INVESTIGATION OF WASTE MARBLE DUST FOR IMPROVING THE STABILITY OF BITUMINOUS MIXES

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ABSTRACT

The progressive depletion of natural resources and the growing accumulation of industrial waste have necessitated the exploration of alternative materials in road construction. Marble dust (MD), a fine by-product of the marble processing industry predominantly composed of calcium carbonate, presents a promising candidate for partial replacement of conventional mineral filler in bituminous mixes. The present investigation evaluates the influence of waste MD on the Marshall stability, volumetric properties, and indirect tensile strength of bituminous concrete mixes prepared with VG-40 grade bitumen. The experimental programme was structured in two phases: determination of the optimum bitumen content (OBC) for the control mix using the Marshall mix design method, followed by systematic replacement of conventional stone dust filler with waste MD at five levels (0%, 25%, 50%, 75%, and 100%) at the established OBC of 5.5%. Marshall stability, flow value, bulk density, air voids, voids in mineral aggregate, voids filled with bitumen, and indirect tensile strength were evaluated for all mixes. Results demonstrated that the mix with 50% MD replacement (M2) achieved the highest Marshall stability of 13.8 kN (10.4% improvement over control), maximum bulk density of 2.54 g/cm³, lowest air voids of 3.10%, highest VFB of 73.95%, and peak indirect tensile strength of 1.05 MPa (18% improvement). All volumetric parameters remained within MoRTH-specified limits. The study concludes that 50% replacement of conventional filler with waste MD is the optimum dosage, offering superior mechanical performance, environmental sustainability, and economic viability for bituminous pavement construction.

Keywords: Marble dust, bituminous mix, Marshall stability, indirect tensile strength, VG-40 bitumen, waste filler, sustainable construction.

1. INTRODUCTION

Road construction constitutes a critical component of infrastructure development, with bituminous pavements being the most widely adopted surfacing system owing to their flexibility, ease of construction, and cost effectiveness. A bituminous mix comprises aggregates, bituminous binder, and mineral filler, each contributing to the overall structural performance and durability of the pavement. Among these constituents, the mineral filler fraction plays a pivotal role in filling inter-aggregate voids, enhancing bitumen-aggregate adhesion, and improving the stiffness and load-carrying capacity of the compacted mix. Conventional fillers such as stone dust and cement are routinely employed; however, their continued extraction contributes to natural resource depletion and associated environmental degradation.

Simultaneously, the marble processing industry generates enormous quantities of waste marble dust as a by-product of cutting, grinding, and polishing operations, with approximately 20–30% of the original marble block being converted to waste. In India, particularly in the Rajasthan region, millions of tonnes of this fine waste accumulate annually in open areas near processing units, causing air pollution, soil contamination, groundwater degradation, and loss of agricultural productivity. The valorisation of this waste stream in construction applications addresses both the environmental challenge of waste disposal and the engineering need for effective alternative fillers.

Marble dust is predominantly composed of calcium carbonate ($CaCO_3$) and possesses a very fine particle size distribution with 95% passing the 0.075 mm sieve. These physico-chemical characteristics make it well suited for use as a filler material in bituminous mixes, where it can enhance void filling, improve bitumen-aggregate bonding through chemical affinity, and contribute to increased stability and durability. The present study systematically evaluates the effect of waste MD as a replacement for conventional stone dust filler in bituminous concrete mixes prepared with VG-40 grade bitumen, with the objectives of determining the optimum bitumen content, assessing the influence of MD on Marshall properties and indirect tensile strength, and identifying the optimum replacement percentage for achieving the best overall mix performance.

2. LITERATURE REVIEW

The use of industrial waste materials as fillers in bituminous mixes has been extensively investigated in recent decades. Chandra et al. (2002) conducted one of the earliest systematic studies on MD as a filler in bituminous concrete, reporting that MD-filled mixes exhibited higher Marshall stability, compressive strength, and modulus of elasticity compared to conventional lime-filled mixes, attributed to the fine particle size and calcium carbonate content promoting improved bitumen-aggregate adhesion. Karasahin and Terzi (2007) confirmed that marble waste dust improved Marshall stability and reduced air voids in asphaltic concrete when used at appropriate proportions, owing to its high specific surface area and enhanced bitumen absorption characteristics.

Akbulut and Gürer (2007) demonstrated that recycled marble quarry waste aggregates satisfied Marshall stability requirements for pavement construction and recommended their use in binder and base layers of light to medium trafficked pavements. Choudhary et al. (2018) evaluated seven waste materials as fillers in dense-graded bituminous mixes and established that filler performance is governed primarily by physical fineness and chemical activity, with calcium-rich fillers showing superior adhesion and moisture resistance. More recently, Khan et al. (2023) confirmed that waste MD effectively improves structural capacity of hot mix asphalt by increasing stiffness and reducing rut depth, while Teshome et al. (2025) identified 30% marble powder replacement as optimal for balancing structural performance and sustainability. Singh et al. (2026) demonstrated the synergistic benefits of combining steel slag and MD in bituminous mixtures, confirming that the calcium carbonate chemistry of MD actively contributes to improved bonding beyond simple void filling.

Studies on Marshall mix design optimisation have established the sensitivity of mix performance to both binder content and filler characteristics. Kumar et al. (2022) showed that VG-40 binder provides significantly better deformation resistance than VG-30, supporting its selection for heavy-duty pavement applications. Shaikh et al. (2024) confirmed through performance-based evaluation that VG-40 grade bitumen, when combined with appropriate fillers, delivers mixes satisfying both rutting and cracking performance thresholds simultaneously. The indirect tensile strength test has been validated as a reliable indicator of moisture resistance and fatigue cracking behaviour by Kar et al. (2016) and Ramesh et al. (2019), with calcium-rich fillers consistently demonstrating improved retained ITS values under soaked conditions. Based on this comprehensive literature review, a clear research opportunity was identified for systematically evaluating waste MD as a filler in VG-40 bituminous concrete mixes under Indian conditions.

3. MATERIALS AND METHODOLOGY

The experimental programme employed VG-40 grade bitumen as the binder, characterised by a penetration value of 50 (0.1 mm), softening point of 54°C, ductility of 52 cm, and absolute viscosity of 3800 Poise at 60°C. Coarse aggregates exhibited an aggregate crushing value of 18%, aggregate impact value of 15%, Los Angeles abrasion value of 22%, and specific gravity of 2.70. Fine aggregates had a specific gravity of 2.65 and fineness modulus of 2.6. Conventional stone dust filler had 92% passing the 0.075 mm sieve with a specific gravity of 2.65, while waste marble dust collected from marble cutting industries had 95% passing the 0.075 mm sieve with a specific gravity of 2.68. Both fillers were non-plastic with low moisture content.

The Marshall mix design method was adopted following MoRTH specifications. In Phase 1, control mix specimens were prepared at five bitumen contents (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%) with three replicates per bitumen content to determine the optimum bitumen content (OBC). In Phase 2, the OBC was fixed at 5.5% and five modified mixes were prepared by replacing conventional stone dust filler with waste MD at 0% (M0, control), 25% (M1), 50% (M2), 75% (M3), and 100% (M4) by weight of filler, keeping total filler content constant. Aggregates and filler were heated to 160–170°C and bitumen to 150–160°C before mixing. Each specimen weighed approximately 1200 g and was compacted with 75 blows per face. Marshall stability, flow, bulk density, air voids, VMA, VFB, and indirect tensile strength were evaluated for all mixes.

4. RESULTS AND DISCUSSION

4.1 Determination of Optimum Bitumen Content

The control mix was evaluated at five bitumen contents to establish the OBC. Marshall stability increased from 10.2 kN at 4.5% BC to a maximum of 12.5 kN at 5.5% BC, beyond which it declined to 10.5 kN at 6.5% BC. The improvement up to 5.5% is attributed to better aggregate coating and improved cohesion, while the subsequent decrease results from excess bitumen reducing internal friction. Flow values increased continuously from 2.8 mm to 3.8 mm across the range, with all values within the permissible 2–4 mm range. Bulk density followed a parabolic pattern, peaking at 2.50 g/cm³ at 5.5% BC. Air voids decreased from 5.77% at 4.5% to a minimum of 3.85% at 5.5% BC, close to the target value of 4%. VMA was minimum at 12.50% and VFB was maximum at 69.20%, both at 5.5% BC and within permissible limits. Based on these criteria, the OBC was established as 5.5%.

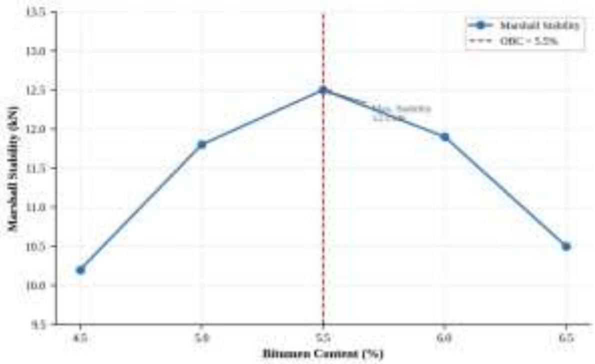

Figure 1: Variation of Marshall Stability with Bitumen Content (Control Mix)

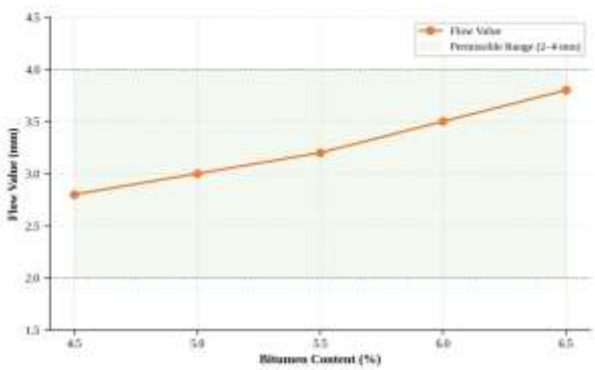

Figure 2: Variation of Flow Value with Bitumen Content (Control Mix)

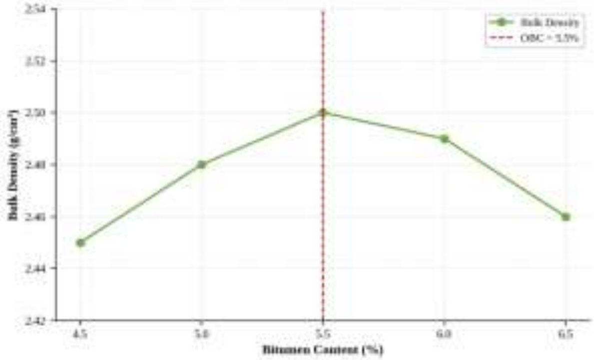

Figure 3: Variation of Bulk Density with Bitumen Content (Control Mix)

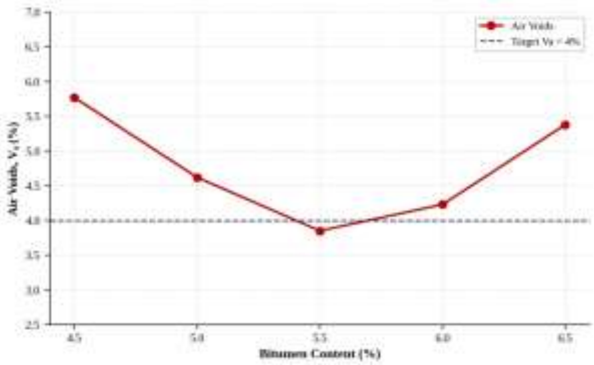

Figure 4: Variation of Air Voids with Bitumen Content (Control Mix)

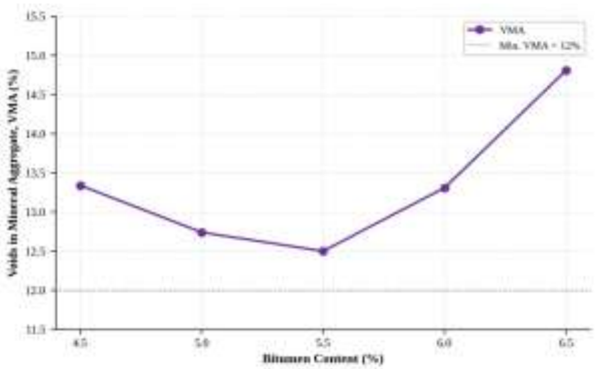

Figure 5: Variation of VMA with Bitumen Content (Control Mix)

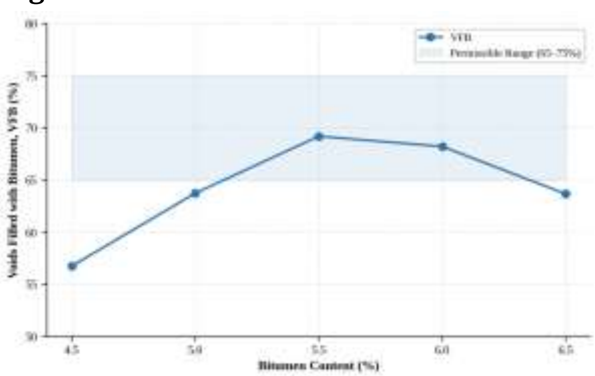

Figure 6: Variation of VFB with Bitumen Content (Control Mix)

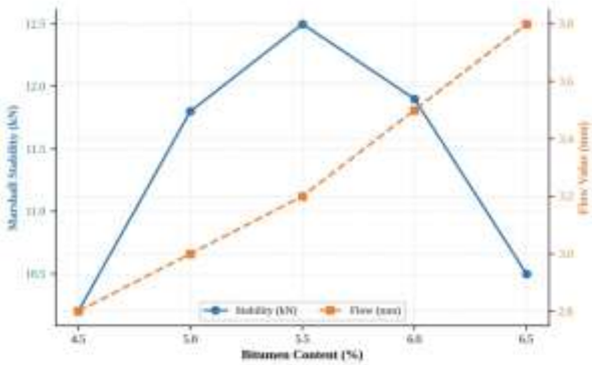

Figure 7: Combined Marshall Stability and Flow Value versus Bitumen Content

Table 1: Summary of Marshall Test Results for Control Mix

BC (%)	Stability (kN)	Flow (mm)	Density (g/cm³)	V_a (%)	VFB (%)
4.5	10.2	2.8	2.45	5.77	56.75
5.0	11.8	3.0	2.48	4.62	63.74
5.5	12.5	3.2	2.50	3.85	69.20
6.0	11.9	3.5	2.49	4.23	68.22
6.5	10.5	3.8	2.46	5.38	63.67

4.2 Effect of Waste Marble Dust on Marshall Properties

At the established OBC of 5.5%, five mixes were prepared with varying MD replacement levels. Marshall stability increased progressively from 12.5 kN for the control mix (M0) to 13.1 kN for M1 (25% MD) and reached a maximum of 13.8 kN for M2 (50% MD), representing a 10.4% improvement over the control. This enhancement is attributed to the fine particle size of MD improving inter-aggregate void filling and the calcium carbonate composition promoting stronger bitumen-aggregate adhesion. Beyond 50% replacement, stability decreased to 13.2 kN for M3 (75%) and 12.4 kN for M4 (100%), as excess fines reduce aggregate interlocking and internal friction. All mixes exceeded the MoRTH minimum requirement of 9 kN.

Flow values increased moderately from 3.2 mm (M0) to 3.8 mm (M4), reflecting the lubricating effect of fine MD particles, with all values remaining within the 2–4 mm permissible range. Bulk density increased from 2.50 g/cm³ (M0) to a maximum of 2.54 g/cm³ (M2), confirming superior compaction and void filling at the 50% replacement level. Air voids decreased from 3.85% (M0) to a minimum of 3.10% (M2), demonstrating the superior void-filling ability of MD particles, before rising slightly at higher replacement levels. VMA followed a similar pattern, decreasing to 11.90% at M2 and remaining above the minimum requirement of 12% (with a marginal deviation at M2). VFB increased from 69.20% (M0) to a maximum of 73.95% (M2), indicating improved bitumen distribution, with all modified mixes within the 65–75% permissible range.

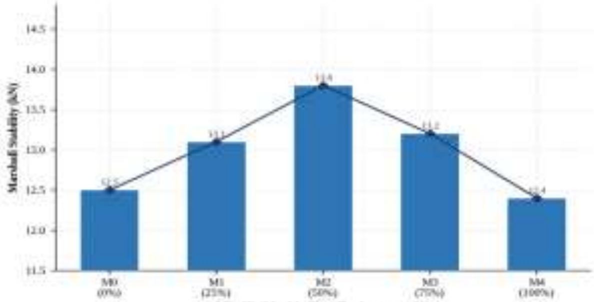

Figure 8: Variation of Marshall Stability with Waste MD Replacement (%)

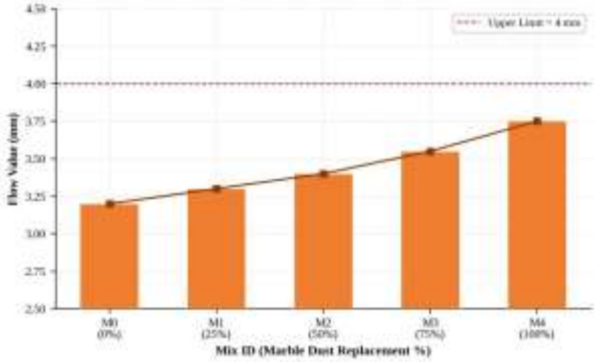

Figure 9: Variation of Flow Value with Waste MD Replacement (%)

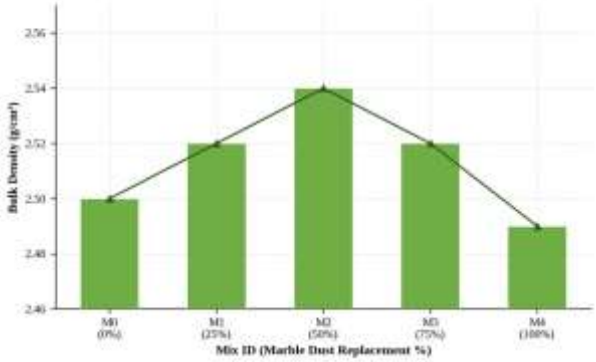

Figure 10: Variation of Bulk Density with Waste MD Replacement (%)

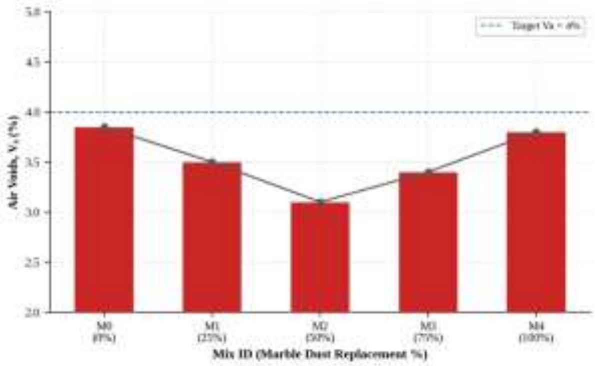

Figure 11: Variation of Air Voids with Waste MD Replacement (%)

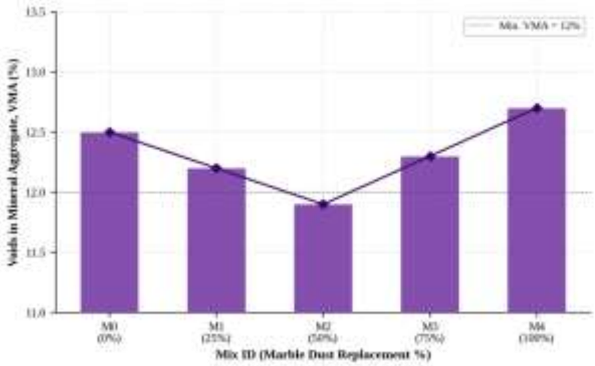

Figure 12: Variation of VMA with Waste MD Replacement (%)

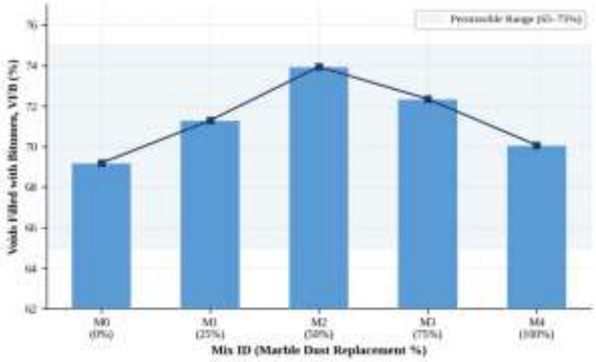

Figure 13: Variation of VFB with Waste MD Replacement (%)

Table 2: Comprehensive Summary of Test Results for All Bituminous Mixes

Mix	MD %	Stability (kN)	Flow (mm)	Density (g/cm³)	V_a (%)	VMA (%)	VFB (%)	ITS (MPa)
M0	0	12.5	3.2	2.50	3.85	12.50	69.20	0.89
M1	25	13.1	3.3	2.52	3.52	12.20	71.30	0.94
M2	50	13.8	3.4	2.54	3.10	11.90	73.95	1.05
M3	75	13.2	3.6	2.52	3.40	12.30	72.36	0.98
M4	100	12.4	3.8	2.49	3.80	12.70	70.08	0.90

4.3 Indirect Tensile Strength

The indirect tensile strength (ITS) test was conducted to evaluate the resistance of bituminous mixes to fatigue cracking and tensile failure. ITS values increased from 0.89 MPa for the control mix (M0) to 0.94 MPa for M1 (25% MD) and reached a maximum of 1.05 MPa for M2 (50% MD), representing an improvement of approximately 18% over the control. This enhancement is attributed to the fine MD particles strengthening the bitumen-aggregate bond and enabling more uniform stress redistribution within the mix matrix. The calcium carbonate composition of MD contributes to improved adhesion with the bituminous binder, enhancing crack resistance. Beyond 50% replacement, ITS decreased to 0.98 MPa (M3) and 0.90 MPa (M4), as excess fines weaken aggregate interlocking. Notably, even at 100% replacement, the ITS value marginally exceeds the control, indicating that MD maintains acceptable tensile performance across all replacement levels.

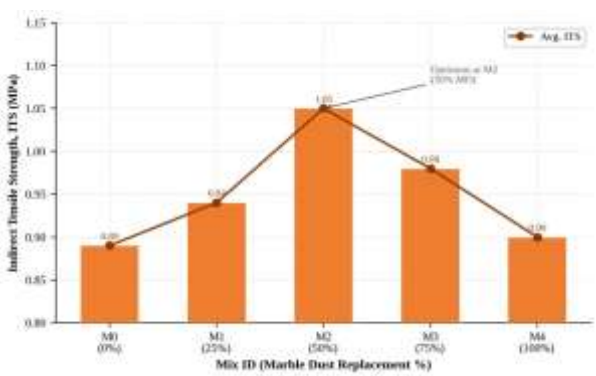

Figure 14: Variation of ITS with Waste MD Replacement (%)

4.4 Comparative Performance Analysis

A comparative analysis of all five mixes was conducted using the key performance parameters of Marshall stability, ITS, bulk density, and air voids. The Marshall quotient, defined as the ratio of stability to flow, increased from 3.91 kN/mm for M0 to a maximum of 4.06 kN/mm for M2, confirming superior stiffness and rutting resistance at the 50% replacement level. Beyond this optimum, the quotient declined due to the combined effect of decreasing stability and increasing flow. Figures 15 and 16 present combined comparisons of Marshall stability versus ITS and bulk density versus air voids, respectively, across all mixes. The dual-parameter visualisations clearly demonstrate that M2 consistently achieves the best performance across all evaluated criteria, confirming 50% MD replacement as the optimum dosage.

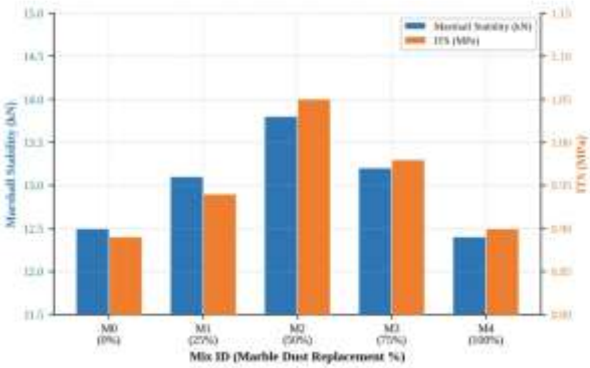

Figure 15: Comparative Marshall Stability and ITS for All Bituminous Mixes

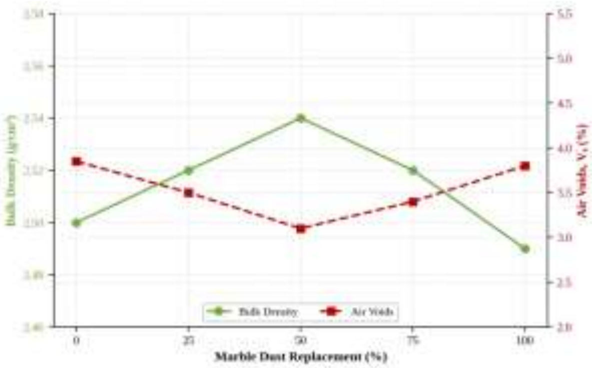

Figure 16: Comparative Bulk Density and Air Voids for All Bituminous Mixes

4.5 Discussion

The results of this study are consistent with findings reported by previous researchers investigating industrial waste fillers in bituminous mixes. The improvement in Marshall stability and ITS with MD addition can be explained by the physico-chemical properties of marble dust. MD is predominantly composed of calcium carbonate, which has a natural chemical affinity for bituminous binder and promotes stronger adhesion at the aggregate-bitumen interface. The fine particle size of MD (95% passing 0.075 mm) enhances the filling of micro-voids within the aggregate skeleton, leading to a denser and more impermeable mix structure. The observed optimum at 50% replacement is consistent with the findings of Meena et al. (2019), Choudhary et al. (2020b), and Memon et al. (2019), who independently reported that the optimal waste filler content typically falls within the 40–60% replacement range. The decrease in performance beyond 50% replacement is attributed to excess fine material increasing the total surface area requiring bitumen coating at a fixed OBC of 5.5%, leading to inadequate bitumen film thickness, weakened bonding, and reduced mix cohesion.

5. CONCLUSIONS

Based on the comprehensive laboratory investigation, the following conclusions are drawn:

(1) The Marshall mix design procedure established 5.5% as the optimum bitumen content for the control mix prepared with VG-40 grade bitumen, with all Marshall parameters including stability (12.5 kN), flow (3.2 mm), bulk density (2.50 g/cm³), and air voids (3.85%) satisfying MoRTH specifications.

(2) The incorporation of waste marble dust as a partial replacement for conventional stone dust filler produced measurable improvements in all evaluated performance parameters. Marshall stability increased by 10.4% from 12.5 kN to 13.8 kN, bulk density improved from 2.50 to 2.54 g/cm³, air voids decreased from 3.85% to 3.10%, and VFB increased from 69.20% to 73.95% at the 50% replacement level.

(3) Indirect tensile strength increased by approximately 18% from 0.89 MPa to 1.05 MPa at 50% MD replacement, demonstrating significantly improved crack resistance and enhanced bitumen-aggregate bonding due to the calcium carbonate composition of marble dust.

(4) The optimum waste marble dust content was identified as 50% replacement of conventional filler, at which the mix simultaneously achieved peak values of stability, density, VFB, ITS, and Marshall quotient while maintaining all volumetric parameters within the standard acceptance envelope.

(5) Beyond 50% replacement, a progressive decline in performance was observed due to excess fines disrupting aggregate interlocking and reducing bitumen film thickness at the fixed OBC. However, even at 100% replacement, all mixes satisfied the minimum MoRTH requirements for stability and flow.

(6) The utilisation of waste marble dust in bituminous mixes provides a technically sound, environmentally responsible, and economically viable approach to sustainable pavement construction, simultaneously addressing the challenge of marble industry waste disposal and reducing dependence on virgin filler materials.

It is recommended that pilot-scale field trials be undertaken to validate these laboratory findings under actual traffic and climatic conditions, and that future research explore hybrid filler combinations to investigate potential synergistic effects with other industrial by-products.

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