EFFECT OF STEEL SLAG AGGREGATES ON ENGINEERING PROPERTIES AND RESIDUAL MARSHALL STABILITY OF OPEN-GRADED ASPHALT CONCRETE

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Abstract - This study investigated the influence of steel slag (SS) aggregates on the mechanical properties of open-graded hot mix asphalt (OGA), replacing crushed stone at 50%, 75%, and 100% by volume. Results showed that the optimum bitumen content (OBC) increased significantly with higher SS usage (up to 87.9% for 100SSA), likely due to SS's higher absorption. The initial Marshall stability also drastically improved, increasing by up to 172.1% for 100SSA (8.18 kN), attributed to the superior strength and interlocking of SS particles. However, the residual Marshall stability (after moisture/heat exposure) decreased as SS content increased, indicating lower moisture resistance. 75SSA provided the best balance, exhibiting 24% higher residual stability than 100SSA.The paper suggests that OGA with 75% or more SS can be used as a pavement base layer, provided it is placed at a minimum depth of 7 cm and exposed to favorable hydrothermal conditions to mitigate moisture damage.

Kewords - Steel slag aggregates; open-graded hot mix asphalt; engineering properties; Marshall stability; residual Marshall stability

1. Introduction

Steel slag (SS), a byproduct of the steel manufacturing process, has garnered attention as a potential substitute for natural aggregates in construction, aiming to conserve natural resources and mitigate environmental pollution [1]. Globally, the use of SS as aggregates in asphalt concrete (AC) for road construction has become increasingly common [2], [3]. Previous studies have demonstrated that incorporating SS into dense-graded AC improved performance properties such as resistance to deformation and Marshall stability [4], [5]. Xue et al. [6] found that replacing coarse aggregates with SS yielded more significant performance enhancements than replacing fine aggregates.

In Vietnam, SS has been certified to meet national standards and technical regulations for construction materials, aligning with government policies encouraging sustainable resource use and environmental protection [7]. However, the application of AC incorporating SS (SSA) presents challenges related to moisture sensitivity and long-term durability, especially under harsh climatic and environmental conditions [8] - [10]. The SS water absorption and swelling properties can negatively impact the moisture resistance of SSA [11], increasing the risk of cracking, spalling, and pavement deterioration [12].

For steel slag open-graded asphalt concrete, Pathak et al. replaced 0%, 25%, 50%, and 100% of BOF steel slag for coarse aggregates. The results of this study showed that steel slag open-graded asphalt concrete increased rutting resistance, improved cracking resistance, increased elastic modulus, and extended fatigue life [13]. Open-graded asphalt concrete is more susceptible to strength loss due to the effects of water and temperature. However, detailed studies evaluating the residual Marshall stability of this material are minimal. This study aims to assess the physical and mechanical properties, along with the residual Marshall stability, of steel slag open-graded asphalt concrete with a nominal maximum aggregate size of 19 mm, incorporating steel slag as a partial or complete replacement (0%, 50%, 75%, and 100%) for crushed stone aggregate volume (>2.36 mm). Additionally, the residual Marshall stability of steel slag open-graded asphalt concrete is also assessed under the actual working conditions of this material in Vietnam.

2. Materials and experiments

2.1. Materials

The crushed stone used in this study was sourced from the Phu My Hoa quarry in Danang, Vietnam. The conventional aggregates meet the required grain size distribution and quality specifications for producing OGA, as specified in TCVN 13567-3:2022 [14].

Electric Arc Furnace SS aggregates were taken from a steel factory in Danang. To mitigate volume expansion caused by lime content, SS was weathered in natural conditions for over three years before being used in the laboratory [15]. Properties of crushed stone and SS were tested and reported in Table 1.

Table 1. *Properties of conventional and SS aggregates for OGA*

Testing items	Testing standards	Crushed stone	SS
Apparent density (g/cm^3)	TCVN 7572-4:2006 [16]	2.75	3.29
Bulk density (g/cm^3)		2.72	2.82
Water absorption (%)	TCVN 7572-2:2006 [16]	0.81	5.06
LA abrasion loss (%)	TCVN 7572-12:2006 [16]	21.4	33.11
Minimum particle size (mm)	TCVN 13567-3:2022 [14]	2.36	2.36
Nominal maximum size of aggregate (mm)		19	19

The 60/70 penetration grade bitumen provided by Petrolimex and the mineral filler sourced from the Phuoc

Thinh Phat asphalt mixing station met all quality requirements by TCVN 13567-3:2022 [14].

2.2. OGA mixture design

The OGA mixtures were designed using the median gradation between the upper and lower specification limits for aggregates with a nominal maximum size of 19 mm, following TCVN 13567-3:2022 [14]. SS was used in these mixtures to replace the crushed stone aggregates with particle sizes greater than 2.36 mm. The particle size distribution curve for the OGA mixture is presented in Figure 1.

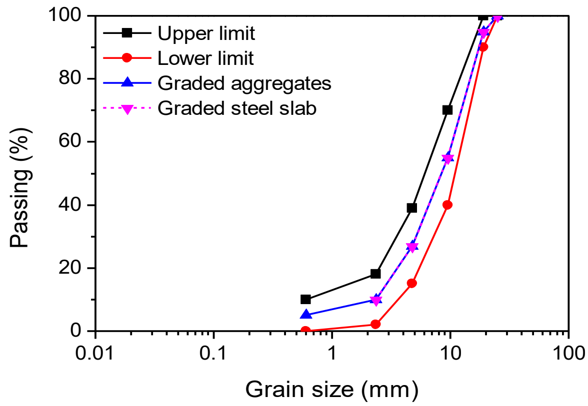

Figure 1. *Gradation curve of graded aggregates used for OGA*

Due to the difference in bulk density between SS and natural crushed stone, the replacement was conducted on a volume-equivalent basis to ensure consistency in particle size distribution. The required mass of SS (m_{ss}) in the 2.36–25 mm sieve size range for each replacement level was calculated using Equation (1), while the remaining mass of crushed stone (m) was determined using Equation (2). Where p_{ss} represents the percentage of SS replacement (50%, 75%, and 100%); m_a is the initial mass of crushed stone in the 2.36–25 mm size range (g); and γ_a, γ_{ss} are the bulk densities of crushed stone and SS, respectively (g/cm³).

$$m_{ss} = p_{ss} \frac{\gamma_{ss}}{\gamma_a} m_a \quad (1)$$

$$m = (1 - p_{ss}) m_a \quad (2)$$

As a result, four OGA types, including 0%, 50%, 75%, and 100% of SS, were designed, denoted as 0SSA, 50SSA, 75SSA, and 100SSA, respectively. The samples were prepared using the Marshall method [17]. The test plan is described in Section 2.3.

The optimal bitumen content of four OGA mixtures was first investigated. Five bitumen content values, differing by 0.5%, were tested for each OGA. After preparing the samples, the relationship between bitumen content and the SSA's physical and mechanical properties was evaluated. At least three samples were cast for each test, including bulk specific gravity and unit weight, Marshall stability and flow, and maximum specific gravity and density of loose bituminous paving mixtures, as demonstrated in section 2.4.

2.3. Experimental programme

This study was structured into three main phases to comprehensively evaluate the performance of steel slag open-graded asphalt (OGA). Initially, the optimum asphalt content was determined for four distinct OGA mixes, namely OGA 0SSA, OGA 50SSA, OGA 75SSA, and OGA 100SSA. Following this, the physical and mechanical properties of each of these steel slag asphalt types were meticulously assessed at their respective optimum asphalt contents. The final phase involved evaluating the residual Marshall stability of the various steel slag open-graded asphalt mixes under varying immersion durations and temperatures.

2.4. Experimental methods

2.4.1. Bulk specific gravity and unit weight tests

The OGA bulk specific gravity and unit weight were determined by Part 5 of TCVN 8860-5:2011 [18], shown in Figure 2.

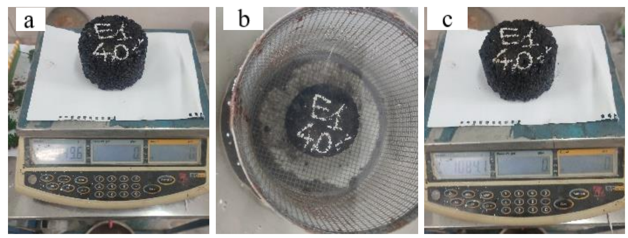

Figure 2. *Determination of open-graded SSA bulk specific gravity and unit weight*

2.4.2. Marshall stability and flow tests

Marshall stability and low tests are carried out according to part 1 - TCVN 8860-1:2011 [18], as illustrated in Figure 3.

Figure 3. *Marshall stability and flow tests*

2.4.3. Maximum specific gravity and density of loose bituminous paving mixtures

Figure 4. *Test of maximum specific gravity and density of loose bituminous paving mixtures*

The maximum specific gravity and density of OGA are determined by part 4, TCVN 8860-4:2011 [18]. Based on these experimental parameters, additional properties, such as air voids and voids in the mineral aggregate, were obtained.

3. Results and discussion

3.1. Optimal bitumen content

3.1.1. Unit weight

Figure 5 illustrates a clear difference in the unit weight of OGA incorporating different SS contents. The increase in SS rate resulted in an increased unit weight of SSA. This difference is attributed to the higher apparent density of the SS compared to crushed stone aggregate. The optimal bitumen contents for 100SSA, 75SSA, 50SSA, and 0SSA are 5.93%, 4.77%, 4.00%, and 3.39%, respectively. The relationship between the unit weight of SSA and bitumen content follows a parabolic curve, which can be explained as follows: (i) low bitumen content is insufficient to coat and bind the material particles effectively, resulting in low particle cohesion and, consequently, a lower unit weight. (ii) as the bitumen content increases to the optimal level, the bitumen is adequate to facilitate the sliding and closer arrangement of particles despite the same compaction effort (50 x2 blows). When the bitumen content exceeds the optimal level, it creates a thicker film that separates the aggregate particles, resulting in a decrease in unit weight.

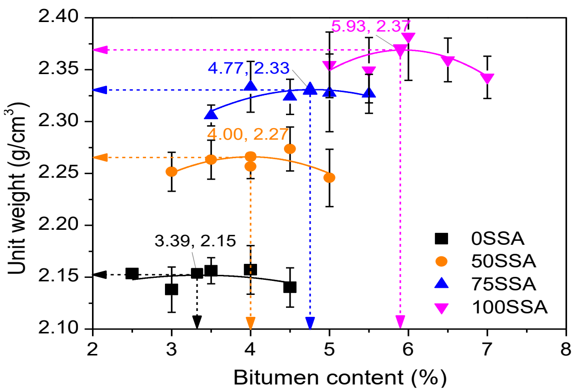

Figure 5. *Correlation between the unit weight of open-graded SSA with different bitumen contents*

3.1.2. Marshall stability

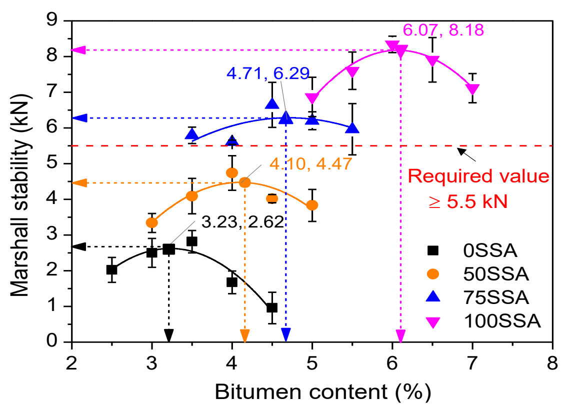

Figure 6. *Correlation between Marshall stability and bitumen content of open-graded SSA*

Figure 6 presents the correlation between Marshall stability and bitumen content. The findings indicated that the Marshall stability of all SSA increased with increasing content bitumen up to a certain point, after which it decreased. This behavior can be attributed to bitumen acting as a binder; however, excessive bitumen reduces internal friction, decreasing stability. Both OGA 100SSA and 75SSA achieved the required Marshall stability value (≥ 5.5 kN) as specified by TCVN 13567-3:2022 [14].

Table 2. *Bitumen content for optimal Marshall stability of OGAs*

OGA	Bitumen content (%)	Increase in bitumen content compared to 0SSA (%)	Marshall stability (kN)	Increase in Marshall stability compared to 0SSA (%) (%)
100SSA	6.07	87.9	8.18	172.1
75SSA	4.71	45.8	6.29	113.4
50SSA	4.10	26.9	4.47	57.3
0SSA	3.23	0	2.62	0

Table 2 highlights a significant difference in Marshall stability when incorporating different SS contents in SSA. Higher SS content resulted in increased Marshall stability and bitumen content. The bitumen content of 100SSA, 75SSA and 50SSA rose by 87.9%, 45.8%, and 26.9%, compared to 0SSA, respectively. Similarly, the Marshall stability value of these SSA increased by 57.3%, 113.4%, and 172.1%, respectively. The increase in bitumen rate with increased SS content can be attributed to the surface characteristics of SS. SS has a rougher surface and more pores than conventional crushed stone aggregates, leading to a higher bitumen adsorption capacity. Additionally, the surface porosity of SS contributes to the increased bitumen content required to cover and bind the grain components in OGA mixtures effectively.

3.1.3. Flastic flow

Figure 7 shows that the flow increases as bitumen content rises, indicating that higher bitumen content facilitates the movement of aggregate particles over others. The standard requirement for the flow is between 2 and 4 mm. 100SSA met the criteria when the bitumen content was less than 7%. Other SSAs also satisfied the requirements specified by TCVN 13567-3:2022 [14].

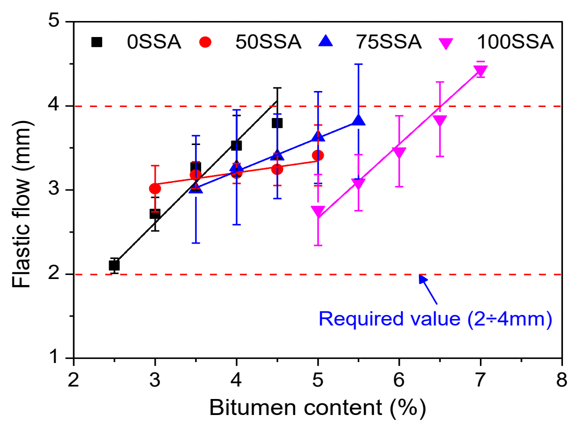

Figure 7. *Correlation between plastic flow and bitumen content of open-graded SSA*

Figure 7 indicates that the influence of bitumen content on the plastic flow of 50SSA and 75SSA is lower compared to 0SSA and 100SSA. Sun et al. have compiled findings from previous studies, demonstrating that the aggregate skeleton significantly impacts the performance of asphalt concrete (AC), and the interaction mechanism between bitumen and aggregate in AC also depends on this aggregate skeleton [19]. Using SS at ratios of 50% and 75% helped create a superior aggregate framework, allowing the aggregates to interlock more effectively. This mechanism would explain why the plastic flow values for 50SSA and 75SSA showed less variation when the asphalt content was changed.

3.2. Properties of OGA

The experimental results from sections 3.1a to 3.1c demonstrate that 100SSA and 75SSA satisfied Marshall stability and flow requirements. The 100SSA and 75SSA had optimal bitumen contents of 6.07% and 4.71%, respectively. The study still evaluated the physical and mechanical properties of these OGAs (Marshall stability, plastic flow, residual stability, and air voids) at their optimal bitumen content.

Table 3. *Properties of OGA with 75SSA and 100SSA content*

Mechanical properties	OGA		TCVN 13567 – 3:2022 [14]
	75SSA	100SSA	
Number of blows, blows	50×2	50×2	50×2
Marshall stability, kN	6.20	8.18	≥ 5.5
Plastic flow, mm	3.20	3.46	2 ÷ 4
Residual Marshall stability, %	62	50	≥ 65
Air void, %	7,48	7.99	7 ÷ 12

Table 3 shows that 75SSA and 100SSA met the requirements for Marshall stability, plastic flow, and air voids, as specified in TCVN 13567-3:2022 [14]. However, the residual stability was insufficient according to the criteria (≥ 65%). While 100SSA exhibited superior stability, it had significantly lower residual stability than 75SSA, suggesting that SS may deteriorate when exposed to water, potentially due to the swelling properties of SS. The study further investigated the residual stability of SSA under varying temperature and humidity conditions in section 3.3.

3.3. Residual stability

OGA is suitable for pavement structures as a base or subsurface layer [3]. According to Thao et al. [20], the working temperature of paving layers deeper than 7 cm is typically below 60°C, with the highest temperature maintained for no more than 6 hours. Therefore, it is recommended to test the residual stability after soaking the samples at four water temperature levels: 45°C, 50°C, 55°C, and 60°C for 6 hours. Additionally, to evaluate the effect of temperature and water exposure over time on residual stability, the study included sample soaking at four-time intervals: 6 hours, 12 hours, 24 hours, and 48 hours at 60°C.

3.3.1. Residual Marshall stability of open-graded SSA over soaking time

Figure 8 indicates that as the immersion time increases, the residual stability decreases. Prolonged exposure to water causes steel slag to expand due to its free lime content, leading to a reduction in the bond between the steel slag and bitumen, which weakens the material structure and reduces its bearing capacity [21]. Although the Marshall stability of 100SSA is higher than that of 75SSA, the residual stability of OGA 75SSA exceeded that of 100SSA, especially when the soaking time exceeded 24 hours. The findings showed that 100SSA had poorer residual stability than 75SSA due to its higher slag content. This result is consistent with the research of George Wang et al. [22].

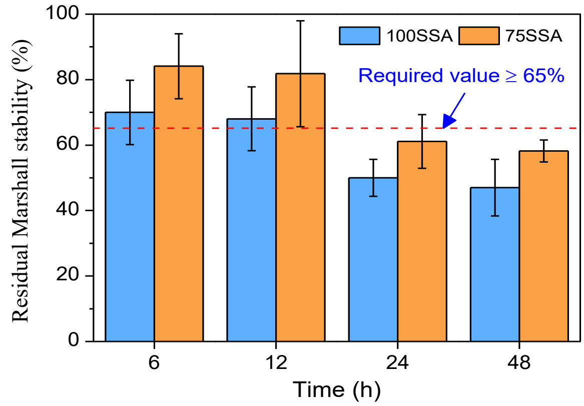

Figure 8. *Correlation between open-graded SSA residual Marshall stability and soaking time*

The results from Figure 8 also show that when samples were immersed for ≤ 12 hours at 60°C, the residual stability of both SSA types met the requirements stipulated by TCVN 13567-3:2022 [14]. This observation indicates that, when evaluating the stability of the pavement structure at depths exceeding 7 cm under actual working temperature conditions, the residual stability of the SSA types meets the requirements specified in TCVN 13567-3:2022.

3.3.2. Residual Marshall stability of open-graded SSA over soaking temperature

Figure 9 shows a decrease in residual Marshall stability as the temperature increases after soaking SSA for 6 hours. This observation demonstrated that high temperatures affected the quality of the SSA sample, caused by bitumen softening, reducing its viscosity and shear strength, ultimately leading to a decrease in bearing capacity. However, the residual stability of both 100SSA and 75SSA met the requirements at all tested temperatures.

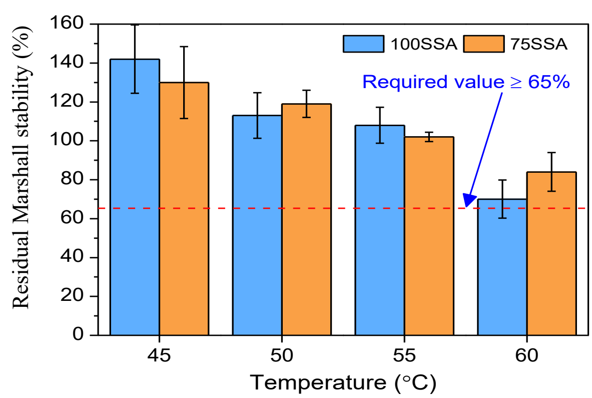

Figure 9. *Correlation between residual Marshall stability of open-graded SSA versus soaking temperature*

The results also show that when samples were immersed for 6 hours at temperatures ≤ 60°C, the residual stability of both SSA types met the requirements stipulated by TCVN 13567-3:2022. This result demonstrates that when assessing the residual stability of SSA types within pavement structures under actual working temperature conditions, their stability meets the requirements specified in TCVN 13567-3:2022.

4. Conclusions

This study investigated the impact of SS on the engineering properties and residual Marshall stability of open-graded AC, where crushed stone was replaced with SS by volume. Based on the optimal bitumen content, bulk specific gravity, unit weight, Marshall stability, and flow assessment, the following main conclusions are drawn:

- The optimal bitumen content suitable for 100SSA and 75SSA samples was 6.07%; 4.71%, respectively. The more SS content used to replace crushed stone aggregates, the higher the optimal binder required.

- The OGA 100SSA and 75SSA had Marshall stability of 8.18 kN and 6.20 kN, which satisfied the requirements of TCVN 13567-3:2022 [14] and were 172.1% and 113.4% higher than OGA 0SSA, respectively. OGA 100SSA had superior stability, but the residual stability of 100SSA (50%) is significantly lower than that of 75SSA (62%).

- The OGA 100SSA and 75SSA did not meet the requirements for residual stability when soaking samples according to the standard (60°C for 24 hours). However, when evaluating the residual stability of both OGA 100SSA and 75SSA under real conditions with an environment temperature lower than 60°C for 6 hours, the residual stability met the requirements.

- OGA 100SSA and 75SSA are recommended for use in road bases located at a minimum depth of 7cm from the road surface and exposed to favorable hydrothermal conditions. Also, conducting pilot construction under actual conditions is necessary to re-evaluate the research findings.

The relationship between air voids and residual Marshall stability, particularly after prolonged water immersion, warrants further investigation. Additionally, analyses of the chemical composition of steel slag and the mechanism of action of its free lime content or metal oxides will continue to be investigated.

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