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Suitability of Stone Dust as an Alternative Aggregate in Asphalt Mixtures Using Rothfuch's Method of Aggregate Combination

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Abstract

The increase in pollution across the globe is one crucial area requiring mitigation. The bye product of quarries can pose great health and environmental risks. Construction industries in Nigeria heavily relies on conventional asphalt aggregate for construction of road pavements. This is one area of interest as mineral fillers and different aggregate gradations have a great effect on the mechanical property of asphalt concrete pavements. Stone dust is obtained from quarries across the country is relatively cheaper than the conventional river sand which is becoming depleted and scarce. The use of stone dust is a major initiative on developing the infrastructures such as express highways, power projects, ports, and harbors, to meet the requirements of globalization, in the construction of pavements and other structures concrete plays the key role and a large quantum of concrete is being utilized in every construction practices. The use of stone dust in concrete not only improve the quality of concrete but also conserve the natural river sand for future generations. In the present investigation, an evaluation on the methodology of aggregate is considered using Rothfuch method.

Keywords: Stone Dust, Asphalt Aggregate, Optimum Replacement, Waste and Recycled Materials, Optimum Replacement, Filler, Bituminous Material, Rheology, Morphology

INTRODUCTION

Background to the Study

The construction and maintenance of road infrastructure have always been of paramount importance in modern society, playing a pivotal role in economic development, mobility, and overall quality of life. At the heart of these transportation networks, asphalt pavements are the unsung heroes that bear the burden of millions of vehicles every day. Therefore, the performance of asphalt pavements is not merely a technical concern; it is an economic and societal imperative. Asphalt mixtures, which constitute the top layers of asphalt pavements, are composed of aggregates and a bituminous binder. In recent times, the level of natural resources has depleted and is gradually diminishing due to the development of mining industries (Geremew et al., 2022) [1]. A typical pavement structure consists of the surface course, binder course, base, sub-base, capping and the subgrade (Thom, 2008) [2].

Surface course (or **wearing course**)–*asphalt*

Binder course (or **basecourse**)–*asphalt*

Base–*asphalt*, *hydraulically-bound* (e.g. concrete), or *granular* (often in more than one layer)

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Sub-base–*hydraulically-bound* or *granular*

Capping (or **lower sub-base**)–*hydraulically-bound* or *granular* (only used over poor subgrade; often in more than one layer)

Subgrade (or **substrate**)–*soil*

In order to spare the cost speculation and to increase the service life of asphalt pavement, the utilization of stone dust can be employed to meet the needs of the construction industry (Figure 1).

The selection and proportioning of aggregates are crucial determinants of the performance of these mixtures. Asphalt engineers and researchers have consistently sought innovative ways to optimize aggregate combinations to enhance critical properties such as stability, durability, and rutting resistance. Aggregates in hot mix asphalt (HMA) can be divided into three types according to their size: coarse aggregates (retained on sieve 4.75 mm), fine aggregates (passing sieve 4.75 mm retained on sieve 0.075 mm), and filler (passing sieve 0.075 mm).

In this quest for better asphalt mixtures, attention has turned to the potential benefits of using stone dust. Stone dust, a byproduct of stone crushing and quarrying operations, has emerged as a material with significant potential in the domain of asphalt technology. As the global construction industry increasingly gravitates toward sustainable practices and the reduction of waste, stone dust's suitability as an alternative or supplementary aggregate in asphalt mixtures has attracted considerable interest. This interest is further intensified by its cost-effectiveness compared to traditional aggregates. Innovations requiring the use of stone dust in asphalt aggregate as a filler material is known by scholars and researchers as the modified asphalt mix consisting of bitumen, coarse aggregate, fine aggregate and filler (Wang et al., 2020) [3]. This methodology might someday replace the conventional hot mixed asphalt concrete as a low cost solution which will lead to economic growth and development. Also, it offers the opportunity to explore the innovation of renewable supply. The incorporation of stone dust in asphalt mixtures, however, is not without its complexities. It is imperative to understand how stone dust affects the fundamental properties of asphalt, including its workability, strength, and long-term durability. Additionally, it is essential to consider how stone dust interacts with other aggregates within the mixture and how this interplay influences the final performance of the asphalt pavement.

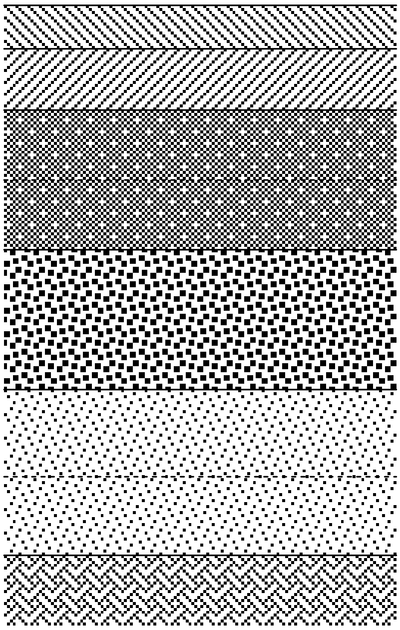

Figure 1. Constituent layers of a typical pavement (Thom, 2008) [2].

The Rothfuch's method of aggregate combinations offers a systematic approach to scrutinize these complex interactions. This method of aggregate blending is used when a number of materials have to be mixed together for obtaining appropriate gradation. Developed as a tool for analyzing the impact of various aggregates in asphalt mixtures, the Rothfuch's method has been widely adopted in the field of pavement engineering. It is a reasonably quick, accurate and simple method, and is used, for design of cement concrete mixes, bituminous mixes and granular mixes. It provides a structured framework for evaluating aggregate blends and their potential effects on the properties of the asphalt mixture.

Statement of the Problem

The environmental pollution from the continuous crushing of stones in the quarries might pose as a major issue in future concerns as stone dust is an efflorescent material capable of drying the moisture from the air (Suman and Srivastava, 2015) [4]. Economic conditions have also withheld the construction of roads leading to accidents and deaths along major cities in the country. With the depletion of the scarce river sand, a need for an alternative granular material for hot mix asphalt. The Rothfuch's method currently used in asphalt production can be utilized to create an ecological solution to end the plummeting concerns in this modern world. As this can possibly reduce environmental pollution, accidents and deaths along major cities in the country.

Aim and Objectives of the Study

The aim of this study will be to evaluate the performance of stone dust on the properties of asphalt mixtures using Rothfuch's method of aggregate combination.

The specific objectives will include; To;

1. Determine the optimal proportion of stone dust in asphalt mixtures,
2. Determine the mix design properties of stone dust modified asphalt mixtures,
3. Determine the durability of the stone dust modified asphalt mixtures in terms of retained stability index (RSI) and tensile strength ratio (TSR) over a specified period, and
4. Conduct a life data or survival analysis on the selected durability indices of modified asphalt concretes.

Significance of the Study

This project explores the potential use of stone dust in infrastructural development in Nigeria citing the heavy reliance on river sand as granular materials for hot asphalt mix production. This study will address the areas of environmental pollution from the continuous accumulation of stone dust and proffer solutions that will aid in the reduction of accidents, deaths and the improvement of the economic condition of the country through infrastructural development. The study will also serve as a reference material for academic purposes as it will serve as guide to future researchers on the use of stone dust for asphalt concrete production [5–8].

Scope and Limitations of the Study

This project focuses on an effective methodology of integrating stone dust into hot asphalt mix for the construction of asphalt pavements in regions across the country.

LITERATURE REVIEW

Related Works on Asphalt Mix

Wang et al. (2020) [3] studied the effects of different coarse aggregate surface morphologies on cement emulsified asphalt adhesion. In their research the explored four kinds of coarse aggregate, including diabase, basalt, steel slag and recycled aggregate using cement and asphalt as a binder thus developing a methodology to study the adhesion and morphology between coarse aggregate and asphalt.

Limitation: According to Wang et al. [3] employed the use of different aggregates in studying their effects on asphalt concrete performance. Stone dust was not considered as an aggregate.

Gedik (2021) [9] investigated the use of a blend of crushed stone dust (CSD) and recycled waste glass (RWG) in asphalt pavement construction. In his research, the mechanical property of recycled glass and crushed stone was examined using Marshall stability test, indirect tensile stiffness modulus, indirect fatigue test and the dynamic creep test. Also the use of conventional methodology such as the penetration, softening point, penetration index and ductility and the rheological methodology such as the rotational viscosity and the dynamic shear rheometer) was employed to evaluate the properties of RWG and CSD mastics and the use of electron microscope to scan the microstructure of the mix inspecting for morphological impacts of RWG.

Limitation: According to Gedik [9] did not consider the use of the Rothfuch's method in combining the aggregates. Durability indices such as retained strength index and tensile strength ratio were not considered.

Pourtahmasb and Karim (2014) [10] investigated the use of recycled concrete aggregate in stone mastic asphalt (SMA) and hot mix asphalt mixtures (HMA) using Granite aggregates, 80/100 penetration grade bitumen, hydrated limestone powder, oil palm fiber, and recycled concrete aggregates (RCA). The resulting mixture was analyzed and tested to obtain results. The outcome of their result is presented in Table 1 and Table 2.

Limitation: Table 1,2 did not consider stone dust as part of the aggregates for SMA and HMA production. Durability indices such as retained strength index and tensile strength ratio were also not considered.

Table 1. ANOVA outcomes for SMA test results.

Tests	SS	MS	*F*	*P*-value
OAC	25.059	2.088	9.44	<0.01
Stability	151.35	12.612	81.779	<0.01
Flow	84.714	7.06	325.708	<0.01
Density	0.051	0.004	181.1	<0.01
VTM	0.094	0.008	6.163	<0.01
VMA	11.539	0.962	228.397	<0.01
VFA	23.068	1.922	32.35	<0.01
Resilient modulus	5813509.59	484459.1	217.121	<0.01
Rut depth	161.43	13.452	91561.39	<0.01
Rut rate	28.854	2.405	8863.566	<0.01

Source: Pourtahmasb and Karim, 2014

Table 2. ANOVA outcomes for HMA results.

Tests	SS	MS	*F*	*P*-value
OAC	17.387	1.449	5.883	<0.01
Stability	159.723	13.31	122.565	<0.01
Flow	58.083	4.84	90.755	<0.01
Density	0.073	0.006	84.631	<0.01
VTM	0.088	0.007	6.972	<0.01
VMA	17.833	1.486	89.263	<0.01
VFA	32.013	2.668	36.321	<0.01
Resilient modulus	4502850	375237.5	144.752	<0.01
Rut depth	134.489	11.207	87945.32	<0.01
Rut rate	4.777	0.398	1587.373	<0.01

Source: Pourtahmasb and Karim, 2014

Table 2. Material composition.

Material	Main Properties	Main Information about Material
Recycled asphalt	granulometric composition, bitumen content	78% of RAP is used +6% added filler
Bitumen emulsion	bitumen content, setting time	cationic stable emulsion C 60 B 4 (60% bitumen)
Cement	chemical composition, mineralogical composition, bulk density, specific surface	CEM I 42.5R (PC)
Zeolite	chemical composition, mineralogical composition, pozzolanic activity class	Particle size < 0.125 mm, Blaine surface area = 8292.97 cm^2/g, Specific weight = 2.386 g/cm^3
Bakelite	softening temperature, pozzolanic activity class	Particle size <0.125 mm, Loss on ignition = 98%
Slag	chemical composition, mineralogical composition, pozzolanic activity class	Particle size < 0.045 mm, Blaine surface area = 2798.90 cm^2/g, Specific weight = 2.689 g/cm^3
Fly ash	chemical composition, mineralogical composition, pozzolanic activity class	Particle size < 0.045 mm, Blaine surface area = 10,212.47 cm^2/g, Specific weight = 2.313 g/cm^3

Source: Zavadskas et al., 2022

Table 3. Asphalt binder quality test.

Test	Test method ASTM	Test result	Specification as per ERA, 2013
Penetration	ASTM D5	63.06	60–70
Ductility	ASTM D113	96.33	Min. 50
Softening point	ASTM D36	51.4	46–56
Flash point	ASTM D92	293.67	Min. 232
Fire point	ASTM D92	353.5	Min. 280
Specific gravity	ASTM D70	1.040	—

Source: Geremew et al., 2022

Zavadskas et al. (2022) [11] investigated the use of application of wasted and recycled materials for production of stabilized layers of road structures using cement and bitumen emulsion, fly ash, zeolite, slag, and Bakelite into seven mixtures and tested in order to increase sustainability. Their outcome is shown in Table 3.

Limitation: Table 3 did not consider stone dust as part of the aggregates for asphalt production. Durability indices such as retained strength index and tensile strength ratio were also not considered.

Geremew et al. in 2022 [1] investigates the performance characteristics of hot mix asphalt mixture using crushed stone aggregate (coarse, fine), bitumen (60/70 penetration grade), mineral filler (crushed stone dust and belessa kaolin dust). The outcome of the study is presented in Table 4.

Limitation: Table 4 did not consider the use of the Rothfuch's method in combining the aggregates. Durability indices such as retained strength index and tensile strength ratio were not considered.

MATERIALS

1. B60/70 penetration graded bitumen will be sourced from black market traders and will be used as binder in this study.
2. Coarse and fine aggregates and crushed stone dust (CSD) are the aggregates to be used in this study which will be obtained from any quarry in Nigeria.

METHODS

Specimen Preparation

1. CSD will be sourced from stone quarry aggregates.
2. A digital high shear mixer will be used for blending.
3. Samples will be allowed to cool, and phase separation will be checked.
4. Control neat bitumen will also undergo the same process.

Asphaltic Mixtures

1. Asphaltic mixtures were prepared following the standard Marshall method (ASTM D1559).
2. Standard Marshall briquettes will be prepared for each mixture type with different binder contents.
3. The mixture components were blended and compacted at specified temperatures for further testing.

Test Methods for Crushed Stone Dust

Oxide composition of the Stone dust

The oxide composition of the stone dust will be evaluated using the Energy Dispersive X-Ray Analysis (EDX).

Conventional Binder Tests

a. The penetration test measured as depth in tenths of millimeters to which a standard sewing needle vertically penetrated the bitumen in 5 seconds with a 100 g weight will be carried out at room temperature.
b. The ring and ball test (softening point test) to assess the temperature at which the binder reached a certain softness will be determined.
c. Ductility test will be measured for standard-sized briquettes at 25°C.

Mechanical and Volumetric Properties

Mechanical properties (Marshall stability, and flow) and volumetric properties (voids in mineral aggregate (VMA), voids filled with binder (VFB), air void content (Va), and dry bulk density (DBD)) were determined for asphaltic mixtures containing CSD.

Stability and Flow Tests

The Marshall Stability and flow test will be carried out in accordance to ASTM D1559 (1989). The stability of a test specimen is the maximum load required to produce failure when the specimen is preheated to a prescribed temperature placed in a special test head and the load is applied at a constant strain (50.8 mm per minute).

Indirect Tensile Strength Test (Split Cylinder Test)

The splitting cylinder test will be used as the measure of the indirect tensile strength in this study. This splitting cylinder test will be conducted in accordance to ASTM C496 (2011).

Volumetric/Density-void Analysis

The density void analysis will involve the determination of the following parameters of the compacted asphalt mixtures; percent voids in compacted mineral aggregate (VMA), percent voids in compacted paving mixture (P_{av}) and percent air voids filled with bitumen (VFB). VMA was determined using Equation (1), P_{av} was calculated using Equation (2) and VFB was determined using Equation (3).

$$VMA = 100 - \frac{G_{bcm} * P_{ta}}{G_{bam}} \quad (1)$$

$$P_{av} = \left(\frac{G_{mm} - G_{bcm}}{G_{mm}}\right) \times 100 \quad (2)$$

$$VFB = \left(\frac{VMA - P_{av}}{VMA}\right) \times 100 \quad (3)$$

Where, P_{ta} represent the aggregate percent by weight of compacted specimen.

Performance Measurements

Retained Stability Index

Durability of asphalt samples will be measured using retained stability index (RSI) after period of submergence according to Ali (2013) as presented in Equation (4).

$$RSI = \frac{S_i}{S_o} \times 100 \quad (4)$$

Where;

RSI = retained strength index

S_i = stability after immersion in water at time t_i or stability of conditioned specimen

S_o = stability before immersion in water or stability of unconditioned specimen

Tensile strength ratio (TSR)

The moisture susceptibility of prepared samples will be determined through measurement of tensile strength ratio (TSR). Tensile strength ratio is evaluated by comparing the tensile strength of samples at wet and dry condition (Equation 5).

$$TSR = \frac{\sigma_{Tw}}{\sigma_{Td}} \times 100 \quad (5)$$

Where;

TSR = Tensile strength ratio

σ_{Tw} = Tensile strength of conditioned specimen

σ_{Td}= Tensile strength of unconditioned specimen

Balanced-Area Method by Rothfuchs

The Balanced-Area method, developed by Rothfuchs, is a well-established approach for analyzing aggregate sieve size distributions. Below, are the outlined steps of this method:

a. *Diagonal Line:* The process will commence by drawing a diagonal line from the origin of the coordinates to the upper right corner of the diagram, connecting point I to point III**.**
b. *Percentage Passing:* The percentages passing each sieve size will be determined based on the midpoint of the specification limits. These percentages will be fixed on the y-axis. For example, if the sieve size is 12.5 mm, the percentage passing will be 78%. This process will be repeated for other sieve sizes.
c. *Sieve Size Scale:* A horizontal line will be drawn from the points determined in step 2 to the diagonal line and extended down to the x-axis. The corresponding sieve size numbers will be placed on the x-axis at these locations, establishing a relative scale on the x-axis.
d. *Sieve Size Distribution:* The sieve size distribution for all aggregate fractions will be plotted onto the diagram.
e. *Balanced Lines:* For each aggregate fraction, lines that create equal areas above and below them will be selected. For instance, line fd will be drawn for aggregate A, line hg for aggregate B, and line rm for aggregate C. Each line will be represented by two points, one at 100% (e.g., point f for line fd) and the other at 0% (e.g., point d for line fd).
f. *Connecting Lines:* The 0% point of one line (e.g., line fd) will be connected with the 100% point of another line (e.g., line hg). This new line, such as line fh, will intersect the diagonal line I II at point n. This procedure will be repeated for other lines, leading to the determination of points n and o.
g. *Aggregate Contributions:* Based on points n and o, the contributions of different aggregates will be calculated.

This method relies on selecting lines with minimum balanced areas around each one. Equal areas above and below each line are key to the analysis. To ensure accuracy in computing these areas, computer-aided design software, such as AutoCAD, can be applied for plotting and area calculations. The final graph illustrates the sieve size distribution of sample one aggregates. The Balanced-Area method by Rothfuchs provides a systematic approach for analyzing aggregate distributions, aiding in the characterization of different aggregate fractions.

CONCLUSION

This article has addressed the possibilities of the use of stone dust as an aggregate in asphalt mix which is instrumental for the further improvement by integrating methodologies relevant to evaluate its use in future works. Using Rothfuch's approach as a framework, it provides concluding remarks on its general suitability and potential for widespread adoption.

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