Performance Evaluation of Magnesia-Type Refractory Brick Waste as Complete Replacement for Fine Aggregate and Filler in Asphalt Concrete Wearing Course Mixtures

Syukuriah Syukuriah
Department of Civil Engineering, Faculty of Engineering, Universitas Hasanuddin, Indonesia
syukuriahkatjo@unsulbar.ac.id (corresponding author)

Muralia Hustim
Department of Environmental Engineering, Faculty of Engineering, Universitas Hasanuddin, Indonesia
muraliahustim@ft.unhas.ac.id

Wihardi Tjaronge
Department of Civil Engineering, Faculty of Engineering, Universitas Hasanuddin, Indonesia
tjaronge@yahoo.co.jp

Rita Irmawaty
Department of Civil Engineering, Faculty of Engineering, Universitas Hasanuddin, Indonesia
Rita_irmaway@yahoo.co.id

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ABSTRACT

Infrastructure development has been rapidly increasing in recent times, and the use of waste materials as aggregates in this process has positively impacted regional and national economies. This study investigates the use of magnesia-type Refractory Brick (RB) waste as a substitute for fine aggregate and filler in Asphalt Concrete-Wearing Course (AC-WC) mixtures. The RB waste is generated from the kiln walls of nickel smelting furnaces and is used to completely replace natural sand by weight. The study compared Marshall empirical values, such as stability, yield, and Marshall quotient (MQ), volumetric characteristics, such as Void In the Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Bitumen (VFB), and Ultrasonic Pulse Velocity (UPV) of AC-WC mixtures containing natural sand at asphalt percentages of 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%. The findings reveal that the optimum Marshall properties were achieved with RB waste at a 5% asphalt content, compared to 6.0% for natural sand. Furthermore, the AC-WC mixture incorporating RB waste exhibited sufficient strength and durability to withstand traffic loads, suggesting that the complete replacement of natural sand with RB waste significantly influences the properties of AC-WC asphalt, promoting the environmentally friendly and economical reuse of waste materials in the industry.

Keywords-refractory brick; Marshall characteristic; AC-WC; stone dust

I. INTRODUCTION

Road pavements are typically constructed using materials derived from natural resources, such as stone and sand, as the foundation layers. This process has contributed to a increased demand for such materials, leading to a significant depletion of natural resources. As a result, it is crucial to consider alternative materials that can function as substitutes in asphalt mixture production, prompting the suggestion to reuse industrial waste as potential constituents. This phenomenon has led to the conceptualization of waste as the byproduct of industrial processes, which is often perceived as economically less valuable and can have various environmental impacts when not managed properly highlighting the importance of mitigating the effects of pollution on society.

The use of construction waste from road pavements as an alternative aggregate can mitigate environmental pollution.

Specifically, the magnesia-type material sourced from Nuha District in Indonesia makes up a significant portion, typically 90% to 95%, of asphalt mixtures [1]. Reducing the consumption of this material can have positive environmental implications [2]. Moreover, an industrial waste with promising applications is RB, specifically magnesia-type sourced from PT Vale Indonesia, Tbk, located in Sorowako, Nuha District, East Luwu Regency, South Sulawesi Province. RB is extensively utilized as a lining for high-temperature combustion kilns due to its dense structure and thermal resistance up to 1000 °C, although efforts to recycle this material have been sporadic [3]. Nonetheless, in the past two decades, the recycling of RB has become a serious consideration owing to environmental concerns and rising landfill costs [4].

RB are a solid and rigid material capable of maintaining their mechanical function for extended periods under various environmental conditions, such as high temperatures, chemical liquids, and corrosive gases. This material is commonly utilized in smokestacks, fireplaces, and nickel-smelting furnaces. Throughout its usage cycle, RB must be routinely disassembled and replaced, leading to the annual disposal of a substantial amount of waste. Approximately 28 million tons of RB waste are generated each year [4]. The waste is also categorized as ceramic, such as bricks, which are considered non-degradable or have a long lifespan of 4,000 years [3]. Consequently, the areas designated for RB waste disposal are continuously expanding, burdening the surrounding environment, and leading to the suggestion of reusing the waste as the optimal solution for the environment. The use of RB waste, ranging from 0% to 100%, to replace fine aggregates after exposure to high temperatures resulted to an increase in the compressive strength of concrete [5]. Replacing 20% of natural fine and coarse aggregates with RB waste produced concrete with better physical and mechanical properties than 20% of brick waste as coarse aggregates [6].

The use of waste materials as alternatives to fine aggregates and fillers has been studied. One example was the use of iron sands as substitute fine aggregates, which were reported to have passed the Marshall test and met the Bina Marga requirements for subsequent use in AC-WC. However, these iron sands exhibited increased voids, both within the mixture and between the aggregates [7]. The use of iron powder waste as a filler material in Hot Rolled Sheet (HRS) resulted in Marshall test findings indicating that 5% and 10% incorporation levels met the requirements for HRS-WC pavements. The incorporation of 10% iron powder by weight of filler was found to produce the highest stability and flow [8]. A range of alternative materials, including soil dust, cement, lime, slag, peat, bagasse, volcanic ash, fly ash, and normal ashes, have been reported to be utilized as fillers to enhance the performance of asphalt mixtures. For instance, using soil dust as a filler in Hot Mix Asphalt (HMA) yielded a stability value of 10.75 kN with a sufficiently high asphalt content, making it a viable option for economic reasons. Bagasse ash has also been proposed as a filler in asphalt concrete mixtures [6]. Furthermore, volcanic ash was employed as a cavity filler and binder in asphalt concrete mixtures due to its fine particle size and pozzolanic properties. The stability analysis revealed that the material had a stability value of 1000.99 kg and a flow of 3.13 mm.

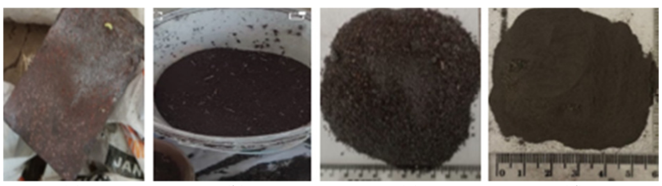
Various materials have been evaluated as fine aggregates, alternative fillers, and Stone Dust (SD) applications, such as the comparison of the performance of asphalt mixtures produced using diverse fine aggregates and fillers, yet the focus was limited to Hot Rolled Asphalt (HRA) and HRS.

Non-Destructive Testing (NDT) techniques have gained widespread application in the evaluation of material properties, particularly in the assessment of concrete, within the field of civil engineering. These methods have demonstrated effectiveness and reliability in determining the early-age strength of concrete, creating an opportunity to assess their suitability for characterizing cement-stabilized materials employed in road construction [9]. The utilization of the UPV method for pavement materials characterization has a well-established tradition. The potential of applying UPV to evaluate the strength and volumetric characteristics of asphalt concrete in the binder course has been explored [10]. Similarly, the possibilities of employing ultrasonic methods have been investigated with laboratory tests and analyses revealing that both UPV and amplitude exhibit a decreasing trend with increasing temperature in both dry and wet conditions [11]. Notably, the potential of using RB waste as an alternative fine aggregate and filler material in AC-WC mixtures has not been thoroughly analyzed, despite its possible contribution to reducing road construction costs. This study aims to analyze the performance of AC-WC mixtures produced using RB waste as a substitute for fine aggregates and filler materials.

II. EXPERIMENTAL PROCEDURE

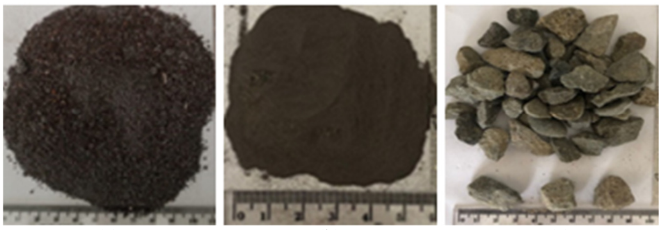
A. Materials Characteristics

The AC-WC mixture is composed of 60/70 penetration grade asphalt, fine aggregates, and fillers derived from SD and magnesia-type RB waste obtained by dismantling nickel slag furnace walls at PT. Vale Indonesia, Tbk's Soroawako facility in Indonesia. The raw RB waste underwent crushing and manual sieving to produce fine aggregates and filler sizes meeting the specified requirements, as depicted in Figures 1 and 2 [12]. Furthermore, the physical properties of the 60/70 penetration grade asphalt and the two types of fine aggregates are provided. The fillers originate from two sources, SD and magnesia-type RB waste, with their physical characteristics detailed. In contrast, those regarding the coarse aggregates are sourced from Sungai Bili-bili, South Sulawesi.



(a) (b) (c) (d)

Fig. 1. (a) Processing of raw RB waste in block form, (b) crushing and sifting of the block form with a hammer, (c) fine aggregates passed through sieve No. 4, and (d) filler passed through sieve No. 200.



(a) (b) (c)

Fig. 2. (a) Filler RB waste, (b) fine aggregate RB waste, and (c) coarse aggregate RB waste.

The particle size distribution of fine and coarse aggregates and the fillers satisfied the gradation standards for AC-WC mixture according to the General Specifications of Bina Marga 2018 Revision 2 for Asphalt Pavement. This was confirmed by the data presented in the following Table I and Figure 3.

TABLE I. GRADATION OF AC-WC MIXTURE

Sieve size (mm)	Specification (%)	Test Result (%)
19.1	100	100
12.7	90-100	91.54
9.52	77-90	76.25
4.75	53-69	64.29
2.36	33-53	49.19
1.18	21-40	35.22
0.6	14-30	23.81
0.3	9-22	14.45
0.150	6-15	10.11
0.75	4-9	7.05

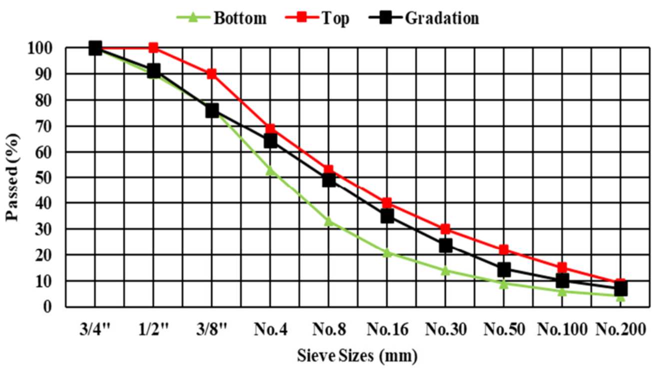


Fig. 3. Gradation of AC-WC mixture.

The asphalt and aggregates were evaluated using the general specifications for HMA developed by Bina Marga in 2018. The findings indicated that the coarse and fine aggregates, as well as the filler materials derived from magnesia-type RB waste and SD, complied with the 2018 Bina Marga standards. Furthermore, the penetration asphalt employed was also verified to have met the required standards.

B. Mixing Proportions and Preparation

The specimens were developed by varying the RB and SD waste content in the asphalt mixtures at 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%. The comprehensive information related to the mixtures is presented in Table II. All the mixtures had a total weight of 1200 gr.

TABLE II. TENSILE STRENGTH OF REINFORCING COMPOSITION OF AC-WC MIXTURE

Code	Asphalt content (%)	Coarse aggregate (gr)	Fine aggregate (gr)	Filler (gr)	Asphalt (gr)
1	5.0	456.0	604.2	79.8	60.0
2	5.5	453.5	601.1	79.4	66.0
3	6.0	451.0	598.0	79.0	72.0
4	6.5	448.8	594.6	78.5	78.0
5	7.0	446.4	591.4	78.1	84.0

C. Test Methods

This study investigated the impact of fine aggregates and fillers derived from magnesia-type RB waste on AC-WC mixtures. This was achieved by conducting the Marshall test based on the SNI 2489-2018 and the UPV test in accordance with ASTM C597:22 [13]. The process began with an evaluation of the constituent materials in the AC-WC mixture. The Marshall test was subsequently performed to determine the Marshall properties, such as stability, flow, and MQ, as well as the volumetric properties, including VMA, VFB, and VIM. The UPV test was utilized to assess the wave propagation velocity in road pavements and the characteristics of the mixture.

1) Marshall Test

The method employed in testing the AC-WC mixture focused on the utilization of the Marshall apparatus related to the stability and flow characteristics of HMA which serve as indicators of the specimen's resistance to applied loads. As depicted in Figure 4, the Marshall apparatus was a modified version of the Universal Testing Machine (UTM).

Fig. 4. Marshall apparatus utilized for this study.

2) UPV

Ultrasonic waves are frequently employed in NDT by utilizing the UPV method. This method can assess the performance of asphalt mixtures by detecting poor compaction through a decrease in wave propagation speed [14]. The principle is that the velocity of compressional waves traversing a material is dependent on its elastic properties and density. The process involves a transmitter transducer emitting waves that are received by a receiver transducer positioned at a distance of *L*. The UPV device then measures the time required for the wave to pass through the specimen, which is referred to as the travel time.

Fig. 5. Device used to implement the UPV method.

III. RESULTS AND DISCUSSION

A. Marshall and Volumetric Properties

The Marshall characteristics of the AC-WC mixture specimens produced through different variations of RB waste and SD were determined. Therefore, the stability, flow, VIM, VMA, VFWA, and MQ recorded are presented in the below [15].

1) Stability

The stability values of the asphalt mixture specimens produced using aggregates from RB and SD waste are presented in Figure 6. The stability values fluctuate depending on the mixture's composition and aggregate types. When RB waste was incorporated, the stability values declined by 4% to 10%, attributed to the larger voids between the aggregate particles compared to SD. This increased void space was a result of the reduced overall weight of RB waste aggregates in the AC-WC mixture, leading to excessive asphalt coating and subsequent bleeding [16]. Additionally, RB waste exhibited a higher specific gravity than SD, yet its value still met the minimum stability standards established by Bina Marga.

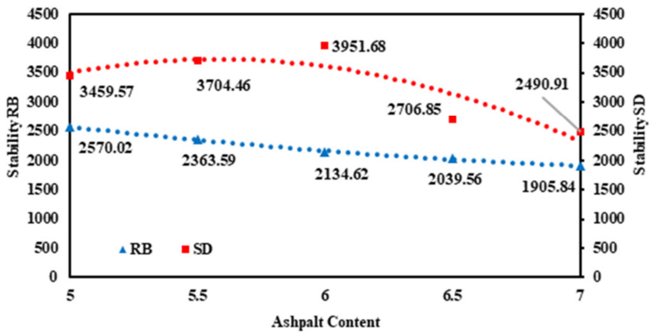


Fig. 6. Stability of RB waste and SD.

Previous studies have reported a similar trend, where iron sand fillers demonstrated less stability and higher specific gravity compared to cement fillers when used as fine aggregates [8]. This suggests that the physical properties of iron sand were aligned with those of RB waste [17]. Furthermore, the increased fatigue caused by the maximum temperature of 150 °C in the hot mix material led to a reduction in the stability value of RB waste when asphalt content was added to the AC-WC mixture. Consequently, efforts have been made to decrease the usage of excessive asphalt in AC-WC mixtures due to the high fatigue levels, that excessive fatigue could impede the mixing process [18].

2) Flow

The results shown in Figure 7 indicate that incorporating RB waste into the AC-WC mixture with a high asphalt content led to a 2% to 9% reduction in the flow. In contrast, the addition of SD resulted in a 3% to 11% increase in flow. The decreased flow rate observed with the RB waste was linked to an increase in the void volume, which was caused by the addition of more asphalt that coated the aggregates and enhanced the bond strength of the mixture. This finding aligns with the previous study, which reported that the incorporation of PET also decreased the flow, contributing to the formation of a stiffer mixture [14].

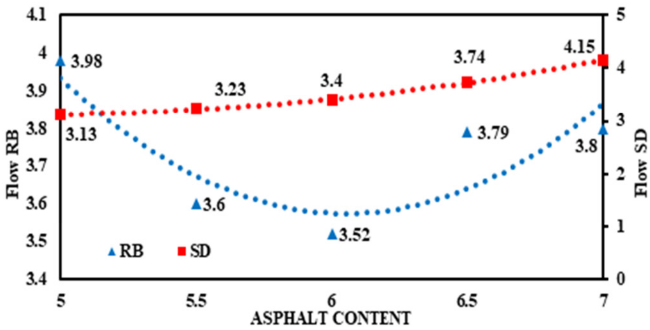


Fig. 7. Flow of RB waste and SD.

3) MQ

The MQ values of the AC-WC mixtures produced using RB and SD waste, presented in Figure 8, met the required criteria.

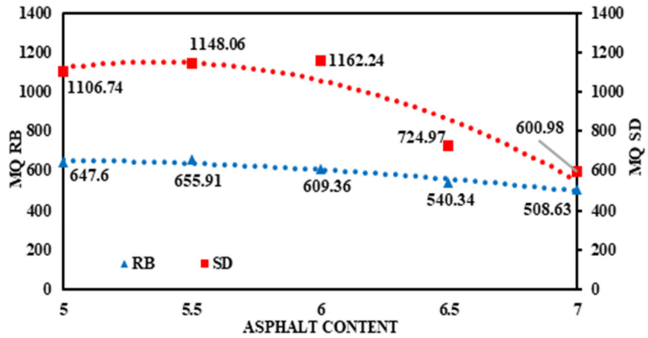


Fig. 8. MQ of RB waste and SD.

However, the specimen containing RB waste exhibited a lower MQ compared to the SD waste. The MQ was influenced by the stability-to-flow ratio, suggesting that the AC-WC mixture with RB waste was more plastic and malleable, potentially leading to increased susceptibility to deformation during use [19]. This characteristic is desirable, as improved deformation and the appropriate asphalt content can enhance the bond between aggregates, which is crucial for enhancing the rigidity of the mixture. This result aligns with the study where a higher MQ was associated with a stiffer and more durable mixture [20].

4) VIM

Figure 9 demonstrates that the void content value influences the durability of asphalt-aggregate mixtures. The VIM value of the specimen produced using RB waste increased by 9% indicating a rise in air voids within the mixture impacting the strength of the mix and is considered a weak point. Greater air voids can facilitate water infiltration into the mix, potentially leading to freezing or abrasion damage. Air voids can also affect the behavior of the mix at high or low temperatures, such as deformation or cracking. Meanwhile, the stability value showed a non-significant decrease of 10%, suggesting the asphalt mixture became less stable. This result aligns with a previous observation that the addition of more PET content led to the production of more air voids. This was associated with the crystalline form of the PET shreds, which caused an increase in the surface area and potentially reduced compaction in the mixture.

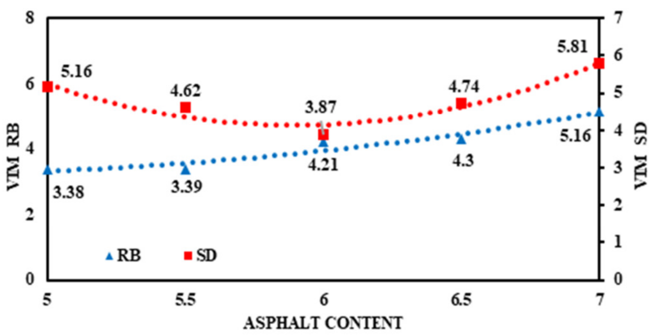


Fig. 9. VIM of RB waste and SD.

5) VMA

The findings presented in Figure 10 demonstrated that incorporating RB waste and SD into the mixture increased the VMA values by 7% and 4%, respectively.

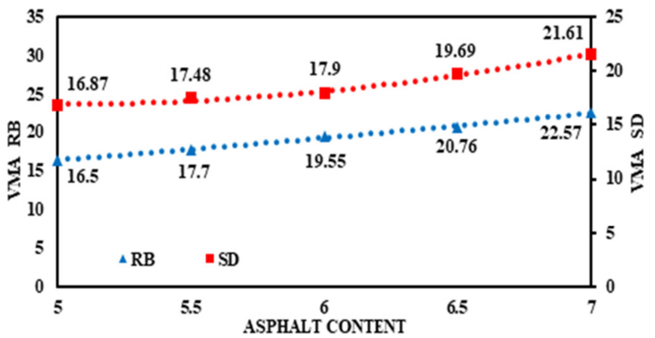


Fig. 10. VMA of RB waste and SD.

This observation led to the conclusion that augmenting the asphalt content elevated the VMA values, consequently enhancing the density of the mixture aligning with the findings of another study [18]. Increasing the asphalt content in the PET mixture elevated the VMA values, thereby proportionally enhancing the strength due to the increased thickness of the aggregate particle layers.

6) VFB

Introducing RB waste and SD at higher asphalt contents was observed to reduce the VFB bitumen by 3% and 4%, respectively. This was attributed to the diminished air voids caused by the asphalt fillings, which led to the exudation of the condensation layers. Furthermore, elevated temperatures can prompt the liquid asphalt to migrate to the road surface and disrupt the normal texture of the asphalt, potentially damaging the road quality and shortening the service life of the asphalt surface. These findings align with the results of a previous study, which demonstrated that increased asphalt-containing plastics contributed to a reduction in the VFB [21].

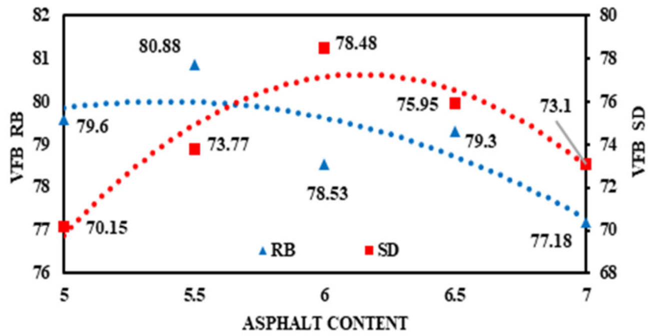
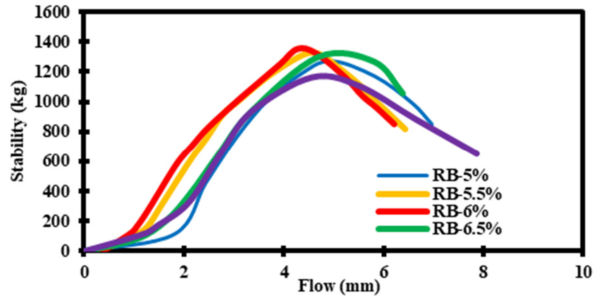


Fig. 11. VFB of RB waste and SD.

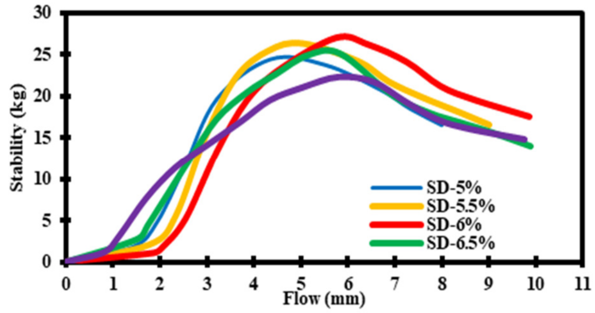
7) Relationship between Stability and Flow

The curve displayed in Figure 12 represents the mixtures containing fine aggregates and fillers, with asphalt content ranging from 5% to 7% in 0.5% increments. The curved lines depict the average of three specimens for each mixture, exhibiting a consistent pattern of mixing behavior. Furthermore, the correlation between stability and flow is attributed to the incorporation of two types of fine aggregates and fillers, including RB waste and SD. The similar trend was attributed to the same asphalt content, while the distinction was in the fine aggregates and fillers used. Both mixtures exhibited increased flow as asphalt concentration increased, likely due to the asphalt filling voids between aggregates and enhancing flexibility. However, the increased asphalt content did not significantly correlate with the stability of the fine aggregates and fillers.

The behavior can be explained through four distinct phases. The first phase involves load adjustment, characterized by a concave curve indicating initial adaptation of the mixture to applied load. The second phase exhibits a direct correlation between stability and flow, demonstrating deformation. In the third phase, a non-linear correlation represents inelastic deformation, with majority of deformation being irreversible. The final phase exhibits significant non-linear deformation, leading to degradation and decreased stability.

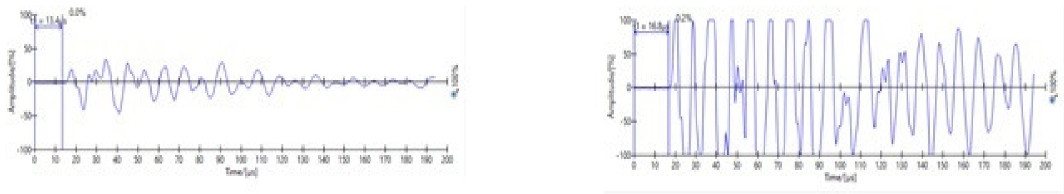


(a)

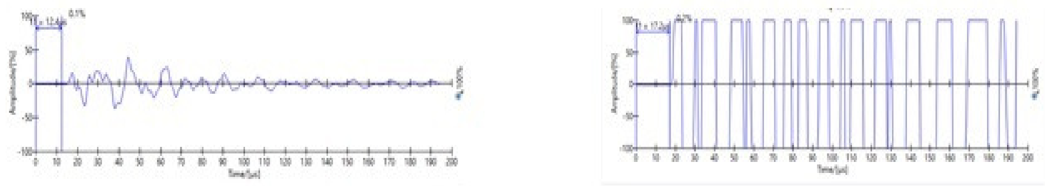


(b)

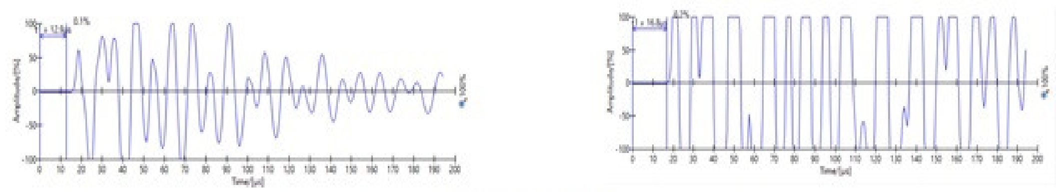
Fig. 12. Correlation between stability and flow of the mixtures containing fine aggregates and filler produced through (a) RB waste and (b) SD.



Asphalt content 5%

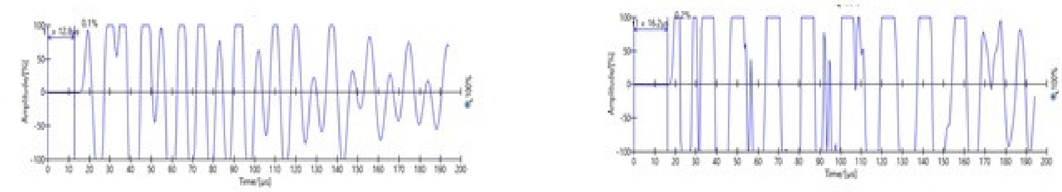


Asphalt content 5,5%



Asphalt content 6%

Asphalt content 6,5%



Asphalt content 7%

(a) (b)

Fig. 13. Ultrasonic wave patterns of the mixtures containing fine aggregates and filler produced through (a) RB waste and (b) SD.

(a)

(b)

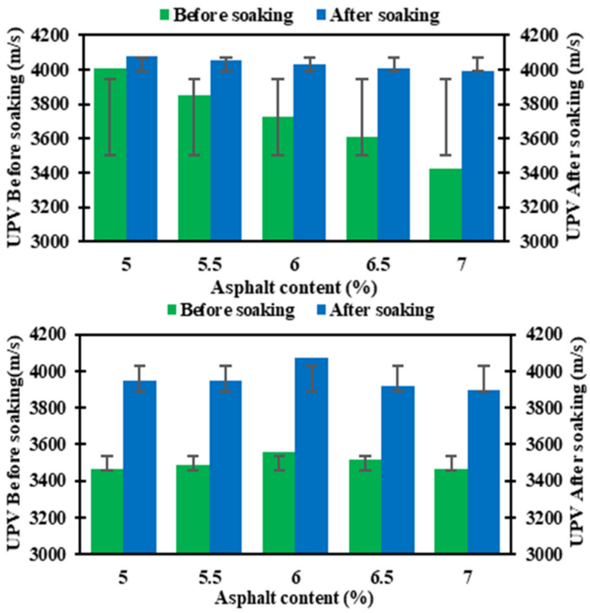


Fig. 14. UPV before and after immersion of the mixtures containing fine aggregates and filler produced through (a) RB waste and (b) SD.

B. UPV

1) Ultrasonic Wave Patterns

Figure 13 demonstrates the relationship between the various mixtures, transit times, and ultrasonic wave patterns [11]. The propagation time of the ultrasonic waves from the transmitting to the receiving transducer in solid asphalt mixtures indicates that the waveforms are effectively generated across all mixtures due to efficient compaction [22]. The results showed that RB waste and SD exhibited effective compaction with the aggregates and asphalt. It is crucial to note that inadequate compaction prevents the formation of significant voids, while excessive compaction can lead to cracking.

2) UPV Measurements Before and After Immersion

The UPV values for RB waste are found to be higher compared to SD both before and after immersion, exhibiting a 1.9% and 14.6% difference, respectively. This observation may be attributed to the generally lower porosity of RB waste relative to SD. The reduced porosity in RB waste diminishes the resistance encountered by ultrasonic wave propagation, leading to faster propagation speeds [23, 24]. Furthermore, RB waste that has undergone combustion typically exhibits lower water content than conventional aggregates. This reduction in water content enhances the propagation speed of ultrasonic waves, as there is less impedance to the wave propagation. Additionally, RB waste possesses a more stable structural integrity and is less susceptible to the influence of water. The lower porosity of RB waste hinders water penetration, minimizing the impact on the speed of ultrasonic wave propagation.

IV. CONCLUSIONS

In conclusion, the application of Refractory Brick (RB) as a substitute for fine aggregates and fillers in the Asphalt Concrete-Wearing Course (AC-WC) mixture produced the following results:

- The optimum asphalt content for RB and stone ash mixtures was found to be 5% and 6% by weight, respectively. This variation is attributable to the differing properties of the raw materials. RB, given their low porosity and dense nature, require a lower asphalt proportion, whereas the more porous stone ash requires a higher asphalt content to attain optimal bonding and adequate structural integrity.
- Incorporating RB waste into the asphalt mixture resulted in a 4% to 10% decrease in stability, but a 2% to 9% enhancement in flow characteristics. In contrast, SD exhibited 3% to 4% stability and 3% to 11% flow. The RB waste-containing mixture displayed low Marshall Quotient (MQ) values, indicating increased flexibility and plasticity, which could make it prone to deformation during service. The volumetric properties showed that the specimen produced with RB waste experienced a 9% increase in VIM, while SD exhibited a non-significant 10% decrease. The inclusion of both RB waste and SD increased the VMA by 7% and 4%, respectively; however, the increased asphalt content in the presence of RB waste and SD tended to reduce the VFB by 3% and 4%.
- The characteristics of the asphalt mixture curves revealed that the RB waste curve was sharper, with a rapid decrease in stability after reaching its peak, suggesting a stiffer nature, which may be attributed to the stronger properties of the RB material or the more angular particle shape. Conversely, the SD curve was smoother and exhibited a slower decline, indicating a more flexible or deformation-resistant behavior at higher flow values, potentially due to the finer or more rounded grain characteristics of SD.
- The use of RB waste appears more suitable for applications requiring high stability, as it more efficiently utilizes the asphalt content, although it may exhibit less flexibility. Conversely, SD can be considered for applications demanding higher flexibility and lower stability.
- Ultrasonic wave patterns for both RB waste and SD mixtures demonstrated effective compaction with the aggregates and asphalt. It is essential to note that inadequate compaction prevents the formation of significant voids, while excessive compaction can lead to cracking.
- The Ultrasonic Pulse Velocity value for RB waste was higher both before and after immersion, compared to SD, by 1.9% and 14.6%, respectively. This may be attributed to the generally lower pore content of RB waste compared to SD.

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