

INCREASING ROAD PERFORMANCE USING WASTE PLASTIC-COATED BITUMEN AGGREGATE WITH TITANIUM DIOXIDE

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ABSTRACT

Vehicle pollution and the management of plastic waste are two of the most serious environmental problems facing the world today. These problems not only threaten the ecosystem but also create significant negative effects to people and other living beings. This study examines bituminous road construction using waste plastic and titanium dioxide (TiO₂). To provide photocatalytic and self-cleaning properties, TiO₂ has been included either as a nano-additive in the binder or as a surface coating. Thermoplastic wastes, including Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE), were shredded and mixed with hot bitumen. According to previous studies, Stiffness, Marshall stability, rutting resistance, and binder-aggregate adhesion are all enhanced by plastic-coated aggregates. Through photocatalysis, TiO₂ also helps reduce nitrogen oxides (NOx) and organic pollutants; however, improvement is needed to increase its dispersion and long-term durability. The present research shows a feasible and reliable approach from laboratory testing to material selection. The results of the experiment indicate that Waste Plastic-Coated Bitumen Aggregate (WPCBA) provides stronger, more resilient, and longer-lasting pavements than traditional bituminous mixtures, with 38.9% increase in Marshall stability, 31% decrease in abrasion value, and 25% decrease in crushing value. This unique mix helps create adaptable, affordable, and environmentally friendly pavements while promoting sustainable waste management.

Keywords: Waste plastic, Waste Plastic-Coated Bitumen Aggregate (WPCBA), Marshall stability, Stiffness.

1. INTRODUCTION

Rapid urbanization and the increasing number of vehicles in India are contributing to two significant environmental challenges: the accumulation of plastic waste and rising atmospheric pollution from vehicle emissions. In 2024, India generates approximately 9.3 million tonnes of plastic annually, which translates to around 25,000 tonnes per day nationwide. Conventional disposal methods, such as landfilling and incineration, not only fail to address the growing plastic burden but also result in environmental degradation and public health hazards. An innovative solution lies in the Utilizing plastic waste in road construction, where shredded plastic is blended with aggregates and coated with hot bitumen. This approach provides an economical and adaptable approach to simultaneously manage plastic waste and enhance the pavements' durability and mechanical properties. In addition to plastic utilization, titanium dioxide, particularly on the nanoscale, has been extensively studied for its properties of photocatalysis, which enable the degradation of nitrogen oxides (NOx) and certain volatile organic compounds (VOCs) under ultraviolet light. Incorporating TiO₂ into pavements can transform ordinary road surfaces into active construction projects that reduce pollution, potentially improving urban air quality and reducing public exposure to harmful pollutants. By combining Using TiO₂ photocatalysis for integrating waste plastic, road construction can evolve into an combined methodology to environmental management, addressing both solid waste and air pollution challenges.

2. LITERATURE REVIEW

The use of waste plastics and nanomaterials in bituminous pavements has gained significant attention in recent years due to environmental concerns and the need for durable road materials.

M. K. Pandey et al. (2022) reported that incorporating waste plastic as a modifier in bitumen not only improves pavement performance but also helps shield the environment from more pollutants, thus contributing to ecosystem sustainability. Similarly, Singh et al. (2018) emphasized the prevalence of plastic in domestic and industrial applications, highlighting the importance of finding sustainable avenues for its reuse in infrastructure. Research into the integration of Materials for photocatalysis has shown promising results. Chavan et al. (2019) tested various bitumen samples with titanium dioxide (TiO₂) as a photocatalyst and observed no negative impacts on the characteristics of bitumen, suggesting its suitability for environmental applications. L. A. Romero et al (2022) conducted experimental trials combining TiO₂ powder added to plastic-modified bitumen, demonstrating the possibility of dual-purpose pavements that offer both environmental advantages and mechanical improvement. Investigations into asphalt binder modification also provide insights into material performance. S. K. Choudhary (2019), who reported enhanced strength and durability of the pavements. Environmental considerations have been noted as well. C.K Lam et al. (2021) raised concerns about the possibly microplastic emission from asphalt processed with polymers, underscoring the need to balance performance improvement with ecological safety. Finally, M. R. Islam et al (2020) discussed the behavior of bituminous concrete in composite, providing a fundamental understanding of how modifications interact with conventional pavement materials. Based on the literature review it has been found that a very few studies have explored the Utilizing waste plastic-coated bituminous aggregates (WPCBA) when combined with titanium dioxide (TiO₂).

3. RESEARCH GAP

Most existing research investigates these materials separately, either focusing on plastic in pavement or TiO₂ for environmental purposes.

Secondly, TiO₂ has predominantly incorporated directly into bitumen rather than applied to plastic coated aggregates. There is a lack of studies analyzing how TiO₂ interacts with the plastic film on aggregate surfaces, including stability of the coating, chemical bonding, and long-term durability.

Thirdly, almost no studies on WPCBA with TiO₂. WPCBA for improved mechanical efficiency with TiO₂ for environmental performance presents an opportunity to develop pavements with several uses that are not only stronger and more durable but also capable of reducing air pollution in cities. Taking into consideration the literature review and research gaps the objectives of the present paper are provided as below.

4. OBJECTIVES

a) To perform laboratory tests in order to evaluate and compare the performance of waste plastic-coated bitumen aggregates (WPCBA) and traditional aggregates in bituminous road construction.

b) To create waste plastic coated bitumen aggregate and add titanium dioxide (TiO₂) in order to investigate how they improve pavement performance and environmental functioning when combined.

5. MATERIALS AND METHODS

5.1 Materials: Waste Plastic: The most common forms of plastic that encounter in the literature are packaging (PP), carry bags (LDPE), and bottles (HDPE). Bituminous concrete consists of a mixture of aggregates continuously graded from maximum size, typically less than 25 mm, through the fine filler that is smaller than 0.075 mm. Bitumen 5.5 % is added to the mix so that the compacted mix is effectively impervious and will have acceptable dissipative and elastic properties. The bituminous mix design aims to determine the proportion of bitumen, filler, fine aggregates, and coarse aggregates to produce a mix which is workable, strong, durable and economical. Mixing temperature of mixed 135°C-165°C and laying temperature 120°C-150°C.

Table 1 Physical properties of plastic.

Sr.no	Property	Value
1	Density	0.92gm/cc
2	Tensile Strength	10MPa
3	Flexural modulus	0.25GPa
4	Max. operating temperature	500c
6	Absorption water	0.01%

Aggregates: Both fine and coarse crushed stone aggregates which fulfill MORTH requirements are used. Aggregates are regularly graded from fine filler to a maximum size of 25 mm.

Bitumen: The weight percentage of bitumen in the entire mixture is 5.5%. Optimal workability, compaction, mechanical strength, and durability are the objectives of the mix's manufacturing process. Temperatures of 135 to 165°C are recommended for mixing, and 120 to 150°C for laying.

Titanium dioxide (TiO₂): TiO₂, in powder form, is applied onto the particles covered with plastic to provide photocatalytic activity, enabling the degradation of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under UV exposure.

6.RESULTS AND DISCUSSION

6.1. Marshall Stability Test: Marshall Stability refers to the maximum load that a bituminous specimen can withstand when subjected to a loading rate of 50.8 mm per minute. The load is gradually applied until it reaches a peak, at which point the test is stopped, and the peak load is recorded as the Marshall Stability. A dial gauge is used throughout the test to monitor the specimen's plastic deformation under the applied load. The term "flow value" represents the vertical deformation measured at the point of maximum load.

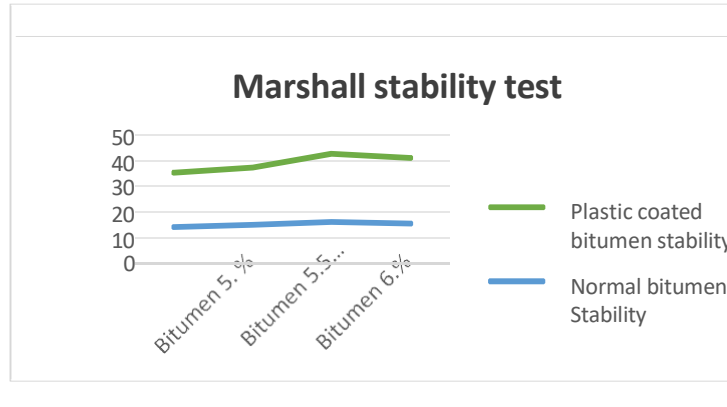


Figure 1: Marshall Stability Test Result

The inclusion of waste plastic forms a thin film between the aggregate and bitumen, enhancing bonding and reducing binder drainage. Literature reports varying degrees of improvement; however, in this study, significant increases in Marshall stability and reductions in flow values were observed. The highest stability was achieved at 5.5% bitumen content, whereas increasing the content to 6% resulted in a decrease in stability, indicating that 5.5% represents the optimum bitumen content for maximum strength. Before testing, specimens are immersed in a water bath at 60°C for 30–40 minutes to ensure proper conditioning.

6.2. Testing Procedure: The specimen is placed in the Marshall Stability testing machine, and the load is applied at a rate of 50 mm per minute. The Stability is recorded as the maximum load in kN before failure. The results indicate that the maximum stability occurred at 6% bitumen content. Increasing the bitumen content to 6.5% resulted in a decrease in Marshall Stability. Mixes incorporating waste plastic and TiO₂ exhibited enhanced stability and reduced flow values, indicating improved mechanical performance.

Table 2: Marshall Stability Test Results

Bitumen content in percentage	Weight of Aggregate (gm)	Stability of Normal bitumen concrete (KN)	Stability Plastic Coated-bitumen (KN)
4.5	1200	14.10	21.16
5.	1200	15.00	22.30
5.5	1200	16.20	26.50
6	1200	15.50	25.50

6.3. Aggregate Crushing Strength Test

The aggregate crushing test determines the strength of coarse aggregates under compressive loading. The crushing value indicates the aggregate's resistance to fracture under progressively increasing compression. Aggregates with high resistance to crushing (low crushing index) are preferable for high-quality paving applications. The results show a comparison between normal bitumen aggregates and waste plastic-coated aggregates:

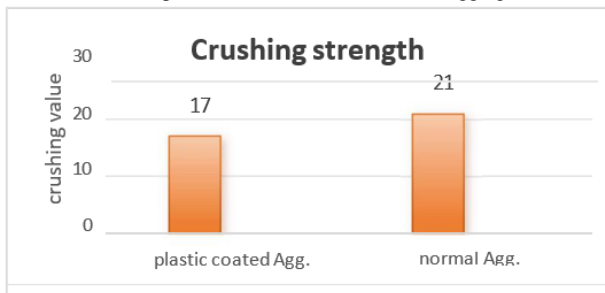


Figure 2: Crushing strength Test Result

Plastic-modified mixes exhibit enhanced rigidity and superior bitumen–aggregate adhesion, which contributes to reduced rutting in wheel-tracking tests. The data indicate improved rutting resistance under moderate temperatures and heavy loading conditions. When aggregates were coated with plastic, the aggregate crushing value decreased from 21 to 17 kN, a reduction of roughly 19–20%. This improvement is primarily attributed to the shredded plastic film, which reinforces the aggregates and makes them more resistant to crushing.

6.4. Abrasion Value Test

The abrasion value of aggregates decreased from 22 to 15, indicating approximately 31% improvement in rutting resistance when waste plastic was applied to the aggregates. Lower abrasion values correspond to higher hardness and improved durability of the pavement surface.

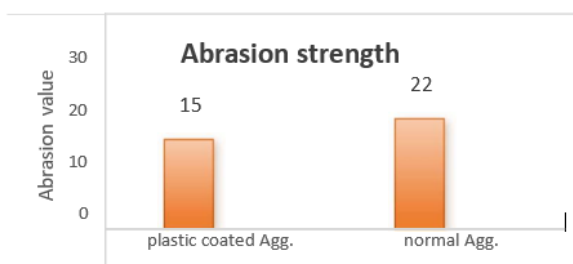


Figure 3: Abrasion Value Test Result

The Los Angeles abrasion value decreased from 22 to 15, corresponding to an approximate 31% improvement in rutting resistance when waste plastic was applied to aggregates. Lower abrasion values reflect increased hardness, improved durability, and enhanced surface wear resistance. TiO₂-coated pavements demonstrate the ability to degrade NO_x pollutants under light exposure. The rate of NO_x reduction depends on TiO₂ concentration, exposure time, light intensity, and surface cleanliness. These results highlight the potential for pavement surfaces to actively improve air quality.

7. CHALLENGES AND LIMITATIONS

Achieving simultaneous use of waste plastic with aggregates remains a significant technical challenge, as consistent adhesion between the bitumen and coated aggregates is critical for maintaining the durability and mechanical performance of the pavement. Maintaining the temperature when mixing is equally crucial: insufficient temperatures prevent proper melting and coating of the plastic onto aggregates, while excessive temperatures may degrade the plastic, potentially releasing toxic fumes and compromising material integrity. Maintaining optimal temperature ranges is therefore essential to ensure quality, safety, and workability. Although the use of waste plastic contributes to sustainability, the suspected microplastics release from pavement surfaces due to wear and tear poses a long-term environmental concern, necessitating proper monitoring and mitigation strategies. Additionally, the Equipment for coating, plastic shredding, and TiO₂ mixing beginning costs can be relatively high, which may limit large-scale adoption. Developing Using economical processing methods and maximizing resource use are critical to improve economic feasibility. Furthermore, modified pavements may require specific procedures for handling, compaction, and maintenance to Improve their mechanical and photocatalytic properties. The absence of standardized guidelines for these processes may present challenges for widespread utilization and reliable field results.

8. CONCLUSION

The present study demonstrates that Adding titanium dioxide (TiO₂) and waste plastic to bituminous pavements significantly enhances their mechanical and functional performance. Coating aggregates with waste plastic forms a thin, consistent film that improves the interfacial bonding, reduces binder drainage, and enhances overall mix cohesion. This results in lowered flow values, enhanced load-bearing capability, and increased Marshall stability, with the optimum performance observed at 5.5% bitumen content. Increasing the bitumen content beyond this value leads to a reduction in stability, highlighting the importance of optimal binder dosage for maximum strength. Furthermore, the Plastic-modified combinations are more resistant to rutting due to enhanced rigidity and improved bitumen-aggregate adhesion, ensuring better performance under moderate temperatures and heavy loading conditions. Aggregate testing showed decreased abrasion and crushing values, indicating higher hardness, durability, and resistance to mechanical deformation. The addition of Photocatalytic functionality is provided by TiO₂, enabling the pavement surface to degrade atmospheric pollutants, such as NO_x, under light exposure. This demonstrates the potential of the modified pavement to contribute to enhancement of air quality, while also enhancing UV resistance and aging durability. Overall, the combined use of titanium dioxide and waste plastic-coated aggregates offers an environmentally safe and sustainable solution for road construction. It improves mechanical strength, durability, and environmental performance, while providing an effective strategy for management of waste plastics.

This strategy is in keeping with the increasing need for sustainable methods of construction and green infrastructure.

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