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Analysis of the effect of steel slag content used as aggregate on the quality of hot mix asphalt

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KEYWORDS

Steel slag
Hot mix asphalt (HMA)
Marshall flow
Marshall stability
Aggregate

ABSTRACT

This paper presents an experimental study on the effect of steel slag content as a replacement for crushed stone on the engineering properties of hot mix asphalt (HMA). Steel slag was used to replace coarse aggregate at replacement levels of 0%, 30%, 50%, 70%, and 100% by weight, and the mixtures were evaluated using the Marshall method. The results indicate that the optimum asphalt content increases with higher steel slag replacement due to its rough surface texture and higher asphalt absorption capacity. Marshall stability increases, whereas Marshall flow decreases as the steel slag content increases, indicating enhanced stiffness and load-bearing capacity. Furthermore, owing to the higher specific gravity of steel slag, mixtures containing steel slag exhibit greater bulk density compared to conventional asphalt mixtures.

1. Introduction

Along with the increasing demand for steel to support socio-economic development, the amount of solid waste generated from the metallurgical industry, particularly steel slag, has been growing significantly. According to data from the steel industry, the production of one ton of steel billet generates approximately 150–200 kg of steel slag. With the current steel output, the total annual amount of steel slag is estimated to exceed 1 million tons [1–4]. This represents a large-scale industrial waste stream; if treated mainly through landfilling, it not only requires substantial financial resources (estimated at tens of millions of USD annually) but also exerts pressure on land resources and poses potential risks of soil, water, and air pollution.

In parallel, natural mineral resources, particularly construction aggregates, are under increasing exploitation pressure to meet infrastructure development demands. Crushed stone is the primary material used in road construction, especially in asphalt pavement structures. However, stone is a non-renewable resource in the short term; excessive and uncontrolled extraction may lead to reserve depletion, landscape alteration, ecological imbalance, and increased environmental pollution. In practice, the southern region of Vietnam continues to experience high demand for construction aggregates, highlighting the urgent need to identify and develop suitable alternative materials.

In this context, the study of reusing steel slag as a material for transportation infrastructure construction is considered a scientifically and practically meaningful approach. This solution not only contributes to reducing the volume of industrial waste requiring treatment and conserving natural resources but also supports the goals of sustainable development and the circular economy in the field of construction materials.

During the metallurgical process, chemical reactions between iron ore and limestone lead to the formation of compounds such as calcium silicates, aluminosilicates, and calcium–magnesium aluminosilicates. Steel slag is generated and becomes fully molten at temperatures ranging from 1400 to 1600 °C, where mineral phases are completely melted. Owing to its lower density compared to molten pig iron, the slag phase floats to the surface and is subsequently separated from the molten metal, forming steel slag (Figure 1).

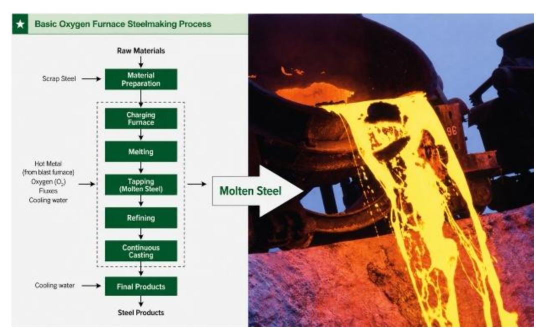

Figure 1. Formation and separation of slag during the steelmaking process.

This study focuses on evaluating the feasibility of using steel slag as a replacement for crushed stone aggregate in the production of hot mix asphalt for road pavements. The effects of different steel slag replacement ratios on the optimum asphalt content and key technical properties of the mixture, including Marshall stability, Marshall flow, and bulk density, were analyzed through an experimental program based on the Marshall method. The research findings provide a scientific basis for considering the practical application of steel slag in pavement construction.

2. Materials, mixture design, and research methodology

2.1. Materials

The influence of materials on the properties and load-bearing capacity of Hot asphalt mixtures (HMA) is significant. An ideal material

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for HMA mixtures should possess a proper gradation, high strength, high abrasion resistance, and angular particle shape. Other desirable properties include low porosity, rough surface texture, cleanliness, and hydrophobic characteristics.

Aggregate gradation, strength, abrasion resistance, and particle shape play crucial roles in structural stability. The porosity and surface characteristics of mineral materials strongly affect the bonding between bitumen and aggregate surfaces. The asphalt binder must adhere firmly to the aggregates while fully coating their surfaces. If the aggregates exhibit low porosity and smooth surfaces, the asphalt binder cannot effectively adhere to them. Adhesion becomes a particularly important criterion when asphalt mixtures are exposed to moisture. If the aggregates are easily wetted, water will compete with bitumen to penetrate the aggregate surface, causing separation between aggregate and binder. This phenomenon is known as bitumen stripping from mineral aggregates.

The materials used in this study include steel slag (Ba Ria–Vung Tau), which serves as an environmentally friendly aggregate produced by Green Materials Company from electric arc furnace (EAF) slag, crushed stone, natural sand, mineral filler, and Petrolimex 60/70 asphalt binder. Steel slag was used as a replacement for crushed stone as coarse aggregate in the asphalt mixture. The physical properties of steel slag and crushed stone are presented in Table 1 and Figure 2.

Table 1. Physical Properties of Steel Slag and Crushed Stone.

No.	Test Item	Unit	Upper Layer	Lower Layer	Crushed Stone	Steel Slag	Remarks
1	Specific Gravity	kg/m3	-	-	2.82–2.88	3.31–3.82	Slag heavier
2	Bulk Density	g/cm3	-	-	2.73–2.77	3.07–3.57	More porous
3	Water Absorption	%	-	-	0.76–1.54	1.44–3.25	Higher absorption
4	Organic Impurities	%	≤2	≤2	0.08–1.04	0.23–0.93	Pass
5	Flakiness Index	%	≤15	≤15	6.78–15.58	1.70–12.15	Pass
6	Los Angeles Abrasion	%	≤28	≤35	24.80–33.00	20.16–26.09	Surface layer use
7	Crushing Value	%	-	-	7.92–10.16	12.82–14.74	
8	Softening Coefficient	%	-	-	0.48–0.76	0.78–1.09	
9	Bitumen Adhesion	Grade	≥3	≥3	4	4	Pass

Figure 2. Crushed Stone (left) Compared with Steel Slag (right).

2.2. Mixture Design

The design of Hot asphalt mixtures (HMA) aims to determine an appropriate aggregate gradation and the optimum bitumen binder content, ensuring economic efficiency while satisfying technical requirements in accordance with current standards. In this study, the dense-graded hot mix asphalt 12.5 (HMA 12.5) was designed using the Marshall method [5–7]. The aggregate gradation of HMA 12.5 is presented in Figure 3. Steel slag was used to replace natural aggregates at replacement levels of 0 %, 30 %, 50 %, 70 %, and 100 % by aggregate mass.

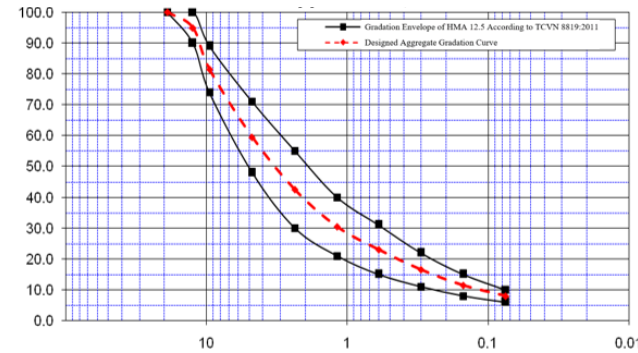

Figure 3. Aggregate Gradation of Dense-Graded Hot Mix Asphalt 12.5.

The relationships between bitumen content and the mechanical properties of the mixture, including air voids (Va), voids filled with bitumen (VFB), Marshall stability, and Marshall flow, were established based on the average values of three specimens for each bitumen content level. Based on these curves and in comparison with current technical requirements, the range of bitumen content satisfying each individual criterion was determined. Subsequently, the bitumen content range that simultaneously satisfies all technical criteria was identified, and a representative value within this range was selected as the optimum bitumen content. The optimum bitumen content may be determined as the arithmetic mean of the bitumen contents corresponding to each satisfied criterion [5–7].

The parameters including Marshall stability, Marshall flow, bulk density, air voids, and voids in mineral aggregate (VMA) were determined in accordance with TCVN 8860:2011 [8].

2.3. Research Methodology

Application of a Combined Theoretical and Experimental Research Approach

3. Research results

3.1. Analysis of the Influence of Steel Slag Replacement Ratio on the Optimum Binder Content

To determine the optimum bitumen content for the asphalt mixture using 100 % steel slag aggregates, test specimens were prepared with bitumen contents varying at 0.5 % intervals within the range of 4.3 % to 6.3 % by total mixture mass. The main mechanical properties, including air voids (Va), voids in mineral aggregate (VMA), Marshall stability, and Marshall flow, were experimentally determined and summarized, as presented in Figure 4.

Based on the chart, the optimum asphalt content was determined according to the technical requirements specified in TCVN 8819:2011 [9] (Table 2).

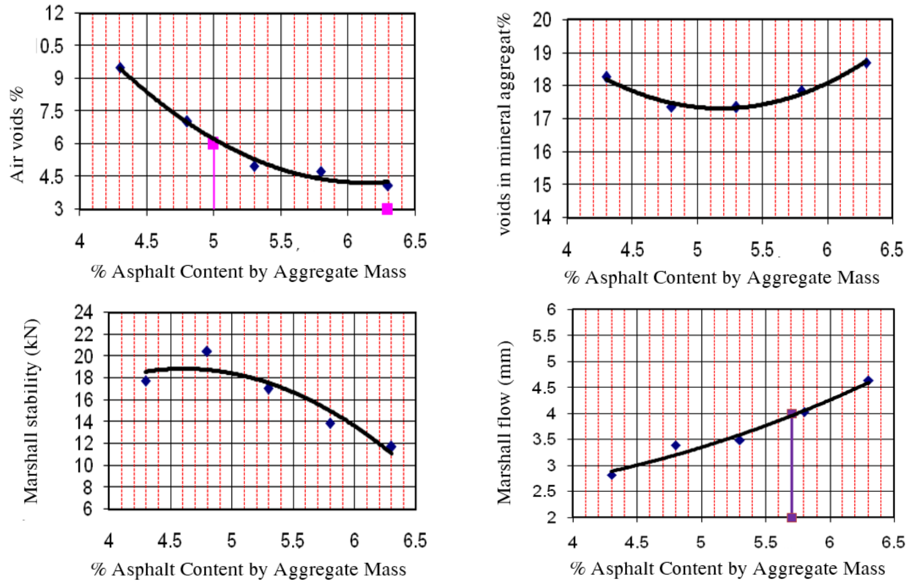

Figure 4. Determination of the Optimum Asphalt Content of HMA with 100% Steel Slag Aggregate.

Table 2. Optimum asphalt content of the asphalt mixture with 100 % steel slag aggregate.

Criteria	Requirement	Asphalt Content (%)	Summary
Air Voids (%)	3 – 6	5.0 – 6.3	5.0 – 5.7
Voids in Mineral Aggregate (%)	≥ 13	4.3 – 6.3	
Marshall Stability (kN)	≥ 8	4.3 – 6.3	
Marshall Flow (mm)	2 – 4	4.3 – 5.7	
Selected Optimum Asphalt Content (% by aggregate weight)			5,3

The optimum bitumen content of asphalt mixtures containing 0 %, 30 %, 50 %, and 70 % steel slag aggregates was determined following the same procedure as that used for the mixture containing 100 % steel slag. The summarized results are presented in Figure 5, illustrating the relationship between the steel slag replacement ratio of crushed stone and the optimum bitumen content of the mixtures.

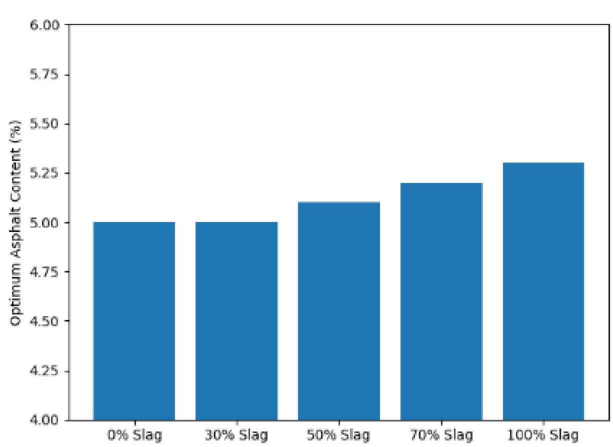

Figure 5. Effect of steel slag content on the optimum asphalt content.

The results indicate that as the proportion of steel slag replacing crushed stone increases, the optimum bitumen content of the asphalt mixtures correspondingly increases. This trend can be explained by the higher bitumen absorption capacity of steel slag compared with natural crushed stone. This is mainly attributed to the porous, rough, and angular surface texture of steel slag, which requires a greater amount of binder to ensure adequate coating and workability of the mixture.

3.2. Analysis of the effect of steel slag content on bulk density

The bulk density of asphalt concrete (AC) at the corresponding optimum bitumen content for different steel slag replacement ratios is presented in Figure 6. The results indicate that as the proportion of steel slag replacing crushed stone increases, the bulk density of the asphalt mixture increases significantly.

This trend can be explained by the higher particle density of steel slag compared with natural crushed stone (see Table 1). Therefore, as the steel slag content in the aggregate gradation increases, the overall bulk density of the mixture correspondingly increases. In particular, when steel slag completely replaces crushed stone (100 %), the bulk density of the asphalt concrete increases by approximately 17.5 % compared with the mixture using conventional crushed stone.

This increase in bulk density may significantly affect transportation and construction processes, as it increases the transport load per unit volume of the mixture.

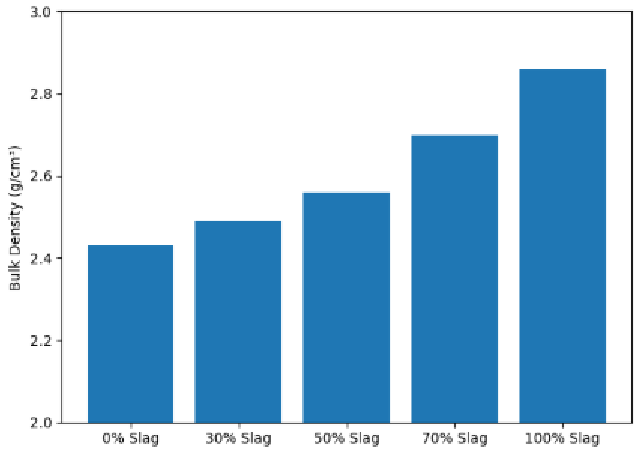

Figure 6. Effect of steel slag content on bulk density.

3.3. Analysis of the effect of steel slag content on Marshall stability and flow

Figures 7 and 8 present the effects of steel slag replacement ratio on the Marshall stability and Marshall flow of asphalt mixtures, respectively. The results indicate that as the proportion of steel slag in the aggregate gradation increases, the Marshall stability of the mixtures tends to increase.

Specifically, for the mixture containing 100 % steel slag aggregate, the Marshall stability increases by approximately 5 % compared with the mixture using 100 % crushed stone. However, this increase is relatively small, indicating that replacing crushed stone with steel slag only provides a limited improvement in load-bearing capacity in terms of Marshall stability (Figure 7).

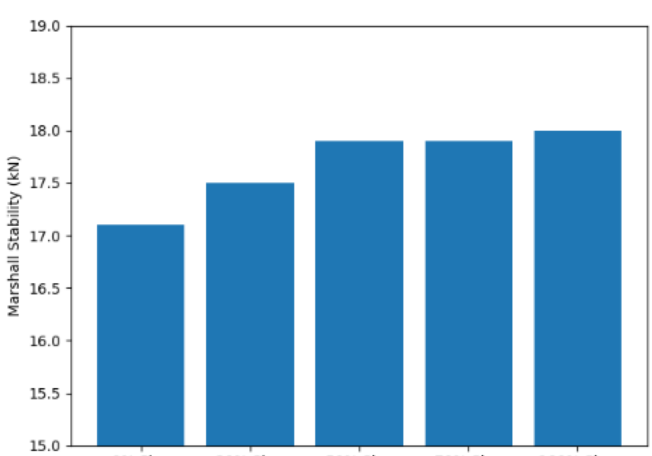

Figure 7. Effect of steel slag content on Marshall stability.

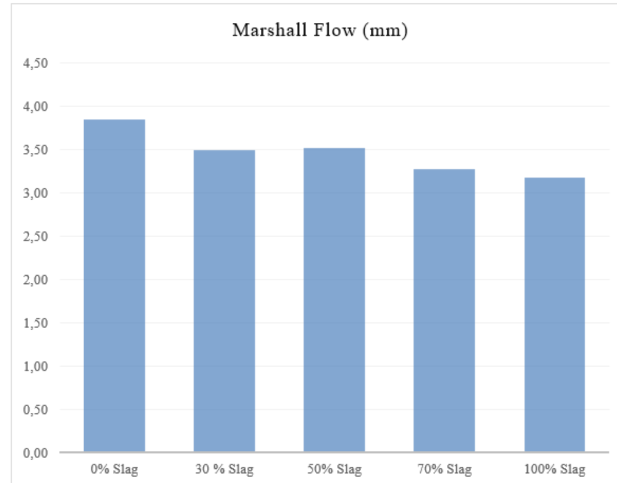

Figure 8. Effect of steel slag content on Marshall flow.

As the proportion of steel slag replacing crushed stone increases, the Marshall flow of asphalt concrete (AC) tends to decrease (Figure 7). For the mixture containing 100 % steel slag aggregate, the Marshall flow decreases by approximately 17.4 % compared with the mixture using natural crushed stone. However, the Marshall flow value of the steel slag asphalt mixture still falls within the required range of 2–4 mm according to TCVN 8819:2011. The influence of steel slag on the properties of asphalt mixtures has also been reported in previous studies [10–12].

4. Conclusion

Based on the experimental results obtained, several conclusions can be drawn as follows:

- Steel slag can be used as a replacement for crushed stone in the production of hot mix asphalt, while still satisfying the technical requirements specified by current standards.

- The optimum bitumen content of asphalt mixtures tends to increase as the proportion of steel slag replacing crushed stone increases.

- Increasing the steel slag content in the aggregate gradation leads to an increase in the bulk density of the asphalt mixture, due to the higher specific gravity of steel slag compared with natural crushed stone.

- As the steel slag replacement ratio increases, the Marshall stability of the asphalt mixture increases, while the Marshall flow tends to decrease. This indicates that steel slag contributes to improving the load-bearing capacity of the mixture but may reduce the plastic deformation capacity of the asphalt concrete.

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