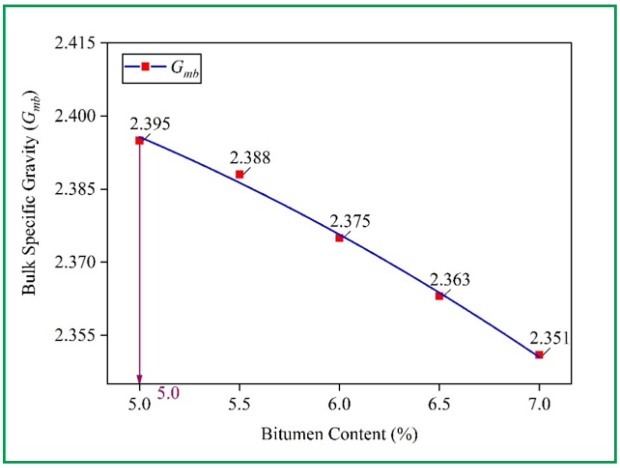

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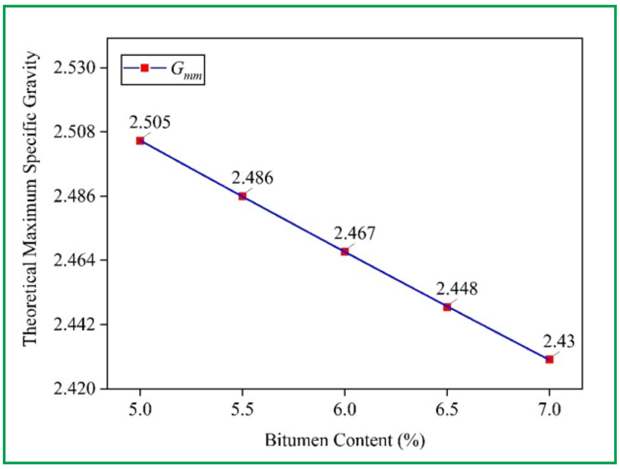

(b)

Figure 12. Specific gravities of asphalt specimens: (a) G_{mb} (b) G_{mm}

the spaces to become denser and compact. The asphalt mixes are dense graded in accordance with ASTM D3203-22 since the VTM for all mix types is less than 10%. In accordance with FMPWH GSRB [19], specimens contained 3% to 5% VTM for required for versality and to handle bitumen expansion and stiffening due to changes in temperature, without compromising performance or increasing moisture susceptibility.

Voids in Mineral Aggregate (VMA): VMA refers to the voids occupied by air and bitumen (exclusive of the volume filled by aggregate), in relation to the volume of the total mix [20]. The fact that VMA increased with more bitumen showed that added binder made particles more slippery and coated, which changed their arrangement and resulted in an aggregate structure that had room between the grains. VMA at all bitumen content exceeded the minimum 14% specified Asphalt Institute (2014) specified by Asphalt Institute [20].

Voids Filled with Bitumen (VFB): The VFB is the VMA that is filled with effective binder [20], and it measures the effective bitumen film between aggregates, in which excess bitumen between aggregate tends to reduce the contact interaction between aggregate, while insufficient bitumen between aggregate

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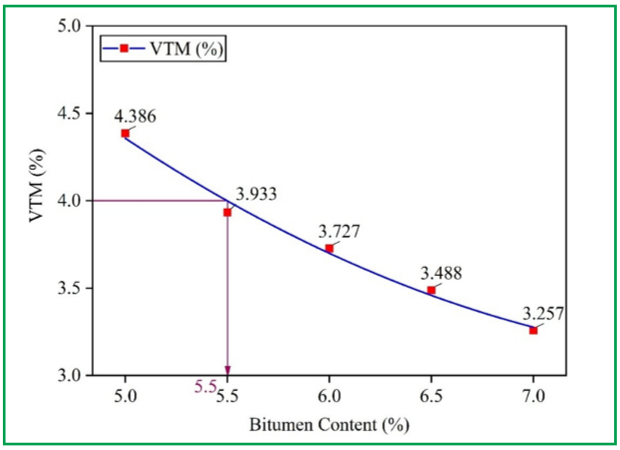
reduces bonding. Increasing VFB indicated reduction in air voids as bitumen content increased. Improvements in resistance to rutting and moisture damage may result from this. Also, adhering to the 72% to 85% thresholds established by the FMPWH GSRB [19] lowers the possibility of fatigue and cracking risk.



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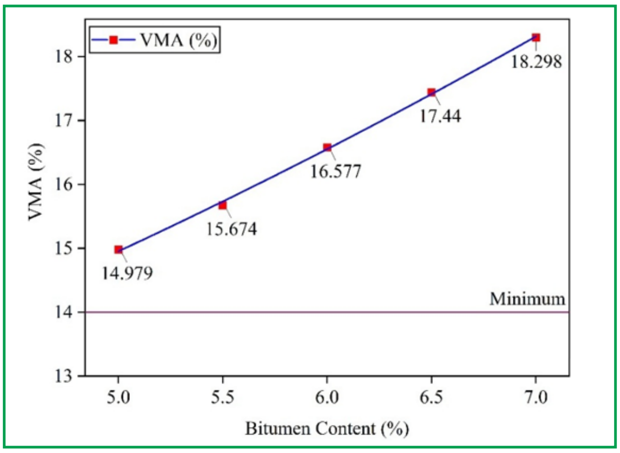

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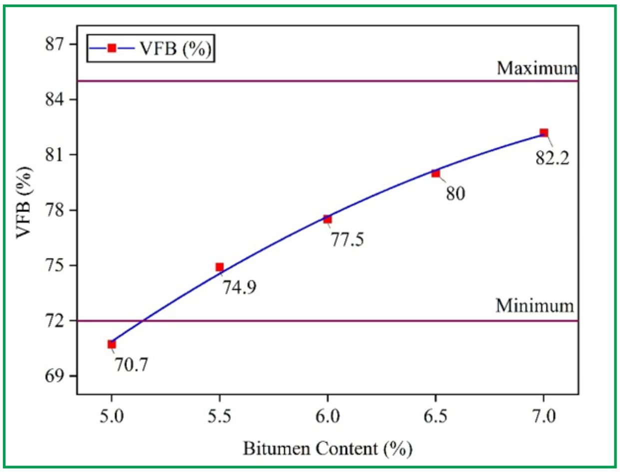

(c)

Figure 13. Voids: (a) VTM (b) VMA (c) VFB

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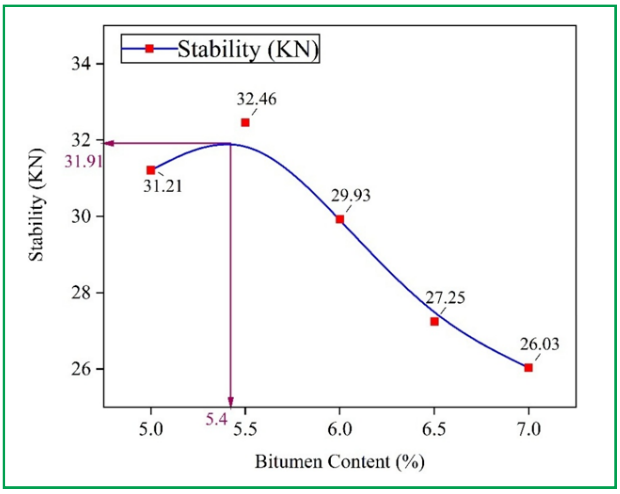
Marshall Properties

The graphs of Marshall stability and Marshall flow are presented in Figure 14. The Marshall stability of the asphalt specimens exceeded the minimum requirement of 3.5 KN as set by the FMPWH GSRB [19] for wearing course asphalt concrete. Increased bitumen content initially led to better cohesion, improved aggregate coating and lubrication until the bonding and internal friction peaked 31.91 KN at 5.4 % bitumen content. At this point, strength and flexibility are balanced in withstanding cracking and rutting in response to temperature variations and traffic loading. Then, as the bitumen increased, excess bitumen functioned more as a lubricant rather than an adhesive by forming thicker binder films around aggregates, which potentially made asphalt specimen less resistant to deformation under loads. Also, the corresponding flow value was within the specified flow limits of 2 to 4 mm for compacted wearing course asphalt, which showed a balance of ductility and stability within the skeleton.



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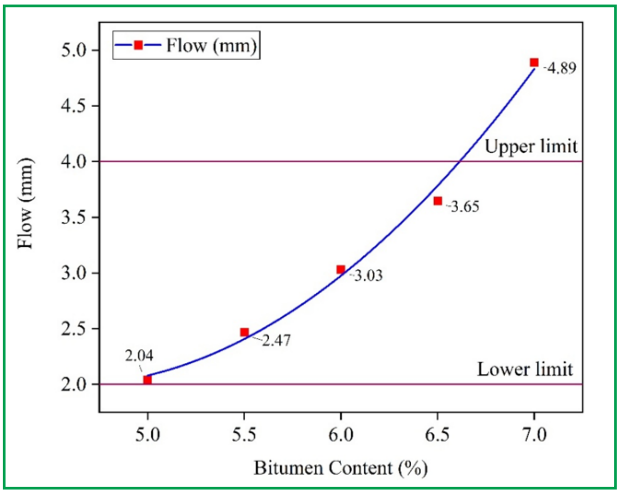

(b)

Figure 14. Marshall properties (a) Stability (b) Flow

Optimum Bitumen Content (OBC)

The respective bitumen contents at peak stability (β), peak Gmb (γ), and 4% VTM (φ), were 5.4%, 5.0% and 5.5%. Thus, the overall OBC for the asphalt mixes was evaluated to be 5.3%. This OBC agrees with the binder content at which the most acceptable Marshall and volumetric properties of this asphalt mix was achieved. The amount of fresh binder necessary to achieve target mix qualities may be less than that required in a wholly virgin mix because of the absorbed old binder in RAP aggregates, which may be active during hot mixing. In that sense, using RAP aggregates could also reduce the consumption and demand of fresh bitumen in a small way, which could cumulate to significant reduction in large road projects.

Conclusion

The assessment of reclaimed asphalt pavement as recycled aggregates for green roads revealed good physical properties, gradation and hardened qualities as an effective replacement for natural aggregates in asphalt.

Key findings

1. RAP samples were found to contain 6.5% aged binder and 93.5% aggregates, which were separated using a centrifuge extraction process with 100% of aggregates recovered.
2. The aggregate impact value of 17.4% and aggregate crushing value of 19.5% demonstrated the viability of RAP aggregates as strong and tough materials for bound and unbound layers of road pavements. These qualities reveal the potential resilience to breaking in the presence of environmental factors and traffic.
3. Absorbed bitumen present in RAP aggregates and strands of bitumen remaining at the aggregate surface after extraction, could hinder chemical weathering and reduce water absorption, which makes these aggregates more durable and comparable to virgin aggregates.
4. RAP samples contained distributed aggregates sizes that produced a balanced distribution of sizes that are adequate for good load carrying capacity, design voids, and stability under traffic. The gradation of RAP samples was sufficient for asphalt production without outsourcing virgin aggregates to complement for meeting with standards. This showed that RAP aggregates are adequate for use in road layers with little or no addition of virgin aggregates.
5. The asphalt mixtures demonstrated acceptable volumetric properties and performance with a peak stability of 31.91 KN at 5.3% optimum bitumen content, where resistance to cracking and rutting caused by temperature changes and traffic loads was achieved by balancing strength and flexibility.
6. It was observed that extracted RAP aggregate contained absorbed bitumen that contributed to higher weight, higher specific gravity and

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lower water absorption, which could also reduce the consumption and demand of fresh bitumen in large road projects.

7. The development of a more economical and robust process for RAP aggregate extraction is recommended for further research. The centrifuge extractor in this study could only be used for limited RAP samples in the laboratory experiment. A large plant that can be used with locally available solvent is necessary to process large RAP samples for road projects.

List of Abbreviations

RAP	Reclaimed Asphalt Pavement
SDG	Sustainable development goals
GSRB	General specifications for roads and bridges
FMPWH	Federal ministry of power, works and housing
ASTM	American society for testing and materials
AASHTO	American association of state highway and transportation officials
BS	British standard
AIV	Aggrgegate Impact Value
ACV	Aggregate Crushing Value
HMA	Hot mix asphalt
VTM	Voids in total mix
VMA	Voids in mineral aggregate
VFB	Voids filled with bitumen
OBC	Optimum bitumen content

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Conflicts of Interest

The authors declare no conflicts of interest

Author Contributions

Reuben Ayodeji Bolaji: laboratory investigations, analysis, original draft, review and editing. Both authors read and approved the final manuscript. **Olugbenga Joseph Oyedepo:** conceptualization, methodology design, project administration, resources, supervision, review and editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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