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Using Crushed Recycled Glass In Asphalt Pavement

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Abstract
Multiple countries across the globe have shifted their attention from virgin aggregate to the possibility of utilising recycled materials in asphalt pavements. The possibility of using waste glass as an alternative to virgin aggregate has gained momentum, with laboratory tests continuing to show promising results. In the US, the practice began in the 1990s, when some states, such as New York, ratified policies allowing waste materials to be used for road pavement. Since then, some countries across Europe and North America have followed suit and are slowly incorporating waste materials, such as glass particles, into asphalt pavement at levels of 5% to 15%. Research into the use of waste glass demonstrates that it is as environmentally friendly as virgin bitumen. While the incorporation of waste glass in asphalt pavement may indeed release some harmful elements, their eventual impact is negligible. Most of the available laboratory results also confirm that with slight improvements, waste glass can be an appropriate alternative to virgin aggregate. Additionally, lower proportions of waste glass are associated with increased performance and durability. The findings from the explored studies reveal the importance of keeping the amounts of waste in bitumen low to avoid rapid cracks triggered by high temperatures. Overall, the results suggest that the percentage of waste glass in bitumen should be kept at a significantly low level to achieve optimal results. On the other hand, laboratory tests were conducted by adding 10% of fine waste glass instead of fine virgin aggregate. The need for sustainable and eco-friendly infrastructure solutions drives the growing interest in utilizing recycled materials for asphalt pavements. Waste glass has emerged as a viable alternative to virgin aggregate due to its abundance and potential to reduce the environmental impact of road construction projects. European and North American countries, inspired by the successful practices in the US, are taking measured steps to incorporate glass particles in asphalt pavements, aiming to strike the right balance between performance and waste reduction. As the demand for greener road construction materials rises, ongoing research continues to explore new ways to optimize the use of waste glass, ensuring its long-term effectiveness and safety. While laboratory results have generally been promising, real-world implementation and long-term monitoring will be essential to validate the performance and durability of asphalt pavements containing waste glass.

1.1 INTRODUCTION

Countries across the world have shifted their attention from virgin aggregate to the possibility of utilising recycled materials in asphalt road pavement. The use of recycled materials has provided an alternative way to manage the rapidly dwindling landfill capacity (Santos, Ferreira, & Flintsch, 2015). At a time when natural resources are becoming increasingly depleted, authorities in many countries have realised the importance of properly utilising various materials that were traditionally regarded as waste (Lynn, Ghataora & Dhir 2016). Countries such as the United States (US), New Zealand, European nations, and Taiwan have recently incorporated crushed glass into asphalt and road base pavement. Roads constitute the most significant percentage of the world's transport infrastructure. The principal role of roads in any country is to link various parts to each other, thus providing a platform through which movement and transportation of commodities can be made. Such road networks require constant significant maintenance, renewal, extension, and monitoring to ensure they serve their intended purpose. With the rapid depletion of natural resources, notably aggregates, innovation has become inevitable in yielding alternative solutions (Ziari, Barakoohi, &

Moniri, 2017). Review and development of materials are one contribution to innovation in road management. Some of the recycled materials widely utilized in road construction in place of virgin aggregate include waste rock, crushed glass, scrap tyres, waste plastic, smelter slag, and crushed bricks. Glass is a non-metallic and inorganic material Khudhair, H. Y., Jusoh, A., Mardani, A., Nor, K. M., & Streimikiene, D., 2019). Thus, it cannot be decomposed or incinerated but can be recycled without loss of productivity. In the US, glass accounts for approximately 7% of the total weight of municipal solid waste, with only 20% being recycled (Monzur, Ali, and Arulrajah, 2012). This trend is replicated in various developed countries worldwide. As one of the alternative modifiers to asphalt, waste glass is considered to have great potential to replace aggregate (Yas, H., Mardani, A., & Alfarttoosi, A., 2020).

The glass industry has been an integral part of human history for many years. Throughout history, glass has been utilized in various ways, and with increasing consumption, a substantial amount of glass waste is generated globally each year (Issa, 2016). Recycling and reusing glass as raw materials or modifiers have become one of the most viable ways of managing waste. Glass recycling can save energy and reduce the amount of waste introduced into the environment (Khudhair, H. Y., & Mardani, A., 2021). Waste glasses are crushed to the required gradation and size, then mixed with bitumen mixtures for surface or wearing courses (Monzur et al., 2012). A significant portion of the available literature has already demonstrated the promising effect of using waste glass in road pavements. The objective of using recycled agents is to restore the consistency and chemistry of asphalt (Krstić & Milenković-Kerković, 2017). To properly understand the application of waste glass in road pavements vis-à-vis virgin aggregate, it is essential to conduct a comprehensive review of the available scholarly literature. Such an investigation would provide a platform to cross-check and draw parallels among various empirical findings, enabling the formulation of more comprehensive conclusions. Therefore, the primary goal of this paper is to investigate the use of waste glass in asphalt pavement and its environmental implications compared to using virgin aggregate (Yas, H., Mardani, A., Albayati, Y.K., Lootah, S.E., & Streimikiene, D., 2020). The second objective is to explore the available laboratory test results on using waste glass in the asphalt pavement to determine their content in terms of road quality, performance, and durability (Yas, H., Dafri, W., Sarhan, M. I., Albayati, Y., & Shwedeh, F., 2024).

1.2 Research Aim & Objective

This research aims to investigate the laboratory test results in using the recommended portion of crushed recycled waste glass in asphalt pavement, whether in the asphaltic concrete base course or wearing course. The objective is to achieve the sustainability of road projects in the UAE and decrease the use of virgin aggregates. The use of a certain percentage of waste glass in conjunction with virgin aggregates has a positive environmental impact (Saeed, M. D., & Khudhair, H. Y., 2024). In the UAE, all road pavements are constructed from natural materials, including coarse and fine aggregates, soil, and asphalt cement. This approach is considered a depletion of natural resources and has an impact on the environment. To achieve the objective and aim of this research, a theoretical background is provided in various areas related to the utilization of waste glass, including its global use in asphalt pavement, environmental impacts, and laboratory results. Additionally, internal laboratory tests were conducted to verify the use of 10% recycled crushed glass in the asphalt mix design. The UAE is exploring the use of recycled waste glass in asphalt pavements to reduce reliance on virgin aggregates and achieve sustainability in road projects. The research, which uses laboratory test results, aims to identify the optimal portion of crushed recycled waste glass to be incorporated into asphalt pavement. This aligns with the global trend of utilizing waste glass in asphalt pavements, which has demonstrated positive environmental benefits. The study uses a comprehensive theoretical background and internal laboratory tests to validate the use of a 10% proportion of recycled crushed glass in asphalt mix designs (Yas, H., Jusoh, A., Nor, K.M., Jovovic, N., Delibasic, M., 2022).

2.1 THEORETICAL BACKGROUND

2.2 The Use of Waste Glass in Asphalt Pavement

As the use of waste glass continues to gain momentum, many scholars have become increasingly interested in the subject. Consequently, a large body of data has been published on the replacement of conventional virgin aggregate with waste materials, such as glass. This section examines the use of waste glass in asphalt pavement and its environmental implications in comparison to virgin aggregate. Finally, it examines and evaluates a range of available laboratory test results on the use of waste glass in the asphalt pavement to determine its impact on road quality, performance, and durability (Yas, H., Dafri, W., Sarhan, M. I., Albayati, Y., & Shwedeh, F., 2024). The accumulation of millions of tons of waste glass has been a significant concern for most industrialized countries worldwide. In the US, for instance, the generation of waste glass began in the 1960s, and its volume grew significantly over the subsequent decades (Arulrajah et al., 2013). However, with the introduction of plastic and aluminium containers in the late 1980s, the proportion of waste glass reduced drastically. Notably, the amount of waste glass decreased from 15 million tons in 1980 to 12.5 million tons in 1988 (Maghool et al., 2017). While this reduction was promising, significant volumes of glass waste still needed effective management. Therefore, there was an urgent need to develop improved recovery techniques for waste glass, as well as other forms of waste (Vorobieff, 2010). The obvious alternative was to recycle glass waste and use it to manufacture new products. Although this was a feasible option, it resulted in the overproduction of glasses that could not meet the immediate market demand (Maghool et al., 2017). The problem was compounded by the fact that only color-sorted and contamination-free cullet types are considered suitable for reuse in the glass industry. Therefore, recycling glass for reuse in the glass industry would not be sufficient in solving the problem of waste accumulation. This implied there were still significant quantities of waste glass that could be used in other secondary purposes (Arulrajah et al., 2015).

Glass waste, also known as cullet, is being explored as an alternative to aggregate in some developed countries. Laboratory tests have shown positive results, and it has gained popularity due to its lack of sorting, color separation, and cost-effectiveness. Crushed glass waste can be utilized in road construction due to its physical properties, which are similar to those of aggregate, and its high angularity, which may enhance the stability of asphalt mixes. Glass is also recognized for its heat retention capabilities, which can help reduce frost penetration. Crushed glass in asphalt was first used in Emerald, New York, in 1990, with a maximum glass content of 40% (Nguyen, Blanc, Kerzrého, & Hornych, 2013). However, current state department specifications limit the percentage of glass in pavement to 5%. The adhesive bond between bitumen and glass particles is a significant concern. The American Association of State Highway and Transportation Officials (AASHTO) has enacted specifications to guide the use of crushed glass in upper pavement layers. These include grinding and screening glass aggregate, allowing suppliers to use up to 20% by mass in composite glass mixtures, and referring to AASHTO methodologies when using materials exceeding the 20% (Nguyen et al., 2013).

2.3 Environmental Impacts of Using Crushed Glass in Asphalt Pavement

The potential environmental impact of using crushed glass versus virgin aggregate in road construction has been a topic of debate in recent times. Several studies have been conducted to assess the potential environmental impacts of using glass waste as an alternative to virgin aggregate. A study by Sadeghnejad, Arabani, and Taghipoor (2018) investigated the possible environmental impacts of cullet by comparing it with the use of virgin aggregate (Aboelazm, K.S., 2024). The findings revealed that pH values, conductivity, heavy metals, and inorganic content levels were within normal or acceptable limits for the extracts in water, acid, and base. When these components are present in high amounts, they are known to cause severe contamination of water bodies and, subsequently, harm to human lives. On the same breadth, the inorganic content was also found to be within the acceptable levels. Nevertheless, the iron content in acid-extracted extracts was shown to be above the acceptable limits. The scholars concluded that, to a large degree, the use of waste glass for pavement and road construction is almost similar to the application of aggregate

(Sadeghnejad et al., 2018). Maghool et al. (2017) found that while glass remains in road pavements, it may leach heavy metals into the soil; however, the environmental impact is negligible. The effects of leached heavy metals on groundwater depend on the pavement's retardative, diffusive, and hydraulic properties (Aboelazm, K.S., Tawakol, F., Ibrahim, E., & Ramadan, S.A., 2025). When these metals come into contact with drinkable water underground, their concentration in the water aquifer becomes negligible. Serpa de Brito and Pontes (2015) found no significant difference in environmental pollution between virgin aggregate and waste glass. In conclusion, waste glass does not pose any harm to the environment when used as a substitute for virgin aggregate in road construction (Aboelazm, K.S., 2023).

2.4 Laboratory Test Results on Using Waste Glass in Asphalt Pavement

Several investigations into the effectiveness of waste glass in asphalt pavements have been undertaken to date. The impacts of cullet on road quality, performance, and durability have especially received growing attention from scholars. This section examines various published laboratory tests to evaluate the impact of using waste glass on road quality, performance, and durability. Singh and Sakale (2018) investigated the impact of mixing waste glass with waste plastic on the quality of bitumen. The findings revealed that the original asphalt had significantly lower stability compared to the one mixed with both waste plastic and waste glass particles. These findings suggest that road stability improves with the addition of waste plastics and waste glass to bitumen. Based on the results, the authors conclude that the maximum dose of glass aggregate in the bituminous mix should be 7.5% with optimal doses of bitumen and waste modifiers. Overall, the study highlights the importance of using aggregate mixed with waste plastics and waste glass instead of constructing roads with virgin aggregate alone.

Handlos's 2010 study found that adding 10% waste glass particles to cement specimens increased comprehensive strength and flexural strength. Curing time enhances the resistance of concrete mixtures to failure. Brushed surfaces exhibited higher skid resistance than grooved surfaces; however, skid resistance was influenced by the depth, spacing, and number of grooves. Closely spaced, concentrated glass gloves increased tire resistance. Shafabakhsh and Sajed (2014) and Tahmoorian, Bijan, Tam, and Yeaman (2017) conducted studies on the use of waste glass in road construction. They found that the addition of waste glass to asphalt improves its stiffness modulus, creep conformity, and fatigue life compared to standard asphalt concrete. The study also found that asphalt mixed with waste glass particles exhibits better workability, compaction, and deformation resistance compared to virgin aggregate (Aboelazm, K.S., & Ramadan, S.A., 2023). However, the addition of waste glass could increase water absorption. Taha and Nounu's (2009) study revealed workability issues in road pavement due to increased viscosity from waste glass particles. To improve performance, they proposed reducing waste glass and increasing the amount of cement to reduce viscosity. The study concluded that reducing the amount of waste glass in bitumen could reduce the occurrence of cracks (Aboelazm, K.S., & Afandy, A., 2019).

3.1 Laboratory Processes

3.2 CCollecting & Preparing Samples

This is the technical part of this study, which involves collecting, preparing, and testing samples of asphalt mix design by adding a portion of recycled glass combined with virgin aggregate, ranging from 5% to 15%. The tests were conducted only with 10% recycled glass, as it was the optimal percentage, and the results were satisfactory compared to those with 5% or 15% recycled glass.

3.3 Preparation of Recycled Glass Cullet

3.3.1 Recycled bottles were cleaned, dried, and crushed initially with the Los Angeles machine

In this experiment, the researchers focused on recycling glass bottles to explore their potential use as a sustainable construction material. The process began by collecting used glass bottles, which were then thoroughly cleaned and dried to remove any contaminants. Once cleaned, the bottles were subjected to crushing using a Los Angeles machine, a commonly used device in civil engineering for evaluating the aggregate's resistance to wear and abrasion. The Los Angeles machine operates by rotating a drum that contains glass bottles and steel balls, simulating the impact and abrasion experienced during transportation and usage. The crushing process aimed to reduce the glass bottles into smaller, more manageable particles, suitable for incorporation into asphalt mixtures. Following the crushing stage, the researchers conducted a series of laboratory tests to assess the properties of the crushed glass (Aboelazm, K.S., Tawakol, F., Dganni, K.M., & AlFil, N.Z., 2024). They analyzed factors like particle size distribution, shape, and specific gravity to understand how the recycled material compared to traditional virgin aggregates commonly used in asphalt pavements. Laboratory tests revealed that crushed glass particles are compatible with asphalt mixtures, indicating their potential as an alternative construction material. The specific gravity of crushed glass particles aligned with asphalt aggregate specifications, demonstrating its feasibility. This study suggests recycled glass could reduce demand for virgin aggregates, promote waste management, and contribute to eco-friendly road infrastructure (Aboelazm, K.S., 2021).

Figure 1: Preparation of Recycled Glass Cullet: Authors' own.

3.3.2 Initial separation of coarse and fine fractions after crushing with the Los Angeles machine

In this experiment, the researchers focused on recycling glass bottles and investigating their potential application in construction materials. After crushing the glass bottles using a Los Angeles machine, the researchers performed an initial separation to obtain distinct coarse and fine fractions of the crushed glass. The Los Angeles machine is commonly used in civil engineering to evaluate the abrasion resistance of aggregates. During the crushing process, the glass bottles were subjected to impacts and abrasion from steel balls, simulating real-world wear and tear. This mechanical treatment reduced the glass bottles into smaller particles, resulting in a mixture of both coarse and fine fragments. Following the crushing stage, the researchers used a sieving process to separate the crushed glass particles into different size fractions. Coarse fractions consisted of larger particles, while fine fractions comprised smaller particles. This separation allowed the researchers to analyze and assess the individual properties of the coarse and fine components of the crushed glass. The laboratory analysis assessed the particle size distribution, shape, and characteristics of crushed glass particles in asphalt mixtures. Understanding the properties of coarse and fine fractions is crucial for optimizing the use of recycled glass in road construction. The findings contribute to sustainable construction practices, waste reduction, resource conservation, and the development of environmentally friendly infrastructure.

Figure 2: coarse and fine fractions after crushing with the Los Angeles machine: Authors' own.

3.3.3 Coarse Fractions were crushed with a Jaw Crusher to produce finer fractions

In this procedure, the researchers focused on further refining the coarse fractions obtained from the initial separation of crushed glass bottles using a Los Angeles machine. The objective was to produce finer particles that could enhance the performance of the recycled material in asphalt mixtures. To achieve this, the coarse fractions were subjected to additional crushing using a jaw crusher. The jaw crusher is a mechanical device commonly used in the mining and construction industries to reduce large-sized materials into smaller particles. In this experiment, the jaw crusher was utilized to break down the coarse glass fragments into finer sizes. The jaw crusher operates by applying pressure to the material, causing it to be compressed and fractured. As a result, the coarse glass fractions were effectively reduced into more finely divided particles. This step was crucial in optimizing the material's particle size distribution, as it produced a greater proportion of fine fractions. Researchers monitored the crushing process of recycled glass to optimize its compatibility with asphalt mixtures. They used a jaw crusher to crush coarse fractions, aiming to produce finer particles. This process enhanced the material's performance in asphalt mixtures, contributing to sustainable construction practices, reducing the demand for virgin aggregates, and promoting effective waste management.

Figure 3. Coarse Fractions were Crushed with Jaw Crusher: Authors' own.

3.4 Glassphalt Mixture and Test Specimens Preparation

3.4.1 Gradation used for recycled glass cullet for both mixes (AC/WC & AC/BC)

The results presented in Table 1 show the gradation used for the recycled glass cullet in both asphalt mixes, AC/WC (Asphaltic Concrete/Wearing Course) and AC/BC (Asphaltic Concrete/Base Course). The gradation represents the distribution of particle sizes in the recycled glass cullet. For the AC/WC mix, the recycled glass cullet demonstrated a consistent gradation, with 100% of the particles passing through the 9.5 mm sieve size. As the sieve size decreased, the percentage of particles passing through the sieve reduced gradually, with 98% passing through the 4.75 mm sieve, 70% passing through the 2.36 mm sieve, and 32% passing through the 0.850 mm sieve. The amount of glass cullet passing through smaller sieve sizes continued to decrease, with 19% passing through the 0.425 mm sieve, 10% passing through the 0.180 mm sieve, and 2.9% passing through the 0.075 mm sieve. The recycled glass cullet showed a similar gradation pattern in the AC/BC mix, with slight variation compared to the AC/WC mix. This well-graded distribution ensures uniformity and stability, making it an eco-friendly alternative for road construction.

Table 1. Gradation used for recycled glass cullet for both mixes

Glass Cullet Typical Gradation		
Sieve Size, mm	**(% Passing)**	
9.5	100	100
4.75	98	85 – 100
2.36	70	50 – 85
0.850	32	20 – 55

0.425	19	-
0.180	10	-
0.075	2.9	0 - 10

3.4.2 Gradation of the mixes used for the control mix and glassphalt (AC/WC mix)

The study compares two asphalt wearing course mixes: AC/WC CONTROL and AC/WC GLASSPHALT. The AC/WC GLASSPHALT mix with recycled crushed glass aligns with job mix formula requirements set by the Road and Transport Authority. The mix's gradation is similar to the AC/WC CONTROL mix, but slightly altered by the presence of recycled glass. The study suggests that incorporating recycled glass is a sustainable option for improving asphalt wearing course mixtures.

Table 2. Gradation of the mixes used for the control mix and glassphalt

ASPHALT WEARING COURSES – GRADING ANALYSIS						
Sieve Size, mm	Passing (%)					Status
	AC/WC CONTROL (without RCG)	AC/WC GLASSPHALT (with Recycled Crushed Glass)			JMF Specification	
		5 %	10 %	15 %	RTA	
25	100	100	100	100	100	Meeting the Spec.
19	99	99	99	99	86-100	Meeting the Spec.
12.5	81	81	81	81	69-87	Meeting the Spec.
9.5	71	71	71	71	58-78	Meeting the Spec.
4.75	50	49	49	49	40-60	Meeting the Spec.
2.36	30	30	29	28	25-45	Meeting the Spec.
0.850	19	18	17	16	15 – 30	Meeting the Spec.
0.425	13	12	11	11	10 – 22	Meeting the Spec.
0.180	7	7	7	7	6 - 15	Meeting the Spec.
0.075	3.8	3.7	3.6	3.4	2-8	Meeting the Spec.

Note: The gradation of the mixes with recycled glass was close but not identical to that of the control mix.

3.4.3 Radiation graph of the mix used for the study (AC/WC mix)

Figure 4 presents the gradation graph of the mix used in the study, specifically the asphaltic concrete wearing course (AC/WC mix). The graph displays the distribution of particle sizes in the mix, showing the percentage passing each sieve size. The x-axis represents the sieve sizes in millimeters, ranging from 25 mm to

0.075 mm. The y-axis represents the percentage passing each sieve, indicating the proportion of particles of that size in the mix. The graph depicts a series of points connected by a line, illustrating the gradation curve. The curve on the graph starts at 100% at the 25 mm sieve size, indicating that all particles in the mix pass through this sieve. As the sieve size decreases, the percentage passing reduces gradually, representing a decrease in particle size. The curve follows a smooth downward trend, indicating a well-graded mixture with a diverse particle size distribution. The gradation graph's shape and characteristics provide valuable information about the mix's uniformity and suitability for asphalt pavement. A well-graded mix with a smooth and continuous curve suggests that the mix contains a balanced proportion of various particle sizes, contributing to better compaction, stability, and overall performance of the asphalt pavement.

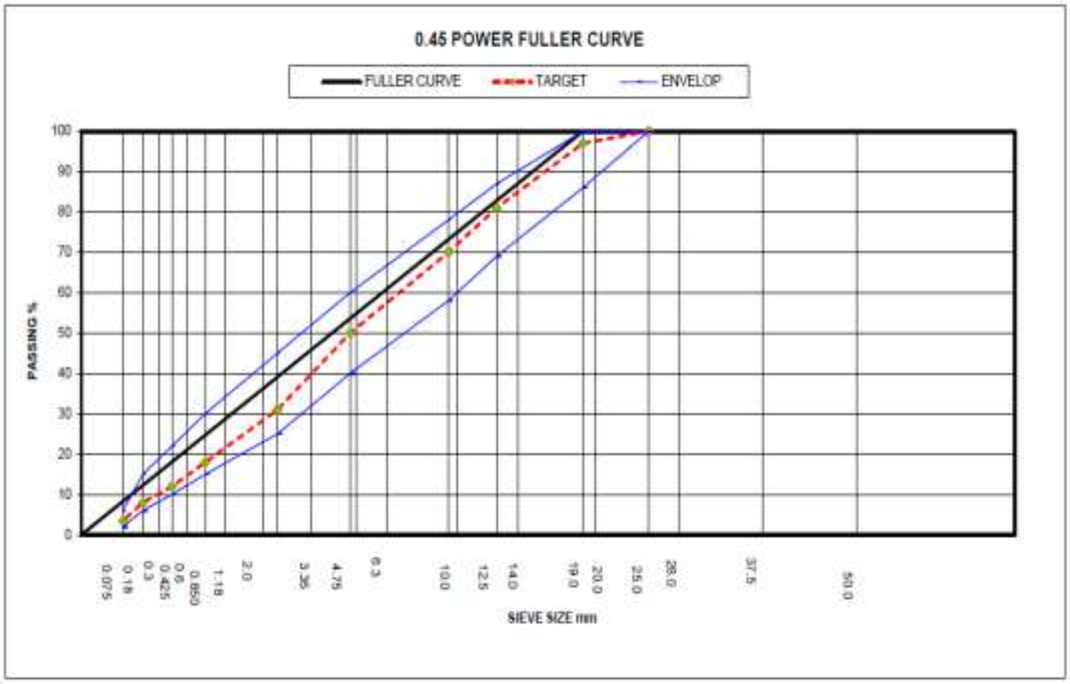


Figure 4. Gradation graph of the mix used for the study (AC/WC mix): Authors' own.

3.4..4 Gradation of the mixes used for the control mix and glassphalt (AC/BC mix)

The table presents the gradation analysis of asphalt base courses for the control mix and glassphalt (AC/BC mix) with various percentages of recycled crushed glass (RCG). The "Sieve Size" column indicates the size of the particles in millimeters, and the "Passing (%)" column shows the percentage of each size passing through the sieve. The "Status" column indicates whether each mix meets the Job Mix Formula (JMF) specification set by the Road and Transport Authority (RTA). From the table, we observe that the control mix (without RCG) and glassphalt mixes (with 5%, 10%, and 15% RCG) meet the RTA specification for most of the sieve sizes. However, it is noted that the gradation of the mixes with recycled glass is close but not identical to that of the control mix. The variations in some sieve sizes indicate that the addition of recycled crushed glass affects the particle distribution in the mix, although it still meets the required specifications. In summary, the table demonstrates that incorporating recycled crushed glass into the glassphalt mix has a minimal impact on meeting the specified gradation requirements for asphalt base courses, providing potential environmental benefits without compromising the mix's performance.

Table 3. Gradation of the mixes used for the control mix and glassphalt (AC/BC mix)

ASPHALT BASE COURSES – GRADING ANALYSIS						
Sieve Size, mm	Passing (%)					Status
	AC/BC CONTROL (without RCG)	AC/BC GLASSPHALT (with Recycled Crushed Glass)			JMF Specification	
		5 %	10 %	15 %	RTA	
37.5	100	100	100	100	100	Meeting the Spec.
25.0	94	94	94	94	90 – 100	Meeting the Spec.
19.0	80	80	80	80	76 – 86	Meeting the Spec.
9.5	60	60	60	60	55- 65	Meeting the Spec.
4.75	47	47	47	46	44 – 52	Meeting the Spec.
2.36	30	29	28	27	28 - 36	Meeting the Spec.
0.850	18	17	16	15	16 – 20	Meeting the Spec.
0.425	12	11	11	10	10 – 14	Meeting the Spec.
0.180	7	7	6	6	6 – 9	Meeting the Spec.
0.075	3.5	3.4	3.2	3.0	2.5 – 4.5	Meeting the Spec.

Note: The gradation of the mixes with recycled glass was close but not identical to that of the control mix.

3.4.5 Gradation graph of the mix used for the study (AC/BC mix)

Figure 5 displays the gradation graph of the AC/BC mix used in the study. The graph represents the particle size distribution of the mix, with the x-axis indicating the sieve size in millimeters and the y-axis showing the percentage passing through each sieve. The graph's line represents the gradation curve, which connects the points corresponding to the percentage passing through each sieve size. A steep slope on the curve indicates a higher percentage of fine particles, while a flatter slope suggests a higher proportion of coarse particles. By examining the graph, we can assess the overall particle distribution and identify the mix's dominant particle size range. Additionally, it helps to evaluate if the mix complies with specified requirements or standards for the project. Overall, Figure 5 provides a visual representation of the AC/BC mix's gradation, enabling researchers and engineers to analyze the mix's particle distribution and make informed decisions about its suitability for the intended application.

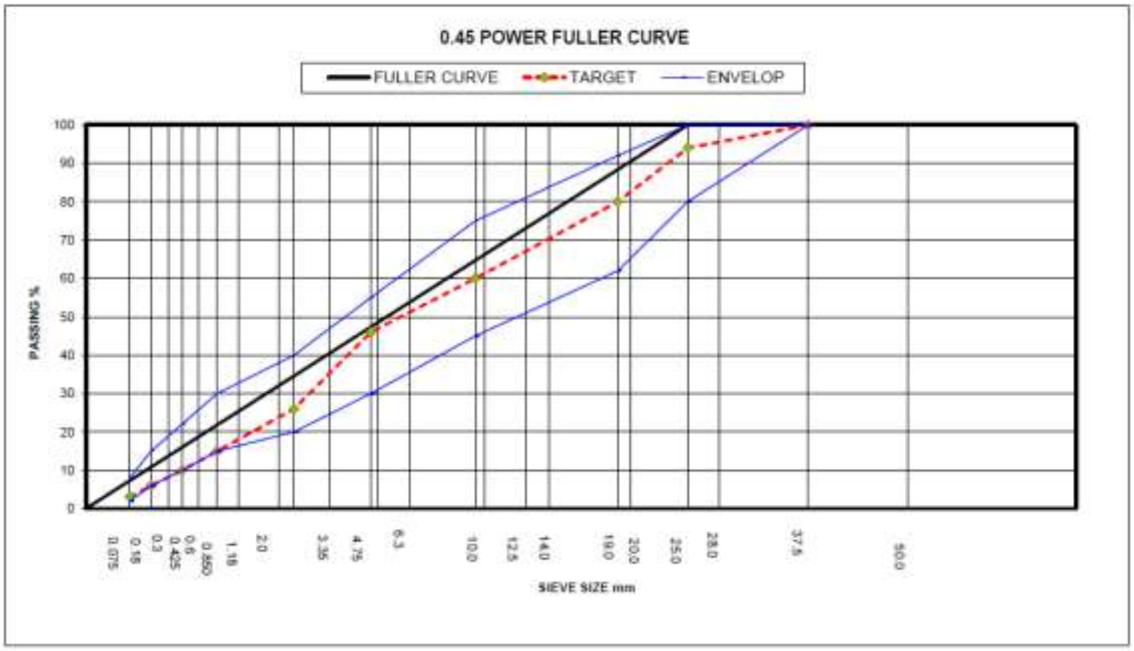


Figure 5. Gradation graph of the mix used for the study (AC/BC mix) : Authors' own.

3.5 Mix Design Materials

a. Aggregates: Mountain aggregates from Siji, Ras Al Khaimah are used in the preparation of Asphalt Mixtures on this study. These aggregates are of high quality materials with low soundness values and with a combined bulk specific gravity of 2.947. The coarse aggregates are having low Aggregates Crushing values and Los Angeles Abrasion values. The coarse aggregates examined had 100 percent at least one partially crushed faces, and there was a high percentage of fully crushed faces.

b. Preparation of Specimens for Mix Design: Batch weights were prepared for each mixture and kept in the oven at a temperature of approximately 15° C higher than the established mixing temperature. Batched aggregate were kept in the oven overnight to equilibrate at the selected temperature.

c. Preparation of specimens using Marshall Method (ASTM D 6926):The batched aggregate was mixed with 60/70 penetration grade bitumen at different bitumen content and mixing temperature. The mix is then transferred to the Marshall mould and 75 blows applied on both sides. Four specimens at each point were compacted using Marshall Hammer.

d. Determination of the optimum bitumen content and other properties: The Bulk Specific Gravity, volumetric properties, strength properties, were determined in the Laboratory. Marshall specimens were tested for Stability, Flow and Stiffness, VIM, VMA, and VFB, and the average is determined.

3.6 Laboratory Test Results

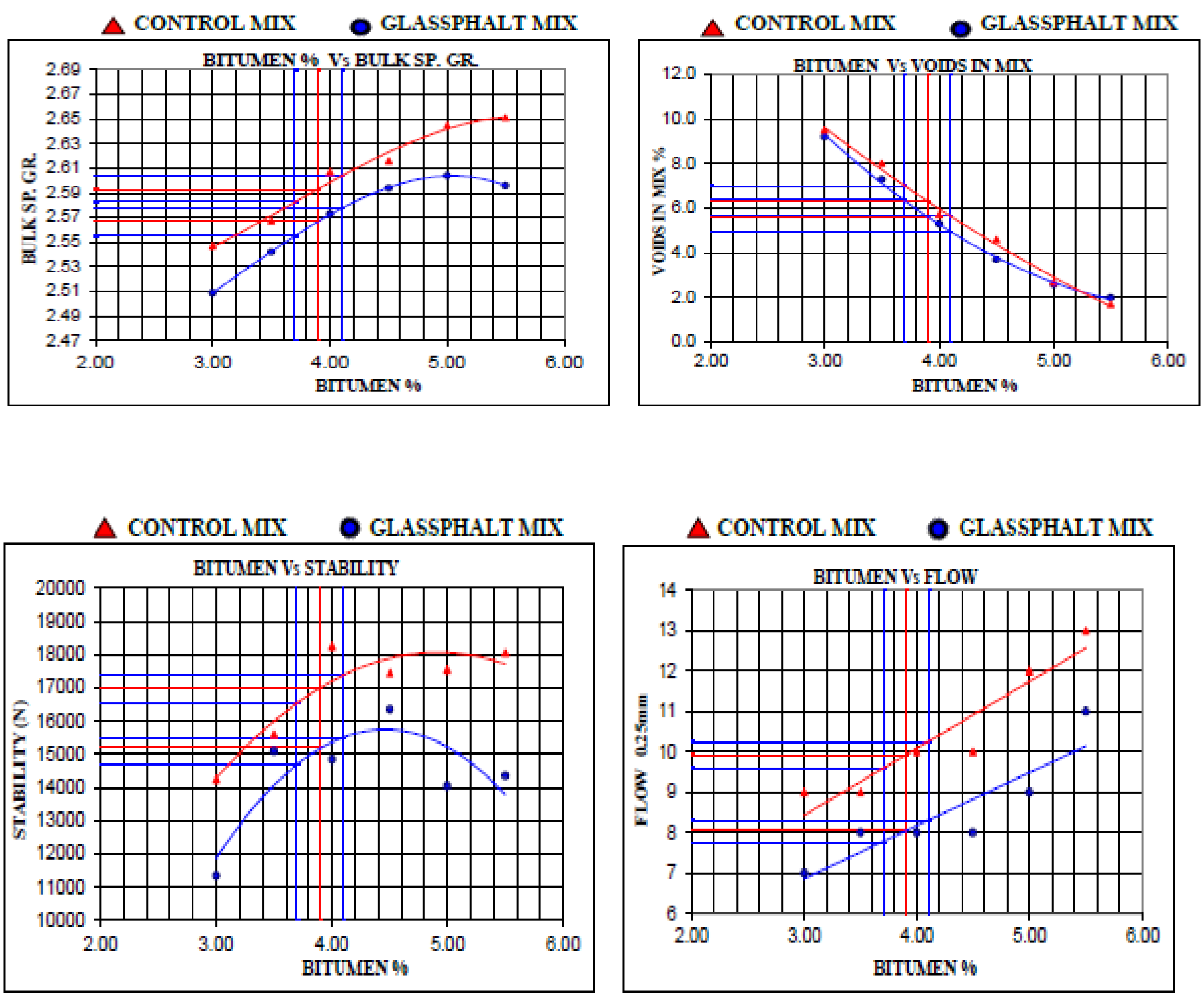
The laboratory results presented in this study pertain to the evaluation of the AC/BC mix, both with and without the addition of Recycled Crushed Glass (RCG). The researchers conducted a gradation analysis on the mixes, which involved sieving the materials to determine the particle size distribution. The results are depicted in Table 3 and Figure 5. Table 3 shows the percentage of each sieve size passing for the control mix and the glassphalt mixes containing 5%, 10%, and 15% RCG. The Passing (%) values indicate the proportion of particles that passed through each sieve size, and the "Status" column indicates whether the mixes meet the specified Job Mix Formula (JMF) requirements set by the Road and Transport Authority (RTA). The gradation curve of the AC/BC mix shows that the addition of recycled crushed glass significantly impacts particle distribution. Although not identical to the control mix, all analyzed glassphalt mixes meet RTA's JMF specifications for most sieve sizes. These results are crucial for assessing the suitability and performance of recycled glass in road construction projects.

3.6.1 AC Wearing Course Mix

a. Marshall Specimens Tests Results (AC/WC mix)

- AC/WC – CONTROL MIX (without RCG)
- AC/WC – GLASSPHALT MIX (with 10 % RCG)

Figure 6 presents the Marshall Specimens Tests results for the AC/WC (Asphalt Concrete Wearing Course) mix, comparing the control mix (without Recycled Crushed Glass, RCG) and the glassphalt mix (with 10% RCG). The Marshall test is a common method used to evaluate the performance and mechanical properties of asphalt mixes. The x-axis in the graph represents the different test parameters and properties evaluated during the Marshall test. These parameters include Stability, Flow, Marshall Quotient (Stability/Flow), Air Void Content, and Voids in Mineral Aggregates (VMA). The y-axis shows the values obtained for each test parameter. For the two mixes, there are two sets of bars representing the results: one for the control mix and the other for the glassphalt mix. The Stability value indicates the resistance of the mix to deformation and failure under load, while the Flow value represents the deformation (in mm) of the mix under a specified load. The Marshall Quotient combines these two values to assess the overall performance of the mix.



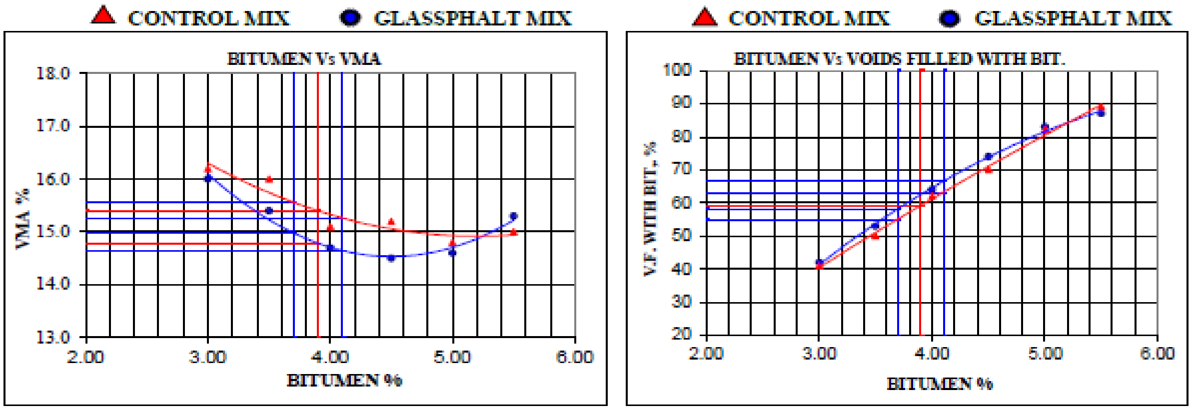


Figure 6. Marshall Specimens Tests Results (AC/WC mix) : Authors' own.

Air Void Content and Voids in Mineral Aggregates (VMA) are essential parameters used to evaluate the mix's compactness and durability. A certain level of air voids is necessary to accommodate thermal expansion and provide flexibility to the pavement. By analyzing the graph, we can observe the differences between the control mix and the glassphalt mix in terms of their mechanical properties. If the glassphalt mix has similar or better values compared to the control mix, it indicates that the addition of RCG has not significantly affected the mix's performance. However, if there are substantial differences, it may require adjustments or further optimization. Overall, Figure 6 provides a comprehensive comparison of the two AC/WC mixes, offering valuable insights into the impact of incorporating 10% RCG on the mix's mechanical properties. These results are crucial for assessing the mix's suitability for road construction and its potential benefits in terms of sustainability and the utilization of recycled materials.

b. **Asphalt mixtures tests results (AC/WC mix)**

Table 4 presents the asphalt mixtures test results for the AC/WC (Asphalt Concrete Wearing Course) mix, comparing the control mix (without Recycled Crushed Glass, RCG) and the glassphalt mix (with 10% RCG). These tests evaluate various properties of the mix to ensure it meets the specifications set by the Road and Transport Authority (RTA). The table provides results for different binder content ranges: LOWER, OPTIMUM, and UPPER. For each range, the following properties are evaluated:

- Bitumen Content (%): The percentage of bitumen in the mix. Both mixes fall within the specified range (3.70% to 4.10%).
- Specific Gravity: The specific gravity of the mix. Both mixes show values within the desired limits.
- Voids in Mineral Aggregate (VIM %): Indicates the air voids in the mix. Both mixes meet the requirement of 4-8%.
- Voids in Mineral Aggregate (VMA %): Represents the voids in the total mixture. Both mixes meet the minimum VMA requirement (15% for 19mm nominal size aggregate).
- Voids Filled with Bitumen (VFB %): Indicates the effective bitumen content in the mix. Both mixes meet the requirement of 50-75%.
- Stability (N) and Flow (0.25mm): Measure the resistance to deformation and deformation under load, respectively. Both mixes meet the required stability and flow values.
- Stiffness (0.25mm): Reflects the mix's stiffness under load. Both mixes meet the minimum stiffness requirement.
- Loss of Stability (%): Indicates the percentage of stability loss under repeated loading. Both mixes meet the maximum allowed value (25%).

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- Refusal (%) and Refusal Gmb: Reflect the resistance of the mix to deformation during testing. Both mixes meet the specified requirements.

Overall, the results indicate that the glassphalt mix with 10% RCG performs well and meets the RTA's specifications, comparable to the control mix without RCG. These findings suggest that incorporating recycled crushed glass in the AC/WC mix is feasible and can contribute to sustainable asphalt pavement construction.

Table 4. Asphalt mixtures tests results (AC/WC mix)

AC WEARING COURSE MIXES					
Bitumen Used:		60/70 Pen. Grade	Bitumen S.G.:	1.034	
Control Mix (w/o RCG)		Aggregate Calibration Factor, (%)		0.48	
Glassphalt Mix (w/ 10% RCG)				0.52	
Control Mix (w/o RCG)		Theoretical Maximum Specific Gravity	Bitumen @ 4.10 %	2.760	
Glassphalt Mix (w/ 10% RCG)				2.713	
Mixing Temp., °C:		153 – 161	Compacting Temp. °C:	142 - 146	
Binder Content Ref.	Test Description	Control Mix (without RCG)	Glassphalt Mix (with 10 % RCG)	Specification RTA	Conclusions
LOWER	Bitumen content, %	3.70	3.70	3.70 – 4.10	--
	Specific Gravity	2.583	2.552	-	--
	VIM, %	7.0	6.2	4 - 8	Meet Requirement
	VMA, %	15.6	15.0	15 min/13 min*	Meet Requirement
	VFB, %	55	60	50 - 75	Meet Requirement
	Stability (N)	16550	14700	11760	Meet Requirement
	Flow (0.25mm)	10	8	8 - 16	Meet Requirement
	Stiffness (0.25mm)	1655	1880	1225 Min.	Meet Requirement
OPTIMUM	Bitumen content, %	3.90	3.90	3.70 – 4.10	--
	Specific Gravity	2.593	2.568	-	--
	VIM, %	6.3	5.7	4 - 8	Meet Requirement
	VMA, %	15.4	14.8	15 min/13 min*	Meet Requirement
	VFB, %	59	64	50 - 75	Meet Requirement
	Stability (N)	17000	15200	11760	Meet Requirement
	Flow (0.25mm)	10	8	8 - 16	Meet Requirement

	Stiffness (0.25mm)		1700	1880	1225 Min.	Meet Requirement
	Loss of Stability, %		8	15	25 Max. %	Meet Requirement
UPPER	Bitumen content, %		4.10	4.10	3.70 – 4.10	--
	Specific Gravity		2.604	2.578	-	--
	VIM, %		5.7	5.0	4 - 8	Meet Requirement
	VMA, %		15.3	14.6	15 min/13 min*	Meet Requirement
	VFB, %		63	66	50 - 75	Meet Requirement
	Stability (N)		17400	15600	11760	Meet Requirement
	Flow (0.25mm)		10	8	8 - 16	Meet Requirement
	Stiffness (0.25mm)		1740	1880	1225 Min.	Meet Requirement
	Refusal Pa %	@ 400 blows	3.8	3.5	2.0 Min. %	Meet Requirement
		@ 500 blows	2.2	2.6		Meet Requirement
		@ 600 blows	2.5	2.4		Meet Requirement
	Refusal Gmb	@ 400 blows	2.654	2.619	NA	NA
		@ 500 blows	2.700	2.642		
		@ 600 blows	2.692	2.647		

* The aggregate gradation design used for the study was based on VMA as per the "New Mix Design Method by NCHRP 9-33 Recommendation," in which the VMA requirement for 19mm nominal size aggregate is 13.0 % minimum.

3.6.2. AC Base Course Mix

a. **Marshall Specimens Test Results (ACBC mix)**

- ACBC – CONTROL MIX (without RCG)
- ACBC – GLASSPHALT MIX (with 10 % RCG)

Figure 7 presents the gradation graph of the AC/BC (Asphalt Concrete Base Course) mix used in the study, comparing the control mix (without Recycled Crushed Glass, RCG) and the glassphalt mix (with 10% RCG). The gradation graph illustrates the particle size distribution of the mix, offering insights into the proportions of different-sized particles in the mixture. The x-axis in the graph represents the sieve sizes in millimeters, while the y-axis shows the percentage passing through each sieve size. The curve on the graph represents the gradation curve for both the control and glassphalt mixes, connecting the points that represent the percentage passing for each sieve size. By analyzing the graph, we can observe the variations in particle size distribution between the control and glassphalt mixes. The steepness or flatness of the curve indicates the proportion of fine and coarse particles in the mix. Ideally, a well-graded mix should have a gradual curve, indicating a balanced distribution of particle sizes. The graph compares the glassphalt mix and the control mix, revealing that 10% RCG has minimal impact on particle distribution. Significant deviations indicate changes due to RCG. Understanding gradation characteristics is crucial for achieving optimal road construction performance and mix design, which can offer potential environmental benefits.

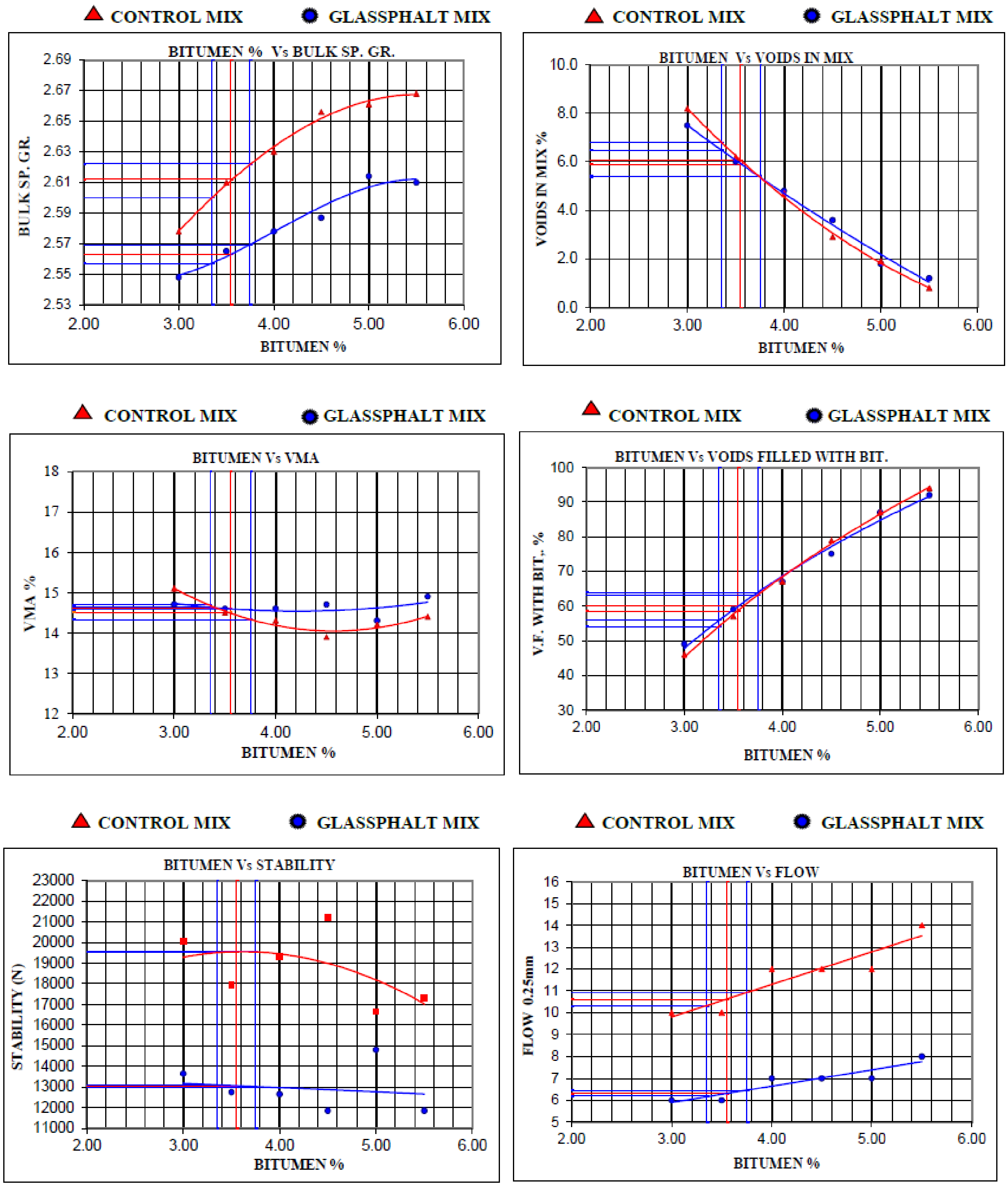

Figure 7. Gradation graph of the mix used for the study (AC/BC mix): Authors' own.

The size aggregate is a minimum of 12.0%.

4.1 DISCUSSION AND CONCLUSION

The feasibility of using waste glass as an alternative to virgin aggregate has gained momentum, with more laboratory tests showing promising results. Dating back to the 1960s, the possibility of incorporating waste glass into road construction has been recently suggested as one of the most efficient methods of waste management. Recycling glass to manufacture new glass elements was initially considered the most viable way of managing waste from used glass. Nevertheless, this possibility did not last long, as the amount of glass waste continued to exceed market demand. As a result, it sparked a debate concerning the efficient management of waste glass without manufacturing excess glass components than the market required. Gradually, it became apparent that putting unsorted glass waste into secondary use would be a feasible option. In the US, the practice started in the 1990s, when some states, such as New York, ratified policies allowing waste materials to be used for road pavement. Since then, various countries across Europe and North America have followed suit and are gradually incorporating waste materials, such as glass particles, into asphalt pavement. Research shows that waste glass is as environmentally friendly as virgin aggregate in asphalt pavement, with minimal release of harmful elements. Laboratory tests show that incorporating 10% waste glass into bitumen increases road stability, while lesser amounts enhance performance and durability. However, keeping the percentage low is crucial to avoid cracks caused by high temperatures. While waste glass can replace 5% to 15% of virgin aggregate, more research is needed to address limitations.

Waste glass can serve as an environmentally friendly alternative to virgin aggregate in road construction, with laboratory tests indicating that it is as environmentally friendly as virgin aggregate. However, concerns about harmful elements from the glass are negligible. Adding 10% waste glass to the bitumen mix improves road stability, but it is crucial to maintain a low content to avoid temperature-induced cracking. Research suggests replacing 5% to 15% of virgin aggregate with waste glass in asphalt pavement for sustainable road construction. However, further research is needed to understand its limitations and perform laboratory tests. The use of waste glass reduces environmental impact and conserves resources. Optimizing the percentage of waste glass and its performance is crucial for successful implementation.

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