

UTILIZATION OF HAZARDOUS ZINC INDUSTRIAL WASTE (JAROSITE) AS A SUSTAINABLE FILLER MATERIAL IN FLEXIBLE PAVEMENTS

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Abstract

Rapid industrialization has caused the generation of large quantities of hazardous solid wastes, among which jarosite, an industrial by-product of zinc hydrometallurgical processing, poses substantial environmental and disposal challenges. Conventional disposal of jarosite in landfills leads to soil and groundwater contamination due to the presence of heavy metals. This study aims to analyze the feasibility of utilizing jarosite as a partial replacement of stone dust filler in bituminous concrete for flexible pavements. For this purpose, Marshall mix design methodology was employed to determine the optimum bitumen content (OBC), followed by replacement of stone dust with jarosite in varying proportions (0–50%). Laboratory experiments were performed to evaluate aggregate properties, bitumen characteristics, and Marshall stability parameters of jarosite-modified mixes. Results reflect that the mix containing 40% jarosite replacement showed a significant improvement in Marshall stability, which indicate an increase of approximately 59.5% compared to the control mix. The findings confirm that jarosite can be effectively used as a sustainable filler material in flexible pavements, which contribute to waste valorization, reduction in natural resource consumption, and environmentally responsible road construction.

Keywords: Jarosite, Hazardous industrial waste, Flexible pavement, Marshall stability, Sustainable materials

INTRODUCTION

Rapid industrialization has resulted in generation of large quantities of hazardous wastes, causing major environmental and public health risks. In India, metallurgical industries substantially contribute to hazardous waste generation, with zinc processing plants producing large amount of jarosite annually (Sinha et al., 2021; Mubiayi & Fayomi, 2021). Jarosite contains high amount of iron sulfate and toxic heavy metals such as lead, cadmium, and zinc, which makes its disposal environmentally challenging (Mehra et al., 2016a).

Flexible pavements are formed of different layers which are designed to distribute traffic loads gradually to the subgrade, as presented in Figure 1. Flexible pavements consume large quantities of aggregates and filler materials, which provide significant scope for including industrial by-products without compromising performance (Sadoudi et al., 2019; Shuaibu et al., 2021). The use of alternative fillers in bituminous concrete has been widely studied, and has reported improvements in stiffness, stability, and durability (Kumar et al., 2019; Hossain et al., 2022). However, literature on the application of jarosite in flexible pavements, particularly as a filler material are limited. Therefore, this study focuses to examine the mechanical performance of jarosite-modified bituminous concrete and evaluate its suitability as a sustainable filler replacement in flexible pavement construction.

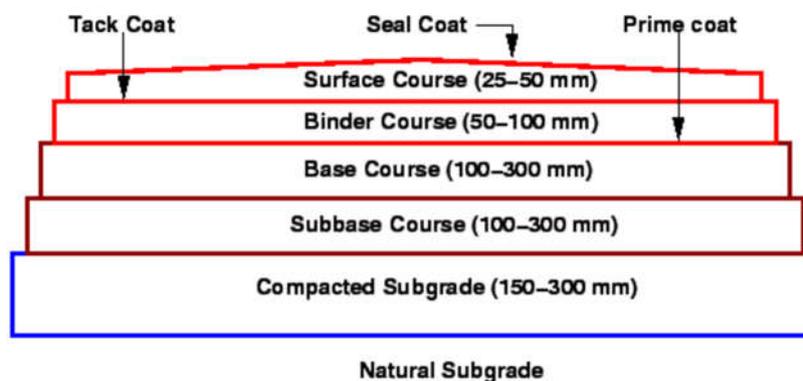


Figure 1: Typical cross section of a flexible pavement showing surface course, binder course, base course, sub-base, and subgrade (Source: IIT Bombay Civil Engineering, 2025).

RESEARCH BACKGROUND AND OBJECTIVES

Previous studies have explored the use of waste materials such as fly ash, silica sand, bagasse ash, quarry dust, and waste plastics in bituminous mixes to enhance pavement performance and sustainability (Jadon and Kansal, 2016; Sadoudi et al., 2019). These studies conclude that filler materials considerably impact Marshall stability, flow characteristics, and resistance to deformation.

Moreover, jarosite has been thoroughly studied in cement concrete and rigid pavement applications. Mehra et al. (2016b) and Nandi and Ransinchung (2021) reported improved mechanical strength and durability of concrete containing jarosite. In addition, Gared et al. (2024) demonstrated the feasibility of jarosite in rigid pavement construction, while Mubiayi and Fayomi (2021) highlighted its potential reuse in construction materials.

Nevertheless, research on jarosite incorporation in flexible pavements remains scarce. Specifically, studies focusing its effect on Marshall stability and filler performance in bituminous concrete are less. Therefore, this study attempts to fill this research gap by systematically analyzing jarosite as a filler material in flexible pavement mixes.

RESEARCH METHODOLOGY

The overall experimental methodology used in the study is shown in Figure 2. Detailed methodology has been discussed further in this section.

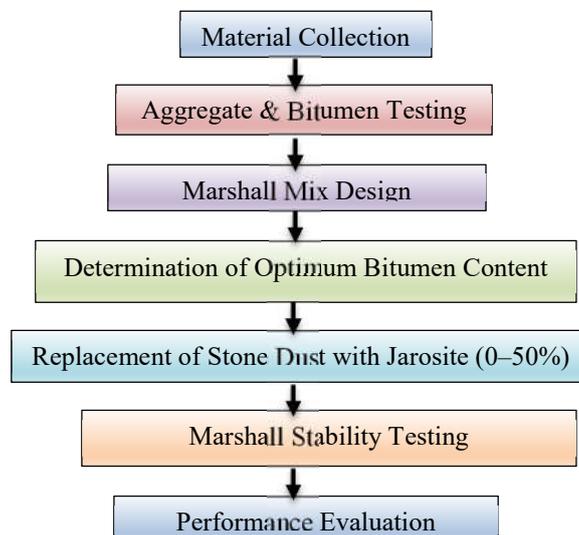


Figure 2: Flowchart illustrating the experimental methodology adopted in the present study.

Materials characterization

Crushed stone aggregates (20 mm and 10 mm), stone dust, VG-40 grade bitumen, and jarosite waste were used in the study. Aggregate properties were evaluated through Los Angeles abrasion test, aggregate impact value, specific gravity test, sieve analysis, and shape tests in accordance with IS:2386 standards (BIS, 1963). The physical properties of aggregates satisfied the requirements for bituminous concrete surface courses as presented in Table 1.

Table 1: Physical Properties of Aggregates

Property	Test Standard	Result	Requirement
Los Angeles abrasion (%)	IS:2386 (Part IV)	27.17	≤ 30
Aggregate impact value (%)	IS:2386 (Part IV)	24.35	≤ 30
Specific gravity (20 mm)	IS:2386 (Part III)	2.747	—
Specific gravity (10 mm)	IS:2386 (Part III)	2.517	—
Flakiness index (%)	IS:2386 (Part I)	23.60	≤ 25

Bitumen properties were assessed through penetration, softening point, specific gravity, and flash and fire point tests as per IS:73-2013 standards (BIS, 2013). All bitumen properties complied with VG-40 specifications, briefed in Table 2.

Table 2: Physical Properties of Bitumen (VG-40)

Property	Test Standard	Result	Specification
Penetration (0.1 mm)	IS:73-2013	52	40–60
Softening point (°C)	IS:1205	51.8	≥ 50
Specific gravity	IS:1202	1.06	≥ 0.99
Flash point (°C)	IS:1448	233	≥ 220

Marshall mix design

Marshall mix design technique was chosen to calculate the optimum bitumen content (OBC) following standard procedures of IRC:105-1988 (IRC, 1988). Specimen samples were prepared with bitumen contents ranging from 4.5% to 6.5% and tested for stability, flow, density and air voids (Va). In addition, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were also evaluated. Marshall properties obtained at varying bitumen contents are presented in Figure 3. The OBC was obtained by averaging the bitumen contents corresponding to maximum Marshall stability, maximum density, as well as 4% air voids. Based on Figure 3, the OBC was estimated as 5.66%.

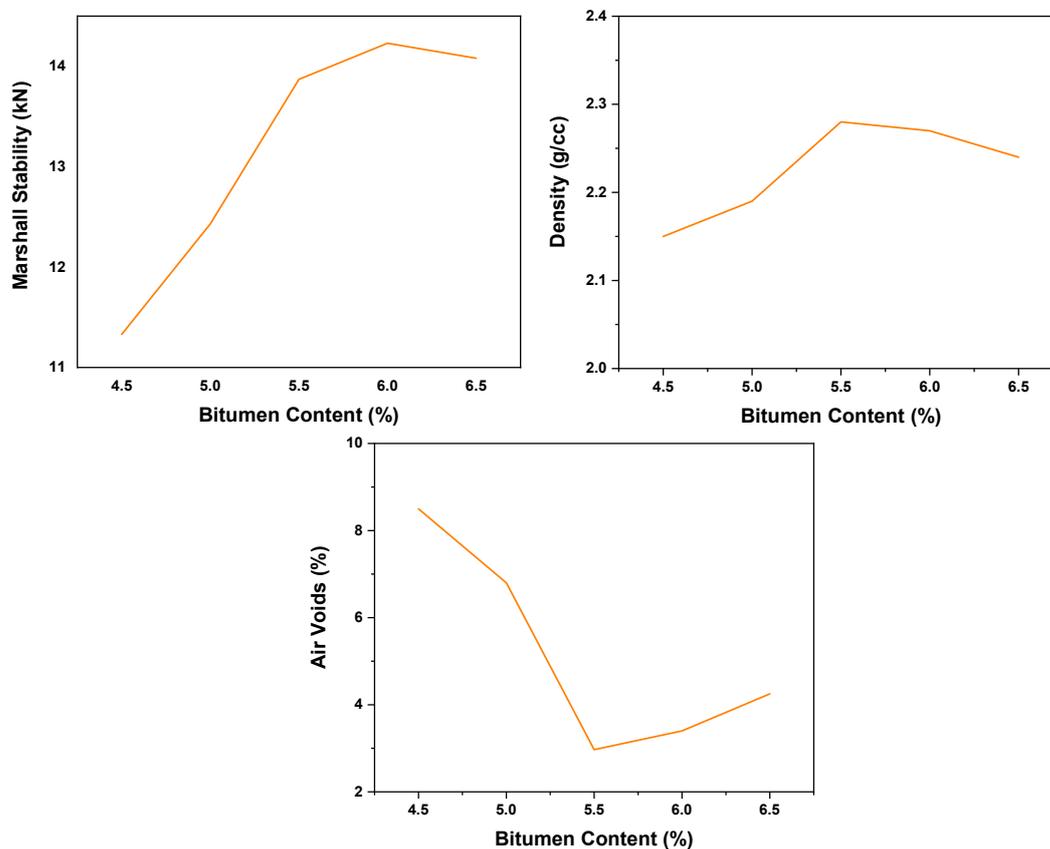


Figure 3: Variation of Marshall stability, density, and air voids with bitumen content.

Jarosite incorporation

After determining the OBC, stone dust was replaced with jarosite at 0%, 10%, 20%, 30%, 40%, and 50% by weight. Marshall specimens were prepared at OBC and tested to assess the effect of jarosite content on stability performance.

Jarosite-modified bituminous concrete

The Jarosite-modified bituminous concrete samples were prepared to assess jarosite as a filler material in bituminous concrete. Jarosite particles were expected to increase bitumen–filler interaction due to their fine size and irregular morphology. All specimen samples were compacted using standard Marshall compaction (75 blows per face) and conditioned in a water bath at 60 °C prior to testing, creating field conditions (Hossain et al., 2022). Marshall specimens having jarosite as filler material are illustrated in Figure 4.



Figure 4: Prepared and tested Marshall specimens incorporating jarosite as filler material.

RESULTS AND DISCUSSION

The aggregate and bitumen properties complied with the requirements for bituminous concrete surface courses. The OBC was estimated as 5.66%, which is consistent with the recommended specifications as per IRC:105-1988 (IRC, 1988).

Marshall stability results demonstrated a consistent increase in stability with increasing jarosite content up to 40% replacement. The maximum Marshall stability was observed at 40% jarosite replacement, representing a 59.5% increase as compared to the control mix, which has been shown in Figure 5. Similar improvements in stiffness and load-bearing capacity have also been reported for alternative filler materials in bituminous mixes (Sadoudi et al., 2019; Shuaibu et al., 2021).

It is important to note that that beyond 40% replacement, stability values decreased due to reduced workability and moisture susceptibility, which is consistent with findings by Kumar et al.

(2019). The higher stability at optimal jarosite content can be attributed to enhanced filler–bitumen adhesion and denser packing of the mix. Figure 5 visibly reflects that 40% jarosite replacement yields the maximum stability.

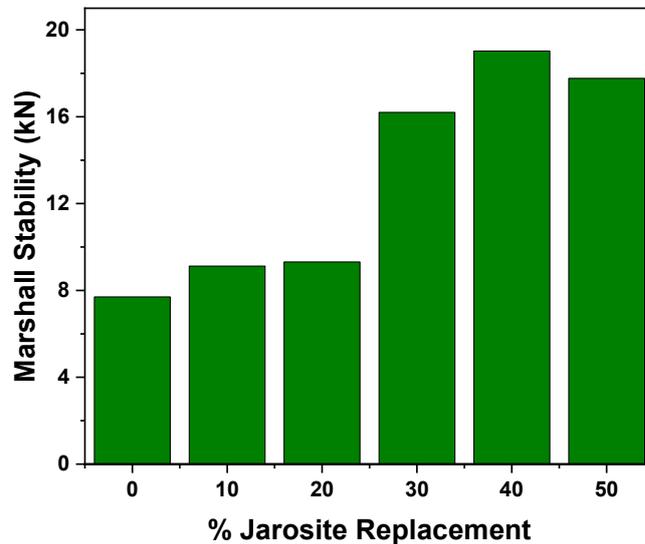


Figure 5: Effect of jarosite replacement on Marshall stability of bituminous concrete

CONCLUSIONS

The major objective of the work was to comprehensively examine jarosite as a filler material in flexible pavement mixes. Experimental results indicated that jarosite can be effectively used as a partial replacement of stone dust filler in bituminous concrete. The value for OBC for the control mix was quantified as 5.66%. Furthermore, maximum Marshall stability was observed at 40% jarosite replacement, which reflects a 59.5% improvement over the conventional mix. Overall, outcomes of this study highlight that utilization of jarosite in flexible pavements supports sustainable waste management and decreases dependence on natural filler materials. However, further research on rutting resistance, fatigue behavior, moisture damage, and leaching characteristics is warranted before large-scale field implementation.

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