International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 3, May-June 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Replacement of Steel Slag as Aggregate in Flexible Pavement

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Abstract:

Natural aggregates are one of the most important materials used in the construction sector. They are widely used in the construction of roads, concrete structures, and railway tracks. In concrete, aggregates make up about 50–60% of the total volume, while in road construction they account for nearly 75–80% of the materials used. Due to rapid urbanization and infrastructure development, the demand for natural aggregates is increasing continuously. Excessive extraction of these materials not only depletes natural resources but also creates environmental concerns.

To reduce the dependence on natural aggregates and promote sustainable construction practices, researchers are exploring the use of industrial by-products as alternative materials. Steel slag, which is generated during the steel manufacturing process, is one such material with significant potential. After cooling and processing, steel slag exhibits desirable engineering properties such as high strength, good resistance to impact, abrasion, and crushing, making it suitable for use in pavement construction.
However, steel slag has certain limitations. Its porous structure results in higher water absorption, which can lead to volume instability and affect long-term performance. Therefore, suitable treatment methods are required before its use as an aggregate. Surface treatments such as cement paste coating and oil paint coating have been reported to reduce water absorption and improve the durability of steel slag at a relatively low cost.

This study focuses on evaluating the suitability of steel slag as a replacement for natural aggregates in flexible pavement construction. Different replacement percentages of steel slag are considered to identify the optimum level that provides satisfactory strength and durability. The performance of treated steel slag is also assessed through various laboratory tests to determine its effectiveness as a sustainable and environmentally friendly alternative to conventional aggregates used in road construction.

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I. INTRODUCTION

The rapid growth of transportation infrastructure has significantly increased the demand for high-quality aggregates used in flexible pavement construction. Aggregates constitute the major portion of pavement layers and play a critical role in providing strength, stability, and durability under traffic loading. However, the continuous extraction of natural aggregates from quarries has led to depletion of natural resources, environmental degradation, and rising material costs. These challenges have encouraged researchers and highway agencies to investigate sustainable alternatives to conventional aggregates.

Steel slag, a by-product generated during steel manufacturing, has emerged as a promising substitute for natural aggregates in pavement applications. Large quantities of steel slag are produced annually by steel industries, and a considerable portion remains underutilized despite possessing favorable engineering characteristics. The material is characterized by high hardness, excellent abrasion resistance, rough surface texture, and angular particle shape, which are desirable properties for pavement aggregates. These characteristics enhance aggregate interlocking and improve the load-carrying capacity of pavement structures.

Fig 1. Steel slag production process.

The utilization of steel slag in flexible pavements offers both environmental and economic advantages. Its use reduces the demand for natural aggregates while simultaneously providing an effective solution for managing industrial waste. Furthermore, previous studies have indicated that steel slag can improve pavement performance by increasing stability, skid resistance, and resistance to rutting. Such improvements contribute to longer service life and reduced maintenance requirements.

Despite its potential benefits, certain limitations such as higher water absorption and the presence of free lime and free magnesia require careful evaluation before large-scale implementation. Therefore, a comprehensive assessment of the mechanical and physical properties of steel slag is necessary to determine its suitability as a pavement aggregate.

The present study investigates the feasibility of replacing conventional aggregates with steel slag in flexible pavement construction. Different replacement levels are examined to evaluate their influence on aggregate properties and pavement performance. The objective is to identify an optimum replacement percentage that satisfies engineering requirements while promoting sustainable utilization of industrial by-products in road infrastructure development.

The utilization of steel slag in road construction offers several advantages:

* Reduction in industrial waste disposal

* Conservation of natural aggregates

* Improved pavement performance

* Enhanced skid resistance

* Sustainable and eco-friendly construction

Despite these advantages, steel slag may undergo expansion due to hydration of free calcium oxide and magnesium oxide. Proper stabilization methods are therefore necessary before its use in flexible pavements.

II.LITERATURE REVIEW

Several researchers have studied the application of steel slag in pavement construction.

Flexible pavements form a vital component of transportation infrastructure, and their performance is influenced by traffic loading, material properties, environmental conditions, and construction quality. Numerous studies have focused on pavement performance evaluation, failure mechanisms, sustainable materials, and innovative design approaches to enhance pavement durability and service life.

Ranadive and Tapase (2012, 2013) investigated methods to improve pavement strength and employed finite element modeling to evaluate pavement behavior under varying conditions. Further studies by Tapase and Ranadive (2016,

2017) established finite element methods as effective tools for predicting pavement performance and analyzing pavement responses under different loading and environmental scenarios. Environmental factors such as temperature, axle loads, layer thickness, and material properties were identified as critical parameters affecting pavement performance (Ranadive & Tapase, 2016).

Comprehensive reviews by Chandak et al. (2017, 2018) and Sayyed et al. (2021) highlighted the influence of traffic, drainage, environmental conditions, and material characteristics on pavement behavior, particularly for low-volume rural roads. Premature pavement failures were attributed primarily to overloading, poor drainage, inadequate materials, and construction deficiencies (Sayyed et al., 2019; Tapase et al., 2020). Patil et al. (2021) further demonstrated the adverse effects of overloading on pavement deterioration.

Sustainable and waste-derived materials have emerged as promising alternatives in pavement construction. Studies by Chandak et al. (2019), Dombe et al. (2019), and Patil et al. (2019) reported improved pavement performance through the utilization of waste plastic, e-waste, crumb rubber, and bagasse ash. Similarly, Sayyad et al. (2022) and Tapase et al. (2022) demonstrated the effectiveness of reclaimed asphalt pavement (RAP), crumb rubber, and waste plastic in enhancing pavement performance while conserving natural resources.

Subgrade improvement has also received significant attention, particularly for expansive black cotton soils. Chandak et al. (2021) developed design charts for black cotton subgrades, while Chandak et al. (2025) demonstrated the potential of cow dung and sugarcane bagasse ash as sustainable stabilizing agents for rural road applications. Additionally, Tapase and Kadam (2014) reported improved pavement performance using polymer-modified bitumen.

Resource conservation and sustainable infrastructure development were emphasized by Tapase et al. (2021) and Tapase (2021), who advocated the use of alternative materials and efficient resource management in road construction. Gade et al. (2019) further highlighted the feasibility of cost-effective construction approaches for rural roads.

Overall, the literature indicates substantial progress in pavement performance evaluation, finite element analysis, sustainable materials, and subgrade stabilization. However, challenges associated with premature failures, overloading, environmental impacts, and long-term performance of recycled materials warrant further research to develop resilient and sustainable pavement systems.

III.RESEARCH METHODOLOGY

3.1 MARETIAL USED

A] AGGREGATE:-

The natural aggregates used in this investigation consisted of crushed stone aggregates of varying sizes. Aggregates with sizes less than 20 mm were selected for the study, with the majority of particles having a nominal size of 16 mm. In flexible pavement construction, aggregates serve as the primary load-bearing component of asphalt mixtures and contribute significantly to the structural integrity of the pavement. The performance of asphalt concrete is greatly influenced by the physical characteristics of the aggregates, including their size distribution, shape, and surface texture. These properties affect key pavement parameters such as density, stability, strength, and resistance to rutting and other forms of deformation under traffic loading and environmental conditions.

B] BITUMEN:-

The asphalt used in preparing all specimens of penetration grade 30-40. These type of bitumen is suitable for hot weather climate due to softening of bitumen. Bitumen of 30/40 grade is a semi-hard penetration grade, meaning its penetration is 30-40 suitable for road construction and repair. Its commonly used in hot mix asphalt for bases and wearing courses. This grade is known for its ability to produce high quality asphalt pavements that meet stringent specifications and ensure durability\

C] STEEL SLAG:-

Steel slag used in this study as a by-product from a steel manufacturing facility operated by a local industries. The surface characteristics of the steel slag were found to be non-uniform, ranging from dense, hard particles similar to basalt to more porous, vesicular particles resembling volcanic cinders. For experimental work, steel slag aggregates from different stockpiles representing coarse aggregates, fine aggregates, and mineral filler fractions.

Fig 2 .Steel Slag

D]CEMENT:-

Ordinary Portland Cement (OPC) was used for coating the steel slag aggregates. The cement coating was applied to improve the surface characteristics of the slag, enhance its bonding with the bituminous binder, and reduce potential absorption issues. This treatment helps in improving the adhesion between the aggregate and bitumen, thereby contributing to better stability and durability of the asphalt mixture.

E] PAINT :-

A coating material (paint/binder solution) was used for treating the steel slag when it was used as a replacement for conventional aggregates. The coating was applied uniformly on the surface of the steel slag particles to reduce surface roughness effects and control excessive absorption. This treatment also helps improve the adhesion between the steel slag aggregate and the bituminous binder, ensuring better bonding characteristics in the asphalt mix. As a result, the overall stability, durability, and performance of the flexible pavement mixture are enhanced.

3.2 THEORETICAL FRAMEWORK

The tests conducted on both natural aggregates and steel slag included the Aggregate Impact Test, Los Angeles Abrasion Test, Water Absorption Test, and Aggregate Crushing Value Test. The Aggregate Impact Value (AIV) provides a measure of an aggregate's ability to resist sudden shock or impact loading, which may differ from its resistance under gradually applied compressive loads. This property is commonly referred to as toughness. During service life, pavement aggregates are repeatedly subjected to impact due to traffic movement, leading to gradual breakdown into smaller particles. Therefore, aggregates must possess adequate toughness to resist such disintegration.

The impact value test is used to evaluate this characteristic and is considered an important mechanical property for road construction materials. It determines the ability of aggregates to withstand stresses caused by moving traffic in the form of impact and crushing. In addition, aggregates must resist crushing during compaction by road rollers as well as under heavy wheel loads. The Aggregate Crushing Value (ACV) test, conducted in accordance with IS: 2386 (Part IV), is used to assess the crushing strength of road aggregates and their suitability for pavement applications.

Fig.3. Crushing strength test of aggregate on UTM

The Los Angeles Abrasion Test is based on the principle of determining the percentage wear of aggregates caused by mutual rubbing action between the aggregate particles and steel balls, which act as the abrasive charge. In addition to abrasion, the impact or pounding effect of the steel balls also contributes to the breakdown of the aggregates during the test.

According to the Indian Roads Congress (IRC), the permissible limits of Los Angeles Abrasion Value for different pavement layers are specified as follows: for sub-base courses, the maximum allowable value is 60%. For base courses such as Wet Mix Macadam (WMM), Bituminous Macadam (BM), and built-up spray grout base courses, the limit is 50%. For surface courses including WBM, BM, Bituminous Penetration Macadam, and built-up spray grout binder courses, the value should not exceed 40%. For more critical surface layers such as bituminous carpet, surface dressing (single or double coat), and cement concrete surface courses, the limit is 35%. In the case of high-quality pavements like bituminous concrete and cement concrete surface layers, the maximum allowable abrasion value is 30%.

Fig4. Los Angeles Abression test on Steel Slag Aggregate

Bitumen is commonly evaluated using three main tests: penetration test, ductility test, and softening point test.The penetration test is used to measure the consistency of bituminous materials and to help classify their grades. It also gives an idea of how the material will perform in practical use. In this test, a standard needle, along with a 100 g load, is allowed to penetrate the bitumen vertically at a temperature of 25°C for 5 seconds. The depth of penetration is measured in units of one-tenth of a millimetre. A higher penetration value indicates a softer bitumen, while a lower value indicates a harder one.

Bitumen is classified into different grades such as 80/100, 60/70, and 30/40 based on this test. For example, 80/100 grade bitumen means the penetration value lies between 80 and 100 (i.e., 8 to 10 mm). In flexible pavement construction, it is important that bitumen forms a strong and flexible film around the aggregates so that the pavement can withstand traffic loads and temperature variations.

Fig.5. Penetration test of bitumen.

If a binder does not have enough ductility, it will crack when it is stretched or bent.Ductility is measured by finding how far a standard bitumen sample (shaped like a briquette) can be pulled into a thin thread before it breaks. The result is given in centimetres. This test is carried out at a temperature of 27°C ± 0.5°C, and the sample is stretched at a speed of 50 ± 2.5 mm per minute.

Fig 6. Ductility test on bitumen

The softening point test determines the temperature at which bitumen or tar begins to soften to a specific level. This temperature indicates when the material becomes soft enough for use. It is important because the binder must become sufficiently workable before it is applied in road construction. The softening point also helps engineers decide how much heating is required for bituminous materials during different paving operations. This test is commonly carried out using the ring and ball apparatus.

Fig 7. .Ring and ball apparatus.

The Marshall stability and flow test is used to evaluate the strength and deformation characteristics of a bituminous mix in the Marshall mix design method. In this test, stability refers to the highest load the sample can carry before it fails, applied at a constant rate of 50.8 mm per minute. As the load increases, the sample gradually deforms. This deformation is measured using a dial gauge and is called flow, which is recorded in units of 0.25 mm. The stability value shows the load-bearing capacity, while the flow value indicates how much the mix deforms under stress.

Fig.5. Marshall test apparatus of bitumen

IV.CONCLUSIONS

The replacement of conventional natural aggregates with steel slag in flexible pavement construction has been found to be a technically and environmentally promising solution. Steel slag exhibits higher strength, better abrasion resistance, and improved skid resistance compared to many natural aggregates, making it suitable for heavy traffic conditions. Its angular shape and rough texture enhance interlocking and improve the overall stability of the pavement mix.

From a durability perspective, steel slag contributes to improved rutting resistance and better load-bearing capacity, which can extend the service life of pavements. Additionally, its utilization helps in reducing the demand for natural aggregates, thereby conserving natural resources and lowering environmental degradation caused by quarrying activities.

However, proper processing and aging of steel slag are essential to minimize the risk of volumetric instability due to free lime or free magnesium oxides. When adequately treated, steel slag can be safely and effectively used in flexible pavement layers.

In conclusion, steel slag is a sustainable and performance-enhancing alternative to conventional aggregates in flexible pavement construction, offering both engineering benefits and environmental advantages when used under proper specifications.

V.ACKNOWLEDGMENT

I would like to express my sincere gratitude to all those who have supported and guided me in the successful completion of my project on the *"Replacement of Steel Slag as Aggregate in Flexible Pavement."*

First and foremost, I am deeply thankful to my project guide/mentor for their valuable guidance, constant encouragement, and insightful suggestions throughout the course of this work. Their expertise and support played a crucial role in shaping the direction of this study.

I am also grateful to the Head of the Department and all faculty members of the Civil Engineering Department for providing the necessary facilities, knowledge, and academic environment required to complete this project.

I extend my thanks to my friends and classmates for their cooperation, motivation, and assistance during the project work. Their support made the completion of this study more efficient and enjoyable.

Finally, I would like to express my heartfelt gratitude to my family for their unwavering encouragement, moral support, and understanding throughout my academic journey.

This project would not have been possible without the guidance and support of all mentioned above.

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