Performance of Asphalt Concrete Mixtures Containing Nickel Slag

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ABSTRACT

Recent advancements in material technology have led to an increased interest in using alternative materials in the asphalt mixtures. One such material is Nickel Slag (SN), a byproduct of nickel ore smelting. With the growing volume of slag produced during nickel smelting, research has focused on using SN as a component in pavement materials to reduce the steel waste accumulation. The primary objective of this study is to explore the optimal use of SN as a coarse aggregate in asphalt concrete mixtures, aiming to achieve the maximum asphalt content. The study also evaluates the impact of SN on the stability, volumetric characteristics of the asphalt mixtures, and Ultrasonic Pulse Velocity (UPV) wave patterns. The research involved Marshall testing using a Universal Testing Machine (UTM) and UPV testing. The results indicated that SN mixtures reached maximum stability at 5.8% asphalt content and demonstrated higher stability values than conventional mixtures. As a coarse aggregate replacement, SN enhances the resistance to permanent deformation due to its hardness, interlocking properties, and the silica content that improves adhesion to the asphalt. Incorporating SN into asphalt mixtures improves mix stability, reduces industrial waste, conserves natural resources, and enhances road infrastructure quality. This method supports the principles of sustainable development.

Keywords-AC-WC; nickel slag; Marshall test; ultrasonic pulse velocity

I. INTRODUCTION

The weight proportion of aggregates used in flexible pavements usually ranges from 90% to 95%, while the volume percentage ranges from 75% to 85%. To preserve natural aggregates, it is important to identify substitute materials that meet the stated requirements while maintaining high quality [1, 2]. The aggregates provide the mixture's strength and stability, while the asphalt binder maintains flexibility [3]. Advances in the contemporary material technology have led to many investigations into the use of alternative materials as components in asphalt mixtures. As the demand for nickel in construction projects rises and nickel production increases, the slag generated from nickel ore smelting also grows. Therefore, it is essential to explore SN as a pavement material to help reduce the accumulation of nickel waste. SN is a byproduct of the ferronickel production process, produced during the combustion of ferronickel. It is silver-gray and has rock-like characteristics. The silicate and lime elements contained in it are quite high, which leads to extraordinary density and hardness. Consequently, it can serve as a suitable material for road construction due to its better heat-retaining ability than natural aggregates [4]. The addition of 10% nickel as a coarse aggregate to grade 1 asphalt-modified mixtures in flexible pavements can improve stability and, consequently, extend pavement life [5]. The government supports the downstream sector by reducing the raw material exports and encouraging the domestic processing of nickel ore. This policy has led to an increase in production, largely due to the use of waste slag generated during the nickel processing. The domestic smelting and refining industry produces approximately 21.8 million tons of slag annually. Both the steel and nickel industries, which are the largest producers of slag, could lower the costs of sourcing natural aggregates by utilizing this slag. Additionally, the ironmaking industry could reduce the waste disposal costs using slag. Asphalt mixtures that incorporate the Reclaimed Asphalt Pavement (RAP) aggregate and SN Steel (with a 2.36 mm sieve pass) as an additional Fine Aggregate (FA) have demonstrated improved fatigue characteristics and performance [7]. The dynamic creep test results show that the Stone Mastic Asphalt mixtures containing steel slag benefit from their ability to enhance resistance to permanent deformation and reduce the groove depth [8]. The main differentiation of this study compared to previous research is the use of SN as a coarse aggregate, specifically focusing on coarse aggregate particles that pass through a 19 mm sieve, but are retained on a 4.75 mm sieve.

II. MATERIALS AND METHODS

A. Materials

This study utilized SN, Crushed Stone (CS), rock ash, and Pen 60/70 asphalt. Table I portrays the overall size distribution of the employed aggregates, while Figure 1 shows the Aggregate Physical Sample Preparation. The utilized asphalt had a penetration grade of 60/70. Table II displays the test methods for the physical properties of the SN, CS, and stone ash materials and Table III illustrates the gradation of the SN used. Table IV shows the specific gravity values of the SN, CS, rock ash, and asphalt materials. The base material deployed was SN produced from the PT Vale Indonesia Tbk (INCO) smelter, while the FA used was rock ash obtained from Bili-Bili. The hot asphalt mix design utilizes slag as a coarse aggregate substitute that meets the requirements of passing the No. 3/4" sieve or equivalent to 12.5 mm, and retaining the No. 4 sieve or equivalent to 4.75 mm in size. The AC-WC gradation is regulated according to [9].

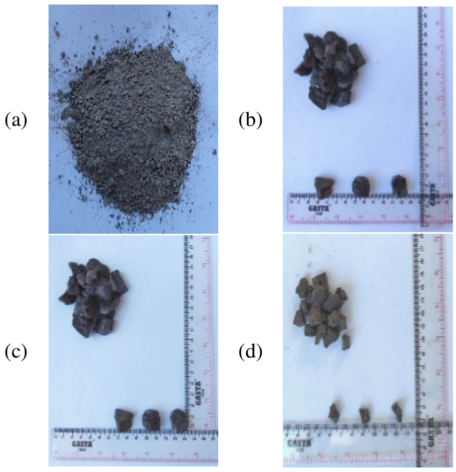


Fig. 1. Physical aggregate sample preparation: (a) Stone ash, (b) Slag nickel 12.5 mm, (c) Slag nickel 9.5 mm, (d) Slag nickel 4.75 mm.

TABLE I. GRADATIONS USED IN THE STUDY AND GRADATION LIMITS

Sieve size (mm)	Gradation limits (%)	Used gradation
25	100	0.00
19	100	100.00
12.5	90-100	95.00
9.5	77-90	83.50
4.75	53-69	61.00
2.36	33-53	43.00
1.18	21-40	30.50
0.6	14-30	22.00
0.3	90-22	15.50
0.15	6-15	10.50
0.075	4-9	6.50

TABLE II. TEST METHODS FROR PHYSICAL PROPERTIY AQUISITION OF SN, CS, AND STONE ASH

Physical property	Method
Apparent specific gravity	SNI03-1970-1990
Bulk-specific gravity on dry basic	SNI03-1970-1990
Bulk specific gravity SSD basic	SNI03-1970-1990
% water absorption	SNI03-1970-1990

TABLE III. GRADATION OF SN (NICKLE SLAG) USED

Sieve size	Percent passing
19	100
12.5	95
9.5	83.5
4.75	61

TABLE IV. SPECIFIC GRAVITY OF MATERIAL (g/cm^3)

Materials	Specific gravity (g/cm^3)
SN (Coarse Aggregate)	3.209
CS (Coarse Aggregate)	3.150
FA	2.595
Asphalt	1.034

In this research, two kinds of material combinations were carried out, including using 100% SN to replace the coarse aggregate, and a normal mixture containing only natural materials or CS and stone ash as FA. The gradient shown in Table I was used to design the experiment. Three test objects were created for each of the five asphalt levels. The asphalt rate used was determined by calculating the initial estimate of KAO (Pb) based on the gradients of the plan. The values for each sample were as follows: Gross Aggregate (GA) = 57, FA = 36.50, Fillers = 6.50, and the constant (C) = 0.75. This calculation resulted in initial asphalt rates (Pb) of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8% of the total weight of the mixture.

B. Test Method

1) Marshall Test

The Marshall Test Method for the AC-WC combinations is defined by [21]. This standard outlines the procedure for evaluating the asphalt mixtures using Marshal equipment. During the Marshal stability test, the specimen is submerged in a water bath at 60 °C for 30 minutes, after having been placed in UTM equipment to determine the correlation between the flow and stability at a varying asphalt content, which is the primary concern of the Marshall mix design method [10].

Fig. 2. UTM testing tool.

2) *Ultrasonic Pulse Velocity Testing*

The UPV testing measures the ultrasonic wave propagation using a direct, non-invasive method that preserves the test object's surface [11]. It is applied to evaluate the surface layer of the sliding solidification model. This research demonstrates the ultrasonic method deployment to assess structural changes in bitumen concrete, as evidenced in previous studies [7, 8]. Ultrasonic wave velocity measurements were performed by the UPV testing, using Vaseline as a coupling between the transducer and the specimen. The Pundit device was used to measure the time taken for the ultrasound waves to be transferred across the specimen [12].

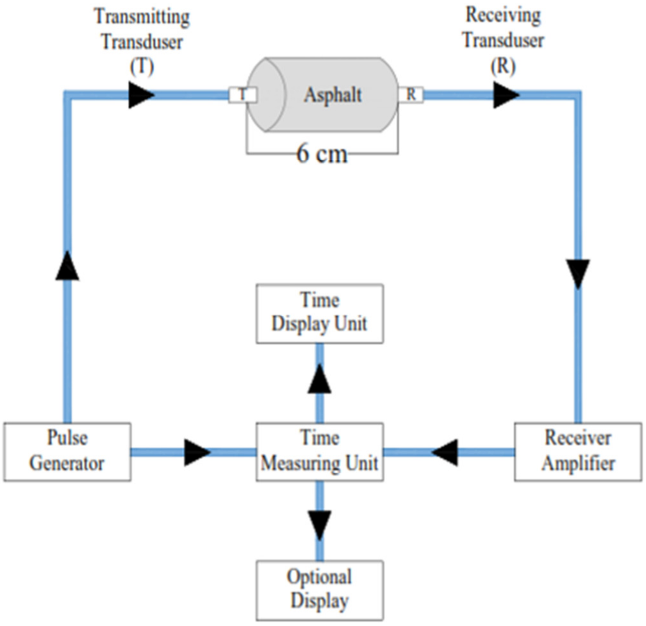


Fig. 3. Schematic of UPV testing tool.

According to [20], the inert UPV method is founded on the measurement of the wave speed through the material. The transmission and reception of high-frequency sound waves on a material are the fundamental principles of ultrasonic testing. Transducers serve as both transmitters and receivers of these waves. The material thickness can be determined, while any imperfections in the material can measure the time it takes for a wave to return to the transducer after reflecting from an inner surface or a defect in the material. In the material, the pace of the sound wave is significantly influenced by its density and elasticity [14]. The ultrasonic pulse speed can be determined by dividing the measured path length by the ultrasonic pulsation time using:

$$V = \frac{L}{T} \qquad (1)$$

where V is the rapid ultrasonic wave frequency (m/s), L is the distance between the transducer's surface swivel (m), and T is the duration of the ultrasonic pulse (s). Figure 3 portrays the scheme of the UPV speed test device, while Figure 4 displays the UPV testing setup with a mélange of asphalt concrete.

Fig. 4. UPV test setup with asphalt concrete mixes.

III. RESULTS AND DISCUSSION

A. *The Relationship between Stability and Flow*

Figure 5 illustrates the relationship between the flow and stability in asphalt mixtures using two coarse aggregates, SN and CS. The test results reveal consistent patterns for both aggregate types, while the data analysis identifies four distinct phases of behavior. Figure 5 indicates that both mixtures exhibit similar trends in the relationship between stability and flow. This leads to the formation of four distinct phases:

- The initial or load adjustment phase is characterized by a curved upward line at any bituminous level, which suggests that the relationship is an adaptation to the load adoption.
- The distance to the maximal voltage is indicated by a straight line in the second, or elastic deformation phase. The elastic phase can be considered to consist of the first and second phases.
- The third phase is referred to as the inelastic phase because the curve shows the maximum tension. The mixture is exhibiting permanent internal structural changes during this phase because of its irreversible deformation properties.
- The fourth phase is the phase after having reached the peak stress, with the curve subsequently showing a decrease. The stress-strain curve demonstrates a significant non-linear behavior in the post-peak region, indicating softening and degradation of the material.

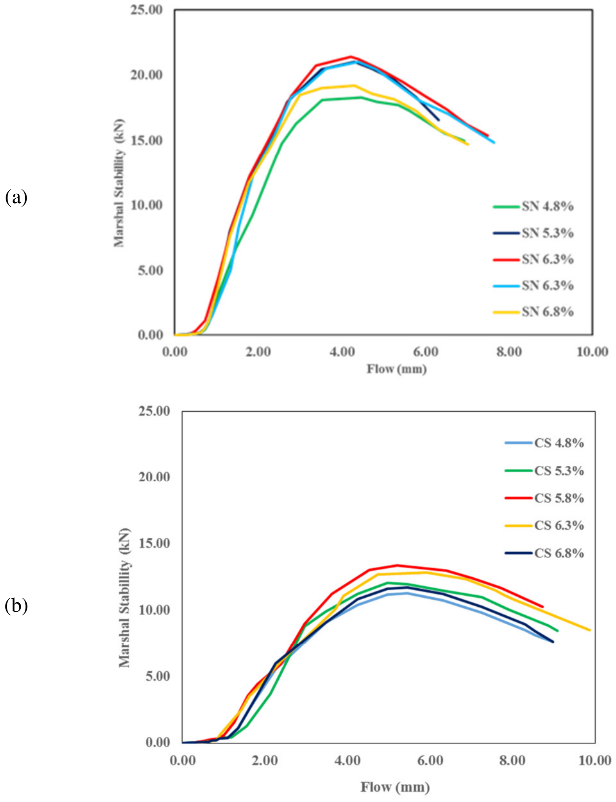


Fig. 5. Stability and flow relationship of the mixture: (a) SN (b) CS.

B. Relationship between Marshall Stability and Asphalt Content

Figure 6 shows the Marshall stability values of the specimens using 100% SN, without using SN, or replacing the coarse aggregate with CS. The diagram demonstrates that when using asphalt at different percentages (4.8%, 5.3%, 5.8%, 6.3%, and 6.8%), and asphalt concrete mixtures using,with SN being utilized as a coarse aggregate replacement material, stability values of 18.32 kN, 21.03 kN, 21.21 kN, 21.03, and 19.20 kN, are, respectively, produced. For specimens that did not use SN or used only CS as a coarse aggregate replacement with the same percentage of asphalt coordination, the resulting stability was 11.27 kN, 12.06 kN, 13.36 kN, 12.86 kN, and 11.71 kN, respectively. The graph exhibits that the stability initially increases and then decreases after having reached the maximum asphalt content of 5.8%. This research shows that the stability rating of a combination utilizing SN as a primary aggregate was superior to that of a mixture without SN. The high stability of SN employment as a substitute for crude aggregate is due to its superior strength compared to natural CS. The observed results may be attributed to prior investigations. Authors in [5] demonstrated that steel slag directly increases the stability values. Specifically, higher amounts of steel slag result in greater stability levels.

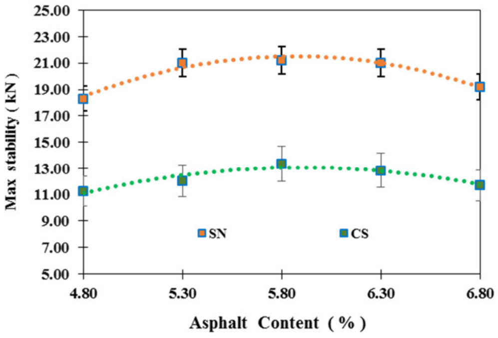


Fig. 6. Maximum stability of asphalt mixtures containing SN and CS.

C. Relationship between Stability and Volumetric Parameters

1) Void in Mix

Figure 7(a) presents the Void in Mix (VIM) and maximum stability values of the asphalt mixtures using SN as a coarse aggregate replacement. The results correspond to asphalt content levels of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8%, with VIM percentages of 5.62%, 4.54%, 3.58%, 2.79%, and 1.90%, respectively. Figure 7(b) displays the VIM values for the mixtures using CS as a coarse aggregate replacement, with percentages of 5.28%, 4.15%, 3.09%, 2.40%, and 1.70%. An inverse relationship exists between the maximum stability and VIM values. That is, higher asphalt content results in lower VIM values. Moreover, the stability increases with an asphalt content of up to 5.8%. Beyond this point, the stability decreases at the asphalt content levels of 6.3% and 6.8%. This indicates that an asphalt content of 5.8% provides optimal bonding between the aggregate particles. However, an excess asphalt content, 6.3%-6.8%, reduces the VIM value by filling the voids excessively, increasing density, and limiting the flow of water and air [12, 13]. The present research confirms that SN and CS used as coarse aggregate replacements at 5.3% and 5.8% asphalt content, respectively, meet the standards provided in [2], which require for the VIM values to fall within the range of 3% to 5%.

2) Void in Material Aggregate

Figure 8 illustrates the relationship between the maximum stabilization value and the variation of the Void in Material Aggregate (VMA) caused by the different asphalt contents (4.8%, 5.3%, 5.8%, 6.3%, and 6.8%) in the mixtures using SN and CS as coarse aggregate substitutes. The VMA values for the mixtures containing SN, as observed in Figure 8(a), were 17.86%, 17.60%, 16.97%, 17.59%, and 17.75%, respectively. The VMA of the mixtures consisting of CS, as depicted in Figure 8(b), yielded percentages of 16.25%, 15.56%, 15.23%, 15.27%, and 15.82%, respectively, which were obtained from the mixtures using CS as coarse aggregate. This increase in stability is due to the voids filled by the asphalt which acts as an adhesive between the particles. The increase in stability, observed in the SN mixtures, can be attributed to the presence of asphalt, which fills the voids, and the increase in stability at 5.8% asphalt content is due to the reduced voids in the asphalt-filled aggregates. However, when the bitumen content reached 6.3% and 6.8%, the stability decreased as it could not fill the voids with bitumen.

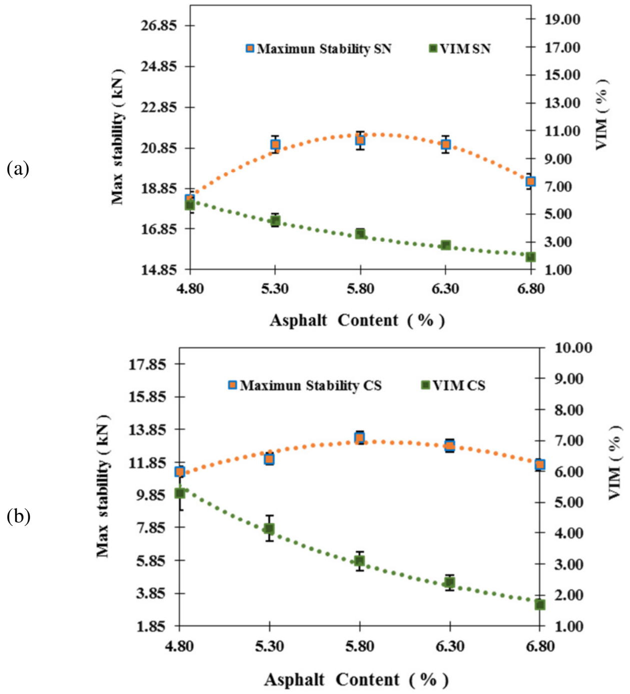


Fig. 7. Maximum stability relationship and VIM mixture: (a) SN (b) CS.

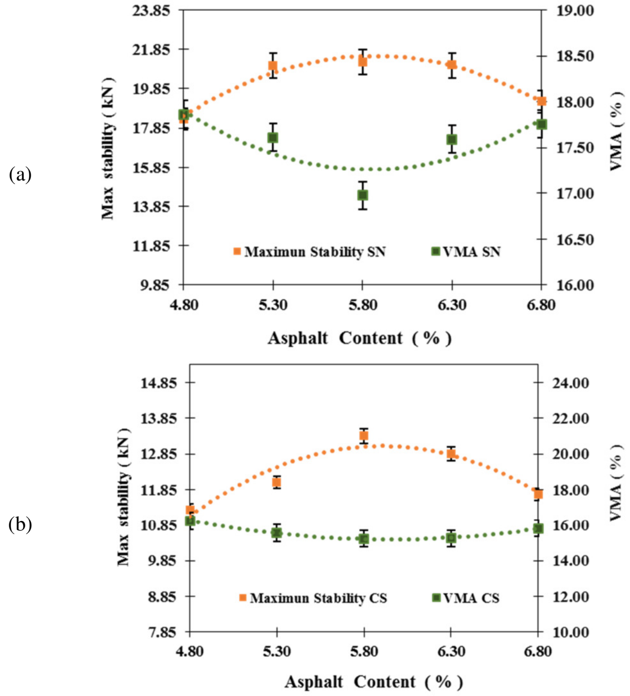


Fig. 8. Maximum stability relationship and VMA mixture: (a) SN (b) CS.

Additionally, the VMA values in the SN and CS mixes helped increase the adhesion strength between the aggregate particles, reducing the likelihood of breakage. Higher asphalt content causes a decrease in VMA due to inadequate filling of voids with asphalt, resulting in excessive asphalt flow and bleeding [14]. Subsequently, it was observed that mixtures using SN as coarse aggregate showed a higher VMA compared to those using CS as coarse aggregate. These values satisfy the minimum criterion of 15% according to [19].

3) Void Filled with Bitumen

Figure 9(a) portrays the maximum stability values and variations in the Void Filled with Bitumen (VFB) values of the asphalt mixtures containing SN. Figure 9(b) presents the maximum stability values and variations in VFB values of the asphalt mixtures containing CS at asphalt contents of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8%. The higher the asphalt content of the asphalt mixture using SN and CS was, the higher was the VFB value. The VFB values for the mixtures containing SN as a coarse aggregate were 67.21%, 74.30%, 80.33%, 85.83%, and 90.09%, while those for the mixtures using CS as a coarse aggregate were 63.36%, 71.98%, 77.67%, 84.09%, and 88.87%. The increase in the VFB value correlates with the increase in the asphalt content, which indicates that more voids are filled with asphalt, making the mixture water and airtight. Therefore, increasing the cohesion of the mixture at 5.8% asphalt content is the optimal choice. However, excessive asphalt contents of 6.3% and 6.8% cause a decrease in stability due to the reduced adhesion, resulting in bleeding. According to [2], the AC-WC-coated asphalt mixture must have a minimum VFB value of at least 65%. However, this requirement is not met only at the stone level of the asphalt mixture, which has a VFB value of 4.8%. Additionally, all other levels meet the minimum VFB requirement.

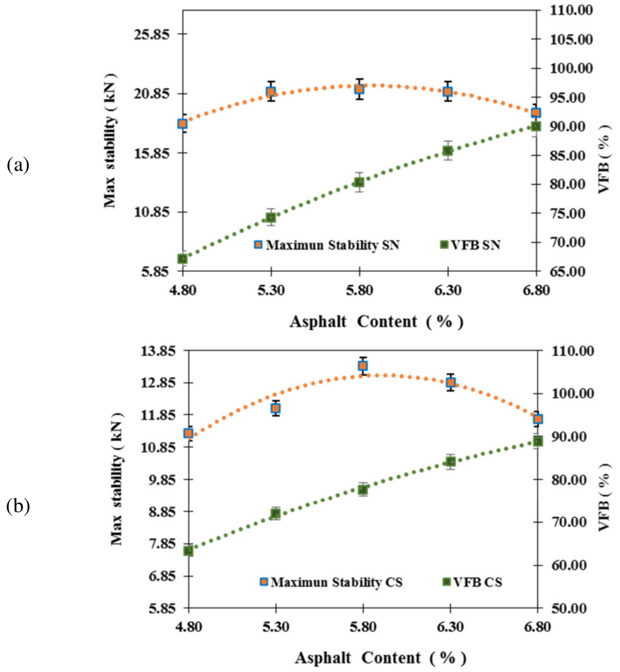
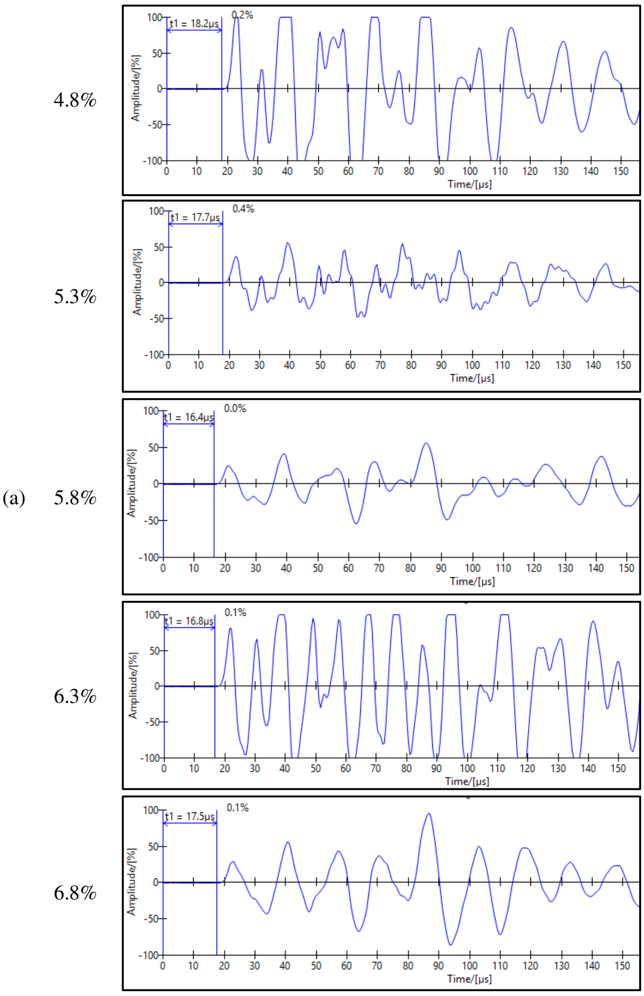


Fig. 9. Maximum stability relationship and VFB mixture: (a) SN (b) CS.

D. UPV

1) Ultrasonic Pulse Velocity Wave Pattern versus Asphalt Content

Figure 10 shows the relationship between the asphalt content, travel time, and ultrasonic wave patterns in each test specimen, including the SN and CS mixes. The data demonstrate that ultrasonic waves successfully propagate from the transducer to the receiver in the solid asphalt mixture, with consistently well-defined waveforms in all mixtures. This indicates that the SN and CS mixes are densely packed with asphalt and aggregate, without significant voids caused by insufficient compaction or cracks from excessive compaction. As the asphalt content increases to 4.8%, 5.3%, and 5.8%, the travel time of the pulse from the transducer to the receiver decreases. However, the travel time starts to increase when the asphalt content reaches 6.3% and 6.8%. Specifically, when SN is used as a coarse aggregate substitute, the travel times are 18.2 µs, 17.7 µs, 16 µs, 16.8 µs, and 17.5 µs. In contrast, when CS is used as the coarse aggregate replacement, the travel times are shorter: 14.8 µs, 14.7 µs, 13.4 µs, 13.9 µs, and 14.1 µs. Figure 10(a) demonstrates that the asphalt mixture with CS as a coarse aggregate replacement has a shorter travel time than the mixture with SN. This is due to the CS-based asphalt mixture having fewer voids, as evidenced by the comparison of the VMA and VIM values for both mixtures.



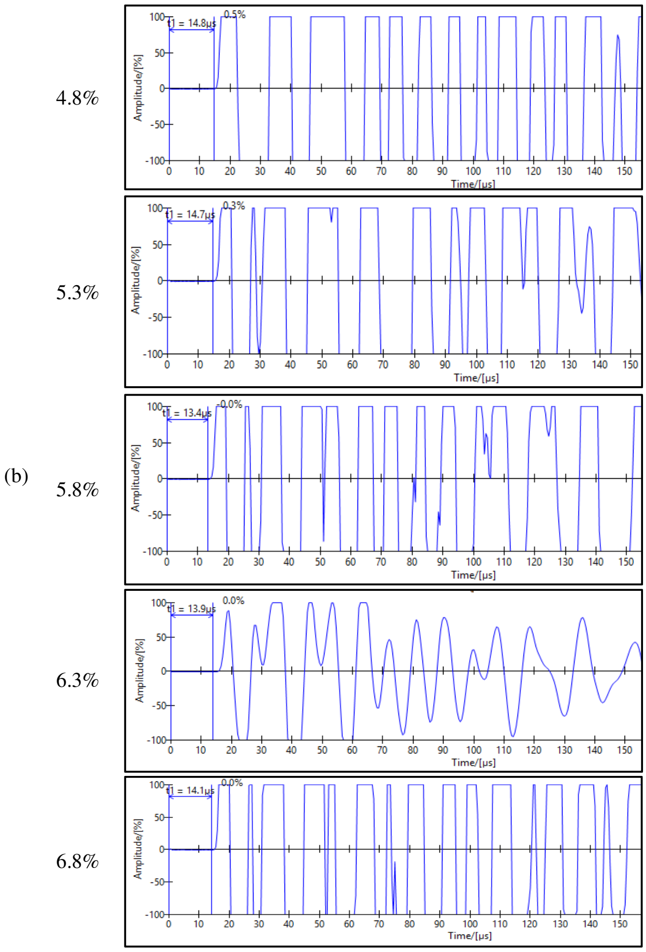


Fig. 10. UPV waves mixed (a) SN (b) CS.

2) *Ultrasonic Pulse Velocity and Stability*

The relationship between the UPV and maximum stability at each asphalt content for the SN and CS mixtures is displayed in Figure 11. The UPV values of 4387 m/s, 4494 m/s, 4695 m/s, 4530 m/s, and 4496 m/s were obtained from the SN mixtures with asphalt contents of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8%, respectively. The UPV values of 4121 m/s, 4225 m/s, 4304 m/s, 4247 m/s, and 4074 m/s were attained from the CS mixtures with asphalt contents of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8%. The UPV values of both mixes showed an increasing trend, peaking at 5.8% asphalt content and then decreasing at 6.3% and 6.8% asphalt contents. Since each increase and decrease in the stability test for the SN and CS mixes exhibited a similar behavior, these results are in line with the observed stability pattern. UPV can be used as a Non-Destructive Test (NRT) to estimate the stability of the asphalt mixtures, especially, those using SN and CS as coarse aggregate replacements. This is indicated by the peak stability to UPV ratio for the SN and CS mixtures as coarse aggregate replacements depicted in Table V. By knowing this ratio, a more effective testing procedure can be established. In addition, the material evaluation process can be improved by using this ratio to compare the results of non-destructive tests with those of destructive tests, such as stability tests.

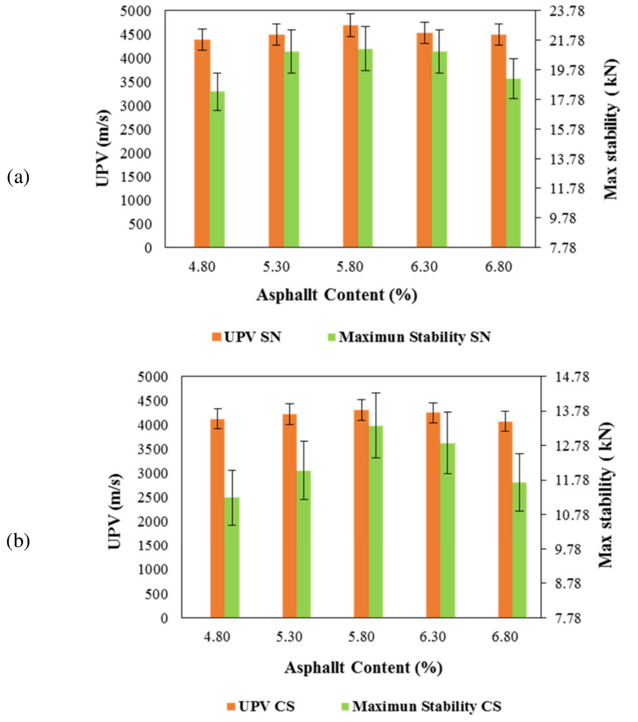


Fig. 11. Relationship between UPV, asphalt content, and maximum stability in coarse aggregate mixtures: (a) SN, (b) CS.

TABLE V. STABILITY AND UPV RELATIONSHIP RATIO OF ASPHALT MIXTURES WITH SN AND CS AS COARSE AGGREGATE REPLACEMENTS

Coarse aggregate	Asphalt content (%)				
	4.80	5.30	5.80	6.30	6.80
	The ratio of peak stability to UPV				
SN	4.18	4.68	4.52	4.64	4.27
CS	2.74	2.85	3.10	3.03	2.88

3) UPV versus VIM

The relationship between the asphalt content, UPV value, and mixture stability is complex, as shown in Figure 12. When the coarse aggregate in the asphalt concrete mixtures is replaced with SN, the asphalt contents vary at 4.8%, 5.3%, 5.8%, 6.3%, and 6.8%. The corresponding UPV values are 4387 m/s, 4494 m/s, 4695 m/s, 4530 m/s, and 4496 m/s, respectively. In contrast, the UPV values of the CS mixtures with asphalt contents of 4.8%, 5.3%, 5.8%, 6.3%, and 6.8% were 4121 m/s, 4225 m/s, 4304 m/s, 4247 m/s, and 4074 m/s, 4181 m/s, 4341 m/s, 4581 m/s, 4479 m/s, and 4410 m/s, respectively. The UPV values and stability will rise with an asphalt content up to the optimal level. An excessive asphalt content reduces the void filling and stability ratings because the surplus asphalt cannot effectively bind the aggregate particles. The increase in UPV at 5.8% asphalt content is attributed to the optimal void filling with asphalt, which acts as a binder between aggregates, like the relationship between stability and VIM.

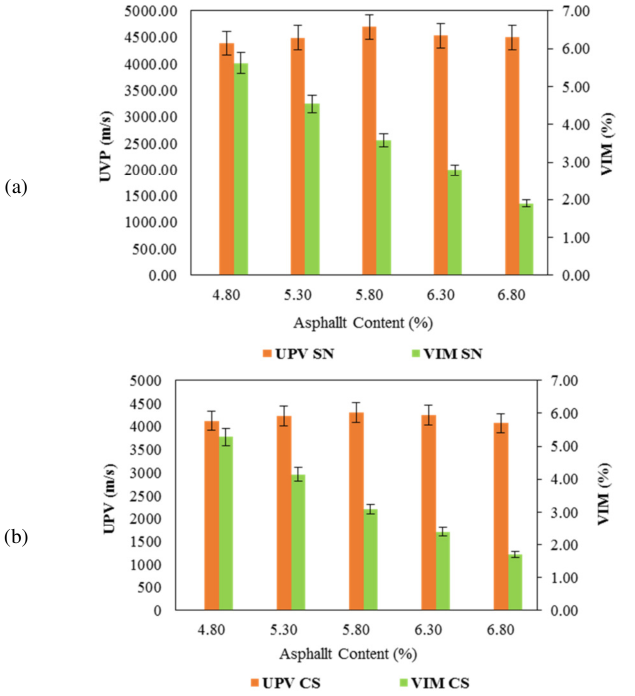


Fig. 12. Relationship between UPV and VIM in mixtures: (a) SN, (b) CS.

IV. CONCLUSIONS

This research compared the Marshall and Ultrasonic Pulse Velocity (UPV) values of asphalt concrete mixtures using the same ratio of Crushed Stone (CS) and Nickel Slag (SN) as coarse aggregate substitutes. The following conclusions were drawn:

- This research showed that the relationship between the stability and flow in asphalt mixtures containing CS and SN as coarse aggregate replacements exhibited a typical development pattern, consisting of initial adjustment, linear elastic, non-linear inelastic, and post-peak phases. It was discovered that the ideal asphalt content was 5.8% at which point stability peaked and then began to decline.
- The grade values of the asphalt concrete mixtures containing SN as coarse aggregate showed higher stability than the mixtures containing CS. In the SN mixtures, substituting the SN with natural materials by limiting the coarse aggregate passing the 19 mm sieve and retained on the 4.75 mm sieve resulted in high stability values. This is due to differences in the surface texture of the coarse aggregate and the effectiveness of the aggregate interlocking. Additionally, the slag material contains silica, which strengthens the bond between the aggregate and the asphalt. All Marshall stability values exceeded the minimum 7.833 kN (800 kg).
- The relationship between the stability and volumetric parameters, namely Void in Mix (VIM), Void in Material Aggregate (VMA), and Void Filled with Bitumen (VFB), was characterized by a negative correlation between the VIM values and bitumen content. The VMA values exhibited a comparable pattern of stability, as all the VMA

values were within the specified limits. The VFB values increased as the bitumen content increased to 5.8%. The minimum requirements were satisfied by all VIM and VFB values that exceeded the 5.8% bitumen content.

- All compositions exhibited satisfactory compression in the UPV wave pattern. The CS mixtures had a shortened lifetime because of the reduced number of cavities. UPV increased to 5.8% bitumen, then decreased by the stability trend. The UPV to asphalt level ratio could be used to establish a correlation between destructive and non-destructive experiments.

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