



PERFORMANCE EVALUATION OF HOT MIX ASPHALT INCORPORATING VITRIFIED TILE WASTE AS FINE AGGREGATE REPLACEMENT

¹Ahmad Deedat Abdullahi, ²Umar Ahmad Masari, ³Abdulmumin Isah Ahmed

¹Civil Engineering Department, Federal University Dutsin-Ma Katsina State.

²Civil Engineering Department, Federal Polytechnic Kaura Namoda Zamfara State.

³Civil Engineering Department, Ahmadu Bello University Zaria.

*Corresponding authors' email: ahmaddeedat004@gmail.com

ABSTRACT

The performance of hot mix asphalt (HMA) largely depends on the properties and gradation of the aggregates used in the mixture. The depletion of natural aggregates and improper disposal of construction waste have posed serious environmental challenges, leading to the need for alternative sustainable materials in asphalt production. This study investigates the influence of vitrified tile waste (VWT) as a partial substitute for natural fine aggregates on the mechanical and volumetric properties of hot mix asphalt (HMA). Fine aggregates were replaced at 0%, 10%, 20%, 30%, and 40% by weight, and mixtures were evaluated based on standard Marshall parameters, including stability, flow, bulk density, air voids (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB), using ASTM D6926–20 and D6927–20. Results show that as the percentage of vitrified tile waste increased, the stability of the mix also increased from 4.68 kN (control) to 5.41 kN at 30% replacement level, while flow decreased from 3.88 mm to 2.40 mm. Bulk density also increased with replacement up to 30%, indicating improved compaction. Air voids and VMA reduced, while VFB increased, signifying better densification and lower permeability. At 40% replacement, stability slightly decreased, showing that excessive substitution of fine aggregate reduces cohesion in the asphalt mix. All properties at 30% VWT met the Nigerian General Specification requirements for wearing course. The findings demonstrate that vitrified tile waste is a viable fine aggregate replacement that improves mixture performance while supporting sustainable material utilization in asphalt production.

Keywords: Hot mix asphalt, Vitrified tile waste, Fine aggregate replacement, Marshall stability, Performance evaluation, Sustainable pavement materials

INTRODUCTION

Hot Mix Asphalt is a composite material consisting of aggregates, bitumen, and filler mixed at elevated temperatures to produce a dense and durable pavement layer. Typically, aggregates constitute between 90–95% of the total mixture by weight, forming the structural skeleton responsible for strength, stability, and load distribution in flexible pavements (Lira, 2020). The bitumen component, usually about 5%, acts as the binding agent that coats the aggregates and provides cohesion. The performance of HMA depends considerably on the quality and gradation of the aggregates, as well as their mineralogical and mechanical characteristics. Proper aggregate selection ensures resistance to deformation, fatigue cracking, moisture damage, and environmental effects (Sunarjono et al., 2024).

At the same time, large quantities of construction and demolition waste are being generated worldwide, with ceramic and tile wastes forming a significant portion of the non-biodegradable fraction. Vitrified tiles, produced at firing temperatures of about 1200–1300°C, undergo a vitrification process that results in a dense, low-porosity, and mechanically strong material (Zanelli et al., 2021). Several studies have explored the use of ceramic-based materials in asphalt and concrete, noting improvements in stiffness, abrasion resistance, and structural performance when used as partial replacements for natural aggregates. For example, research has shown that crushed ceramic waste enhances the deformation resistance of asphalt mixes, increases inter-particle friction, and contributes to improved stability due to its angular texture and high hardness (Silvestre et al., 2013; Fatima et al., 2014).

Fine aggregates play an essential role in filling voids between coarse aggregates, improving workability, compactability,

and stability of the asphalt mixture. Grading requirements for fine aggregates are provided in ASTM C33, which emphasizes that well-graded aggregates enhance the mechanical properties of the mixture and minimize pavement distresses such as rutting and cracking (ASTM C33/C33M-22, 2022). Natural sands, though commonly used, often possess smooth and rounded particles that reduce interlocking, potentially reducing mix stiffness and stability (EN 12697-22, 2022). Due to these limitations, alternative fine aggregate sources with superior mechanical properties are being explored in modern pavement engineering.

However, a substantial volume of tile waste is generated during manufacturing, transportation, handling, installation, and building demolition. Tile waste is non-biodegradable and often disposed of in landfills, contributing significantly to environmental pollution (Pipil et al., 2024). Studies have estimated that up to 35% of raw materials used in ceramic production end up as waste, highlighting the need to develop strategies for recycling this material (Yuan et al., 2022). In Nigeria, increasing urban development and housing construction have led to large amounts of vitrified tile waste from residential and commercial projects (Hossain et al., 2021). Unfortunately, recycling practices remain minimal, and tile waste is commonly discarded indiscriminately.

Several researchers have investigated the potential of ceramic-based materials in asphalt mixtures. Rahman (2013) examined the use of recycled PET as fine aggregate replacement in modified asphalt mixtures and reported improved permanent deformation resistance, showing that waste materials can enhance asphalt performance when appropriately processed.

Shamsaei et al. (2020) evaluated ceramic waste powder as filler in HMA and found significant improvements in

Marshall stability and rutting resistance when ceramic filler replaced conventional limestone filler. Their results indicated that stability increased by up to 23%, and moisture sensitivity improved marginally. Fatima et al. (2014) studied the use of ceramic dust as filler in bituminous concrete, showing that ceramic waste improved stability, density, and mechanical performance. They concluded that ceramic waste can serve as an eco-friendly alternative to conventional fillers.

Similarly, Lim et al. (2019) noted that pulverized ceramic tile waste enhanced stability and met national specifications, suggesting its viability as a mineral filler. Feng et al. (2013) also observed that ceramic aggregates improved thermal properties and reduced temperature gradients when used in wearing course asphalt. Huang et al. (2009) incorporated waste ceramic materials into both Portland cement and asphalt concrete, reporting improved deformation resistance, dynamic modulus, and tensile strength at moderate replacement levels (up to 15%).

Collectively, these studies demonstrate that ceramic and tile wastes possess favorable engineering properties that can enhance asphalt mixture performance particularly in terms of stability, stiffness, and resistance to permanent deformation. Given the mechanical properties of vitrified tiles, including high strength, low water absorption, and favorable angularity, their use in asphalt mixtures holds significant promise. Yet, there remains limited data on their performance under Nigerian conditions, where climatic variations and traffic loads differ considerably from those in regions where previous studies have been conducted. This creates a research gap that must be addressed to better understand the suitability, optimum replacement ratio, and long-term performance implications of using VWT as fine aggregates in HMA.

Therefore, this study evaluates the performance of hot mix asphalt incorporating vitrified tile waste as a partial replacement for fine aggregates. The investigation focuses on key Marshall characteristics including stability, flow, bulk density, air voids, VMA, and VFB to determine how VWT influences the structural and volumetric behavior of HMA. The aim is to identify the optimum replacement level that yields improved performance while maintaining compliance with standard specifications for wearing courses. The findings from this study will contribute to sustainable material usage in pavement engineering and provide guidance for future applications of vitrified tile waste in road construction.

MATERIALS AND METHODS

Materials

The materials used include 60/70 penetration grade bitumen, natural aggregates (coarse and fine), and vitrified tile waste collected from construction disposal sites. The tile fragments were washed, oven-dried, crushed, and sieved to obtain fine particles within the range of 75 μm to 2.36 mm. This particle size ensures compatibility with standard fine aggregate requirements for asphalt mixtures.

All laboratory investigations were carried out at the Highway and Transportation Engineering Laboratory of Ahmadu Bello University, Zaria, following relevant ASTM procedures and the Nigerian General Specification (1997).

Mix Design and Specimen Preparation

The Marshall Mix Design method was used for both the control mixture and the mixtures containing vitrified tile waste. Asphalt specimens were prepared using a predetermined bitumen content of 5.5%, which had been identified as the optimum bitumen content in earlier design stages.

Fine aggregates were replaced with vitrified tile waste at levels of 0%, 10%, 20%, 30%, and 40% by total aggregate weight. Aggregates were heated to 140°C before mixing with bitumen at 160–170°C. Each batch was mixed thoroughly to ensure uniform distribution of materials. The hot mixture was then placed in standard cylindrical molds and compacted using 75 blows on each side with a Marshall hammer.

Specimens were left to cool for 24 hours at ambient laboratory conditions before being removed from the molds and subjected to testing.

Determination of Marshall Properties

The following Marshall properties were determined in line with ASTM D6926 and D6927:

Stability (maximum load sustained by the specimen), **Flow** (deformation at maximum load), Bulk density (G_{mb}), Air voids (V_a), Voids in mineral aggregate (VMA), Voids filled with bitumen (VFB).

Standard formulas were applied to compute volumetric properties. The performance of the modified mixtures was evaluated relative to the control mix and in accordance with the Nigerian General Specification for wearing course asphalt.

Bulk Density (G_{mb})

The bulk density of a compacted asphalt mix is defined as the ratio of the mass of the compacted asphalt specimen in water to the mass of the dry specimen in air. It can be expressed as:

$$G_{mb} = \frac{W_a}{W_a - W_w} \quad (1)$$

Where;

W_a = weight in air,

W_w = weight in water

Voids in Mineral Aggregate (VMA):

The voids in the mineral aggregate are the voids spaces between aggregate particles in the compacted paving mixture. These voids include, air voids and the volume occupied by the effective asphalt content. These voids are expressed in percentage and can be calculated using the equation below:

$$VMA = 100 \left(1 - \frac{G_{mb} \times P_s}{G_{sb}} \right) \quad (2)$$

Where:

VMA - percent voids in compacted mineral aggregates (percent of bulk volume).

G_{mb} - bulk specific gravity of compacted mixture.

G_{sb} - bulk specific gravity of aggregate.

P_s = aggregate percent by weight of total paving mixture.

Air Voids (V_a)

Air voids, which is the air void in the compacted paving mixture, is a ratio between the volume of air voids between the coated aggregates and the total volume of the mixture. These voids are expressed in percentage and can be calculated from the formula

$$V_a = 100 \left(1 - \frac{G_{mb}}{G_{mm}} \right) \quad (3)$$

Where:

G_{mb} = bulk specific gravity of aggregate.

G_{mm} = maximum specific gravity of the mix, and

Voids Filled with Bitumen (VFB):

VFB is the voids filled with bitumen in the interlocking spaces existing between the aggregate particles in the compacted paving mixture. VFB accounts for the volume of the effective bitumen content. Its best described as the volume of the VMA that is filled with bitumen. It can be calculated using equation.

$$VFB = 100 \times \frac{VMA - V_a}{VMA} \quad (4)$$

Where:

VFB - Void filled with bitumen.

VMA - Void in mineral aggregate.

V_a - Air void.

The Marshall Stability test measured the maximum load supported by the specimen before failure, while the flow value represented the deformation corresponding to the maximum load. The ratio of stability to flow was used as an indicator of the stiffness and resistance of the mix to plastic deformation.

Experimental Variables and Control Mix

The experimental program consisted of the following series:

Control Mix: Prepared with 100% natural fine aggregate.

Modified Mixes: Prepared with 10%, 20%, 30%, and 40% replacement of fine aggregate by vitrified tile waste.

The control mix results were used as a reference to determine the optimum replacement level. The optimum bitumen content (OBC) obtained from Paper 1 was 5.5%, and this bitumen content was adopted for the performance evaluation of all modified mixes.

Summary of Laboratory Test Procedures

All tests were performed in accordance with the following standards:

ASTM D6926 – 20: Preparation of asphalt mixture specimens using Marshall apparatus.

ASTM D6927 – 20: Marshall stability and flow of bituminous mixtures.

ASTM D2041 – 11: Theoretical maximum specific gravity and density of bituminous paving mixtures.

ASTM D2726 – 19: Bulk specific gravity and density of non-absorptive bituminous mixtures.

ASTM D3203 – 17: Percent air voids in compacted dense and open asphalt mixtures.

RESULTS AND DISCUSSION

This section presents the results of the laboratory tests carried out on both the control and the modified hot mix asphalt (HMA) incorporating vitrified tile waste (VWT) as a partial replacement for fine aggregates. The results are analyzed and discussed based on the Marshall stability and flow, bulk density, air voids, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) values. The trends observed in these parameters are discussed in relation to the Nigerian General Specification for Roads and Bridges (1997).

Marshall Stability

The Marshall stability values for the control and modified mixes are presented in Table 1. The stability increased steadily with increasing percentages of vitrified tile waste up to 30% replacement, after which it slightly decreased at 40%. This shows that the inclusion of VWT enhanced the strength and load-bearing capacity of the asphalt mixtures up to an optimum level.

Table 1: Marshall Stability Values for Control and Modified Mixes

% Replacement of Fine Aggregate	Stability (kN)
0	4.68
10	4.90
20	5.10
30	5.41
40	5.06

The maximum stability value of 5.41 kN was obtained at 30% VWT replacement, which represents an increase of about 15.6% compared to the control mix. The increase in stability is attributed to the dense and angular nature of the vitrified tile

particles, which improves inter-particle friction and mechanical interlock. A slight decline at 40% replacement indicates that excessive substitution may limit proper binder coating and reduce cohesion.

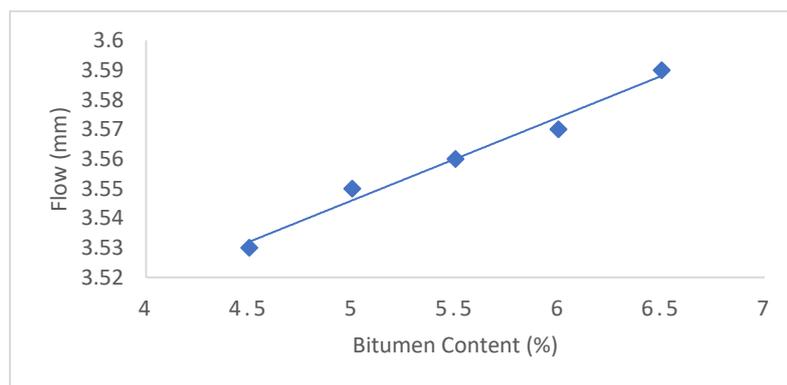


Figure 1: Variation of Flow of Hot Mix Asphalt with Bitumen Content

Similar findings were reported by Silvestre et al. (2013) and Lim et al. (2019), who observed that ceramic waste additions improve stability up to an optimum level before causing marginal reductions at higher replacements.

Flow Values

The flow values of the mixes are presented in Table 2. The flow decreased progressively with an increase in vitrified tile waste content up to 30%, indicating better resistance to deformation and improved stiffness.

Table 2: Flow Values for Control and Modified Mixes

% Replacement of Fine Aggregate	Flow (mm)
0	3.88
10	3.42
20	2.90
30	2.40
40	2.55

Flow values decreased as VWT content increased, reaching the minimum value at 30% replacement. Reduced flow implies higher stiffness and improved resistance to rutting. The slight increase observed at 40% suggests that overly rigid mixtures may compromise flexibility, making them more

susceptible to cracking under severe loading or temperature changes. The result agrees with Fatima et al. (2014), who noted that ceramic-based aggregates enhance rigidity while maintaining structural strength.

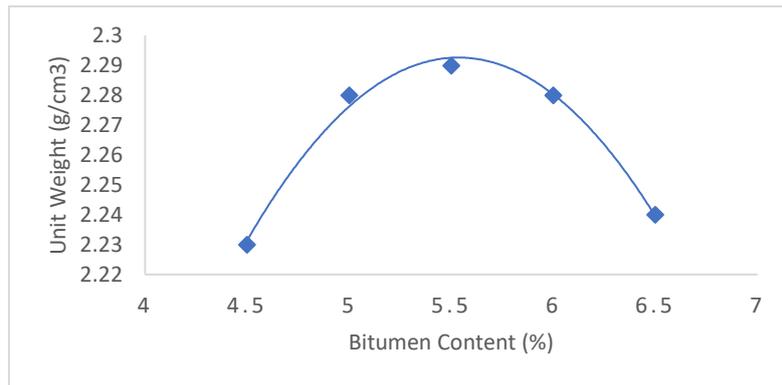


Figure 2: Variation of Unit Weight of Hot Mix Asphalt with Bitumen Content

Bulk Density

The bulk density of the mix increased as the percentage of vitrified tile waste increased, up to 30% replacement, as shown in Table 3.

Table 3: Bulk Density Values for Control and Modified Mixes

% Replacement of Fine Aggregate	Bulk Density (g/cm ³)
0	2.327
10	2.334
20	2.342
30	2.348
40	2.341

Bulk density increased with VWT incorporation up to 30%, reflecting improved compaction and the relatively higher specific gravity of vitrified tile particles. The slight drop at

40% indicates the onset of reduced packing efficiency when excessive fine aggregate replacement occurs.

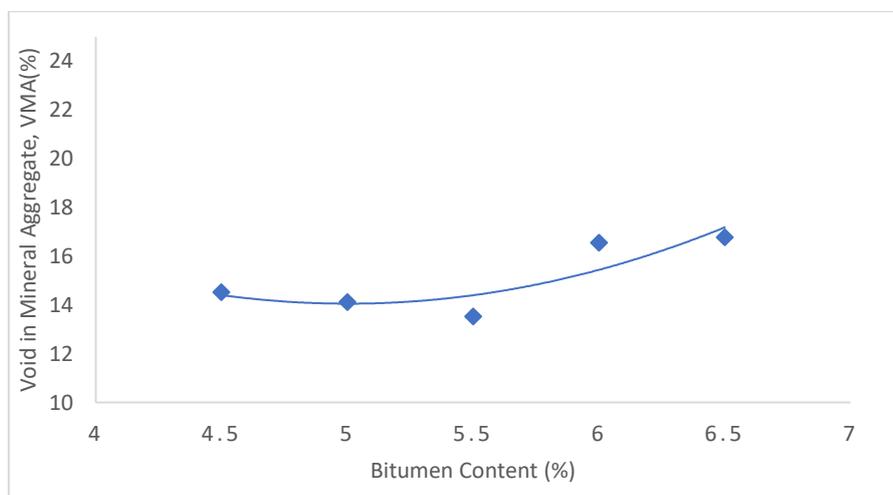


Figure 3: Variation of Void in Material Aggregate of Hot Mix Asphalt with Bitumen Content

Air Voids (Va), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB)

The results of air voids, VMA, and VFB for both control and modified mixes are presented in Table 4. It can be observed

that air voids and VMA decrease with increasing VWT content, while VFB increases correspondingly.

Table 4: Volumetric Properties of Control and Modified Mixes

% Replacement of Fine Aggregate	Air Voids (%)	VMA (%)	VFB (%)
0	4.7	13.9	66.2
10	4.5	13.7	67.1
20	4.2	13.5	68.9
30	3.9	13.2	70.5
40	4.3	13.6	68.3

The reduction in air voids and VMA suggests better packing and densification of the mix with increased replacement of fine aggregates by vitrified tile waste. The increase in VFB values indicates that the bitumen effectively filled the available voids, improving durability and resistance to

moisture damage. The optimum condition was achieved at 30% VWT replacement, which yielded 3.9% air voids, 13.2% VMA, and 70.5% VFB, all within the recommended limits specified by NGSRB (1997).

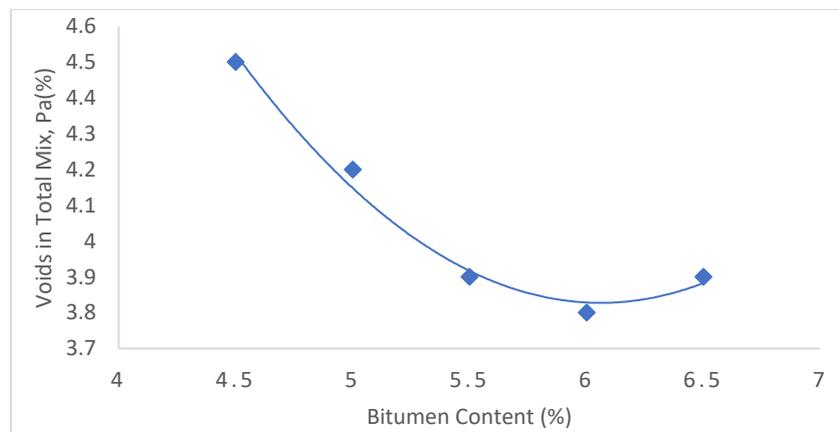


Figure 4: Variation of Voids in Total Mix of Hot Mix Asphalt with Bitumen Content

Comparison with Standard Specifications

A comparison of the Marshall properties of the modified mix at 30% replacement with the Nigerian General Specification

(1997) is shown in Table 5. It can be seen that all the parameters obtained meet the specified requirements.

Table 5: Comparison of VWT-Modified Mix with NGSRB Specifications

Property	30% Replacement	NGSRB Specification (Wearing Course)	Compliance
Stability (kN)	5.41	≥ 3.50	✓
Flow (mm)	2.40	2 – 4	✓
Bulk Density (g/cm ³)	2.348	–	✓
Air Voids (%)	3.9	3 – 5	✓
VMA (%)	13.2	≥ 12	✓
VFB (%)	70.5	65 – 75	✓

The results confirm that vitrified tile waste can be successfully utilized as a fine aggregate replacement in hot mix asphalt. The modified mix at 30% replacement produced superior performance values that fully satisfy the NGSRB specifications.

The improvement in stability and bulk density, along with the reduction in flow and air voids, indicates enhanced cohesion, compaction, and strength of the asphalt mix. This demonstrates that vitrified tile waste contributes positively to the structural and volumetric properties of hot mix asphalt.

CONCLUSION

Based on the laboratory results and analysis, the following conclusions are drawn, The inclusion of vitrified tile waste in asphalt mixtures can be effectively incorporated as a fine

aggregate replacement in hot mix asphalt. The optimum replacement levels up to 30% consistently improved stability, stiffness, and compaction characteristics, producing a mixture with superior mechanical performance. Air voids and VMA decreased with increasing VWT content, while VFB increased, indicating better compaction and lower permeability. All Marshall and volumetric properties at 30% VWT satisfied the Nigerian General Specification for wearing course applications, making this the optimum replacement level. The reuse of vitrified tile waste offers a practical approach for reducing construction waste while providing a technically sound material for flexible pavement construction. This approach encourages sustainable resource utilization and contributes to environmentally responsible engineering practices.

REFERENCES

- ASTM C 33/C 33M-22 (2022). *Standard Specification for Concrete Aggregates*. West Conshohocken, PA: American Society for Testing and Materials (ASTM) International.
- ASTM D2041-11: *Standard Test Method for Theoretical Maximum Specific Gravity and Density of Asphalt Mixtures*. ASTM International, West Conshohocken, PA.
- ASTM D2726-19: *Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixtures*. ASTM International, West Conshohocken, PA.
- ASTM D3203-17: *Standard Test Method for Percent Air Voids in Compacted Asphalt Mixtures*. ASTM International, West Conshohocken, PA.
- ASTM D6926-20. (2020). *Standard Practice for Preparation of Asphalt Mixture Specimens Using Marshall Apparatus*. West Conshohocken, PA: American Society for Testing and Materials (ASTM) International.
- ASTM D6927–20 (2020). *Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures*. West Conshohocken, PA: American Society for Testing and Materials (ASTM) International.
- European Standard (EN) 12697-22:2022 - "Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 22: Wheel Tracking".
- Fatima, E., Sahu, S., Jhamb, A., & Kumar, R. (2014). Use of ceramic waste as filler in semi-dense bituminous concrete. *American Journal of Civil Engineering and Architecture*, 2(3), 102-106.
- Hossain, W. A. (2021). Production of Lightweight Concrete by Using Polystyrene (Cork) Waste. In *Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012128). IOP Publishing.
- Huang, Y. H. (2009). *Pavement Analysis and Design* (2nd ed.). Pearson Prentice Hall, New Jersey.
- Lim, M. B., Mortera, R. I. M., Pangilinan, D. J. C. B., & Macario, V. S. P. (2019). Pulverized ceramic tile waste as potential mineral filler in hot mix asphalt. *Journal of the Eastern Asia Society for Transportation Studies*, 13, 1616–1629.
- Lira, B. E. R. N. A. R. D. I. T. A. (2020). *Influence of aggregates on permanent deformation of asphalt. (Elektroniskt) Tillgänglig: Influence of aggregates (2023-08-17)*.
- Nigeria Specification for Roads and Bridges. (NGSRB) (1997). *Federal Ministry of Works & Housing, Abuja*.
- Pipil, P., Tomer, T., & Payal, R. (2024). *Ceramics as potential materials in pollution prevention and control. International Journal of Applied Ceramic Technology*.
- Rahman, M. T. (2013). Performance evaluation of asphalt mixtures incorporating waste materials. *Journal of Materials in Civil Engineering*, 25(12), 1857–1865.
- Shamsaei, M., Khafajeh, R., Ghasemzadeh Tehrani, H., & Aghayan, I. (2020). Experimental evaluation of ceramic waste as filler in hot mix asphalt. *Clean Technologies and Environmental Policy*, 22, 535-543.
- Silvestre, R., Medel, E., García, A., & Navas, J. (2013). *Using ceramic wastes from tile industry as a partial substitute of natural aggregates in hot mix asphalt binder courses. Construction and Building Materials*, 45, 115–122.
- Sunarjono, S., Mumfaz, Z. Z., Hidayati, N., & Harnaeni, S. R. (2024, February). Durability test method of hot mix asphalt: A review. In *AIP Conference Proceedings* (Vol. 2838, No. 1). AIP Publishing.
- Yuan, Q., Robert, D., Mohajerani, A., Tran, P., & Pramanik, B. K. (2022). Utilisation of waste-to-energy fly ash in ceramic tiles. *Construction and Building Materials*, 347, 128475.
- Zanelli, C., Conte, S., Molinari, C., Soldati, R., & Dondi, M. (2021). Waste recycling in ceramic tiles: A technological outlook. *Resources, Conservation and Recycling*, 168, 105289.

