Effect of Steel Slag on Moisture Susceptibility of Asphalt Concrete Based on Tensile Strength Ratio

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Abstract. Steel slag, a byproduct of steel production, can harm biodiversity and diminish soil fertility when improperly disposed of. However, studies suggest its viability as a pavement material. Given that moisture distress is a major issue in asphalt pavements, this study examines the impact of steel slag on the moisture susceptibility of asphalt concrete based on the Tensile Strength Ratio (TSR). Four Asphalt Concrete (AC) mix variations were prepared, incorporating three different slag proportions (10%, 20%, and 30% of total aggregate weight) alongside a control mix. All AC mixes were subjected to Marshall tests (for medium traffic) and Indirect Tensile Strength (ITS) tests in both dry and wet conditions, along with standard property tests on individual components. All the mentioned combinations met the acceptable standards for AIV, ACV, and water absorption. The optimum binder content (OBC) increased with increased slag due to its porosity, achieving the highest stability at 30% slag, which consistently improved with higher percentages. The unconditioned S20 (20% slag) specimen exhibited the highest ITS, demonstrating excellent resistance to fatigue, thermal cracking, and rutting. It also had the highest TSR at 0.89 while 0.85 for the control mix , indicating strong moisture damage resistance. Material cost savings were estimated 0.7% for S20 and 3.2% for S30 in comparison with control one. In conclusion, replacing 20% stone chips with steel slag can be recommended to enhance stability, boost resistance to fatigue, rutting, and moisture damage of AC mix, and to promote cost savings and effective waste disposal.

Keywords: Steel Slag, Moisture Damage, Tensile Strength Ratio, Freezing and Thawing, Asphalt Concrete.

1 Introduction

When disposed of in the environment steel slag, a byproduct of steel production, poses a risk to biodiversity and reduces soil fertility [1]. Except some little use in constructions, slags and their tailings are moved to specific "slag dumps", where they weather, risking toxic element leaching [2, 3]. This process can lead to hyperalkaline runoff en-

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tering the soil and water, endangering nearby ecosystems, the authors added. Chowdhury (2023) claims that in Bangladesh, around 7.5 million tons of steel are produced annually, generating 40-70 kg of slag per ton of steel [1].

Due to its angular shape, rough surface texture, and hardness, steel slag, has demonstrated potential as a pavement material [4]. Studies have been conducted replacing stone aggregate with steel slag, identifying optimal slag contents of 25% [5] and 30 % [6]. Better stability value was found on replacing stone aggregate by steel slag [7]. Research on slag combined with PET (Polyethylene Terephthalate) and PP (Polypropylene) has revealed several useful properties when used in asphalt concrete (AC) mixtures [8, 9].

One of the primary issues in asphalt pavements is the distress caused by moisture. This damage occurs due to two key failure mechanisms: the breakdown of the cohesive bond within the asphalt binder and the weakening of the adhesive bond between the binder and the aggregate [10, 11]. Adhesion failure occurs when moisture strips the asphalt film from the aggregate, while cohesion failure softens the mastics in asphalt concrete [12].

Various testing methods have been established and utilized to assess the vulnerability of asphalt mixtures to moisture. A study revealed that the Marshall Stability Ratio (MSR) and the Marshall Stability to Flow Ratio (MSFR) are less influenced by moisture impact in assessing moisture resistance, in comparison to TSR (Tensile Strength Ratio) values [13]. Gorkem and Sengoz (2009) conducted the AASHTO T283 test and analyzed TSR values to assess how hydrated lime and polymer-modified bitumen influence the stripping characteristics and moisture sensitivity of Hot Mix Asphalt (HMA) [14]. Behiry (2013) tested asphalt mixtures with hydrated lime and Portland cement, using TSR and MSR, and found both additives improved moisture resistance [15]. Incorporating polyester fiber helped enhance both the wet tensile strength and the tensile strength ratio (TSR) of the modified asphalt mixture [16]. Dalhat & Osman (2023) examined the impact of aggregate characteristics and the volumetric properties of the mix on the moisture susceptibility of asphalt concrete [17]. Aggregate characteristics play a crucial role in moisture damage, yet there has been limited research on how aggregates influence this issue [18].

The suitability of steel slag in asphalt concrete has been researched by many, but its effect on moisture sensitivity remains unexplored. This study aims to assess the impact of steel slag on the moisture susceptibility of asphalt concrete using the Tensile Strength Ratio (TSR) after determining the optimum bitumen content through the Marshall Mix Design. Despite of having many advantages, steel slag has a major disadvantage of consuming more bitumen [7, 8]. And so, cost analysis is done to justify the use of slag in the AC mix.

2 Experimental Procedures

This section presents the step-by-step process of the study, starting with material collection and processing, then moving on to tests on aggregates and binder, followed by the preparation of asphalt concrete samples, testing the mixtures, and finishing with analysis of costs.

2.1 Materials Collection and Processing

Three different materials were utilized in the experiment: stone chips and steel slag as aggregates, and bitumen as the binder. Steel slag was sourced from B.S.R.M. (Bangladesh Steel Re-Rolling Mills Ltd.) and underwent cleaning, drying, crushing, and sieving to obtain different sizes. Stone aggregate, procured from the local market, was also crushed and sieved into various sizes. Moreover, a 60/70 grade bitumen was purchased locally.

2.2 Tests on Aggregates

Two types of aggregate materials were used, and a set of standard tests was performed to assess their suitability for asphalt concrete. These tests were applied to stone chips (limestone), slag, and a mix of both. The evaluations included Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Water Absorption, and Specific Gravity, all conducted in accordance with established guidelines.

2.3 Tests on Binder

Bitumen was used as the binder in this study, and several standard tests were carried out on it. These tests included the Penetration Test, Ductility Test, Softening Point Test, Specific Gravity, and Flash and Fire Point assessments.

2.4 AC Mix Combinations

Four different sets of Asphalt Concrete (AC) mix were prepared. Three varying proportions of slag (10%, 20%, 30% by weight of total aggregate) were mixed with traditional stone aggregate, using bitumen as the binder. Only the coarse fraction of the aggregate was replaced with steel slag. For fine aggregate and mineral filler (Sp. Gr. = 2.75) conventional stone chips and stone dust were used respectively. Additionally, a control set of AC mix without slag was prepared for comparison with the modified mixtures.

2.5 Tests on AC Mix

The asphalt concrete (AC) mixtures were initially evaluated using the Marshall mix design method. Once the Optimum Bitumen Content was determined, the Indirect Tensile Strength Test was conducted on samples in both wet (conditioned) and dry (unconditioned) states.

Marshall Mix Design. The Marshall Mix Design method was utilized to identify the Optimum Bitumen Content (OBC) for all sets of asphalt concrete mixes under medium traffic (50 blows) conditions. Binder contents of 4%, 4.5%, 5.0%, 5.5%, and 6% by weight of the total mix were tested in trials. A total of 60 specimens went through Marshall testing. This study followed the AASHTO R-12 standard, with specific methods referenced from the 7th Edition of the Asphalt Institute's MS-2.

Indirect Tensile Strength. The Indirect Tensile Strength Test was performed on both wet (conditioned) and dry (unconditioned) specimens to determine the Tensile Strength Ratio (TSR). The ITS and TSR tests were conducted in accordance with the guidelines outlined in AASHTO T 283. All the specimens went through a Freezing and Thawing process for being conditioned (wet). A flowchart of the process is illustrated on the figure below.

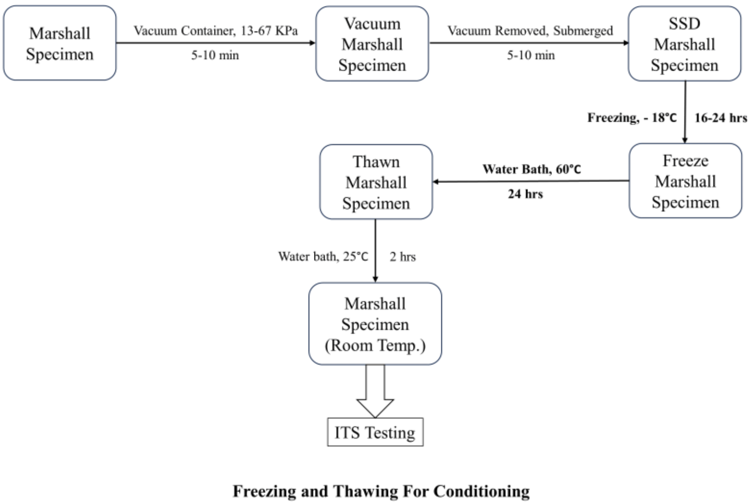

Fig. 1. Flowchart for freezing and thawing.

Adopted Gradation. A gradation of aggregate (max. size = 19.0 mm) was selected that complies with both MS-4 and RHD (Roads and Highways Department) limits. It is near the P=0.45 gradation curve, but not at maximum density to prevent a reduction in VMA. As per the chosen gradation, the coarse aggregate makes up 58%, the fine aggregate accounts for 37%, and the mineral filler constitutes 5% (Table 1, Fig. 2).

Table 1. Different gradation limit with adopted gradation.

Sieve size	Opening (mm)	P=0.45 Power gradation (MS-4 7th Ed.) % Passing	RHD specific lower limit % passing	RHD specific upper limit % passing	Gradation adopted % passing
1"	25.0	100	100	100	100
3/4"	19.0	90	90	100	96

1/2"	12.5	73	65	90	85
3/8"	9.5	66	55	82	76
#4	4.75	48	35	57	42
#8	2.36	35	20	40	26
#16	1.18	26	15	33	18
#30	0.60	19	10	26	13
#50	0.30	14	6	20	9.1
#100	0.15	10	5	13	7
#200	0.075	7	3	7	5
PAN		0			0

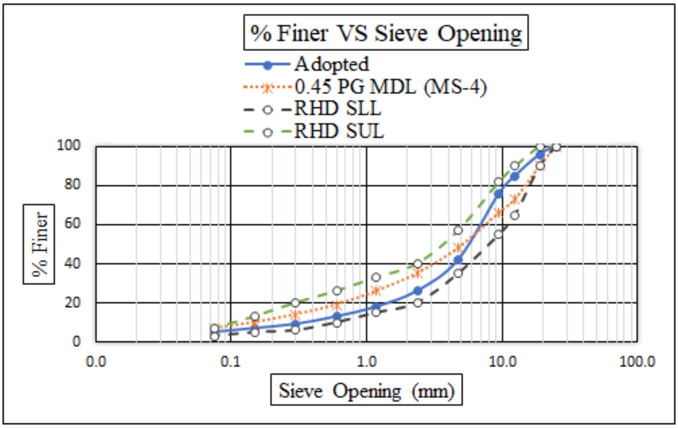

Fig. 2. Different Gradation Limit with Adopted Gradation

2.6 Cost Analysis

The material costs for all combinations were calculated based on current market prices (Table 2) assuming a roadway scenario (Table 3).

Table 2. Market price of the materials.

Material	Processing	Cost (includes processing)	Total cost/kg
Stone	Crushing	BDT 285 per cft	BDT 4.00
Slag	Crushing	BDT 1700 per ton	BDT 1.70
Bitumen		BDT 80.0 per kg	BDT 80.0

Table 3. Assumed roadway.

Feature	Assumption
Type	Regional
Wide	6.2 m
Thickness of Surface Course	40 mm
Volume per km	248 m^3

3 Results

This section presents the results of experimental investigations, including aggregate and binder properties, as well as the characteristics of all AC mixes, addressing Marshall, ITS, and TSR specifications.

3.1 Properties of Aggregates

The Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests were conducted according to BS: 812 (1975) (PART 1, 2, 3). AIV and ACV were measured for full stone aggregate, full slag, and mixtures of 10%, 20%, and 30% slag replacing stone chips. Samples were labeled based on the slag percentage, with S0 representing the full stone sample. As slag content increased, both AIV and ACV values rose. Hussain et al. (2022) claim that AIV and ACV below 30 are acceptable for wearing courses, with AASHTO also flagging values over 30 as concerning [19]. Therefore, the 30% slag substitution was deemed suitable for AIV and ACV requirements.

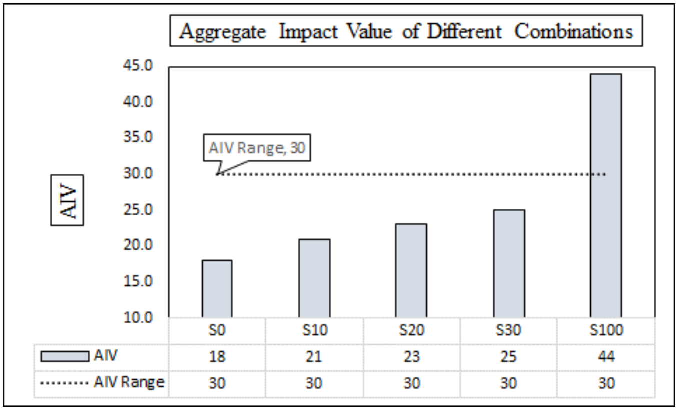

Fig. 3. AIV of different aggregate combinations.

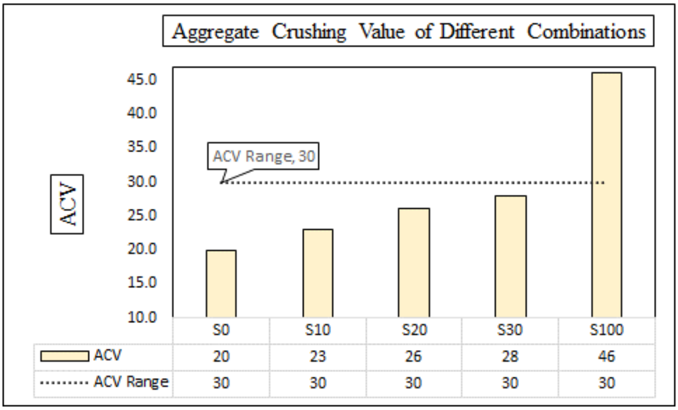

Fig. 4. ACV of different aggregate combinations.

The specific gravity and water absorption of coarse aggregate (stone aggregate and slag) were measured per ASTM C-127, while those of fine aggregate followed ASTM C-128. The mineral filler's specific gravity and water absorption for stone aggregate were assessed using ASTM D-854.

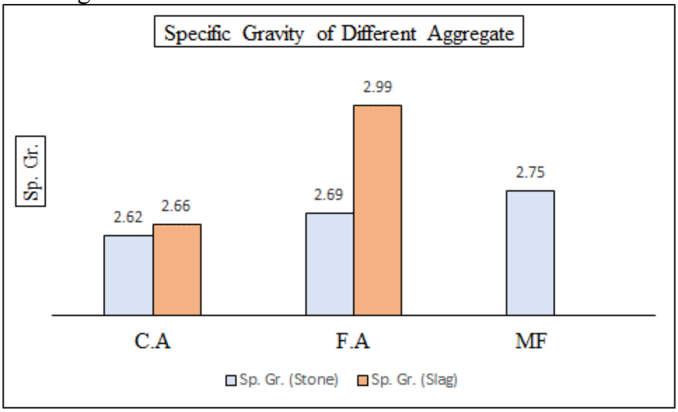

Fig. 5. Specific gravity of different aggregates.

The specific gravity of steel slag was found to exceed that of conventional stone aggregate. This difference was less pronounced in coarse aggregate due to the higher porosity of slag. In contrast, for fine aggregate, breakdown of pores resulted in a significant increase in unit weight.

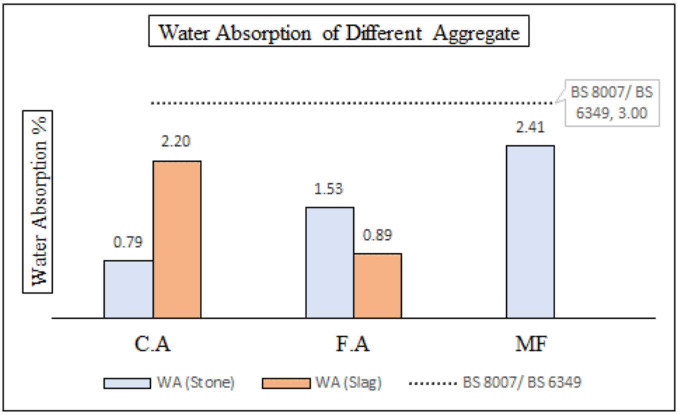

Fig. 6. Water absorption of different aggregates.

Water absorption was higher in steel slag coarse aggregate due to its many pores, while fine aggregate showed lower absorption as its pores were broken down. Mineral filler from stone had the highest absorption, with a trend of increasing absorption from larger to finer stone particles. According to BS 8007 and BS 6349, the maximum allowable absorption for road construction is 3.0%, and all observed values were below this limit.

3.2 Properties of Binder

Bitumen served as the binder in the AC mix, with its routine properties determined through tests following various codes. The locally sourced bitumen was identified as 60/70 grade, which was confirmed in our findings. The table below shows the measured bitumen properties. The flash and fire points were recorded at 310°C and 340°C, respectively, both exceeding the mixing temperature of 160°C. The softening point was found to be 52°C, notably below the mixing temperature.

Table 4. Properties of bitumen.

Properties	Standard	Value
Penetration Test	AASHTO T 49-93'	Avg. = 65, 25°C; Grade= 60/70
Ductility Test	AASHTO T 51-93	> 100 cm
Softening Point Test	AASHTOT 53-92	52°C
Specific Gravity	AASHTO T 228-93	1.02, 25/25°C
Flash and Fire Point Test	AASHTO T 48-91	310°C and 340°C

3.3 Marshall Property Values

A total of four sets of asphalt concrete (AC) mixtures, consisting of 60 specimens, were subjected to Marshall testing. The results showed that all combinations met the standard requirements for medium traffic conditions. The optimum values obtained from the Marshall tests are presented in Table 5, providing a summary of the key findings.

Table 5. Marshall property values at optimum for all the combinations.

Designation		OBC	Air Void %		Unit Wt (Kg/m^3)	VMA %		VFA %		Stability (KN)		Flow (0.25 mm)	
	Standard		min	max		min	max	min	max	min	max	min	max
			3.0	5.0		14.0	-	65.0	78.0	5.3	-	8.0	16.0
S0	Observed	4.93	4.0		2344.8	15.9		75.1		16.62		12.77	
	Remarks		Okay		Okay	Okay		Okay		Okay		Okay	
S10	Observed	5.17	4.0		2389.1	14.6		72.2		17.55		14.85	
	Remarks		Okay		Okay	Okay		Okay		Okay		Okay	
S20	Observed	5.36	4.0		2361.5	15.9		74.9		20.45		15.96	
	Remarks		Okay		Okay	Okay		Okay		Okay		Okay	
S30	Observed	5.53	4.0		2328.0	17.2		74.3		20.45		16.0	
	Remarks		Okay		Okay	Okay		Okay		Okay		Okay	

3.4 Optimum Bitumen Content

The optimum binder content (OBC) was observed to rise with increasing slag content, as the porous nature of slag requires more binder. In the figure below, S0_OBC refers to the OBC of the virgin AC mix, with all slag-inclusive OBC values exceeding this baseline.

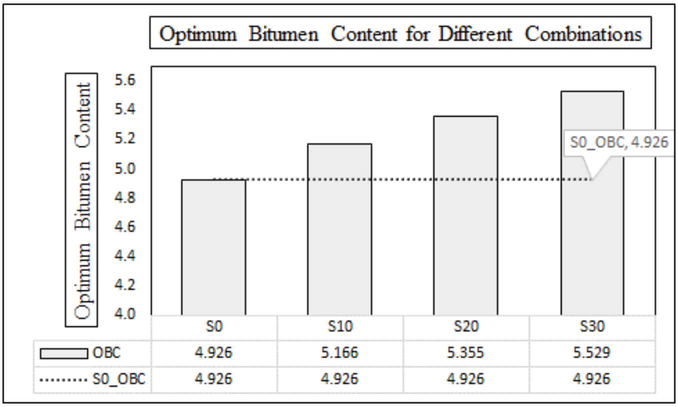

Fig. 7. Optimum bitumen content for different slag percentages.

3.5 Stability at Optimum Binder

The highest stability value was observed with 30% slag content, with increased stability corresponding to higher slag percentages. In this case, S0_Stability represents the stability of the virgin AC mix, and all stability values measured were above this baseline.

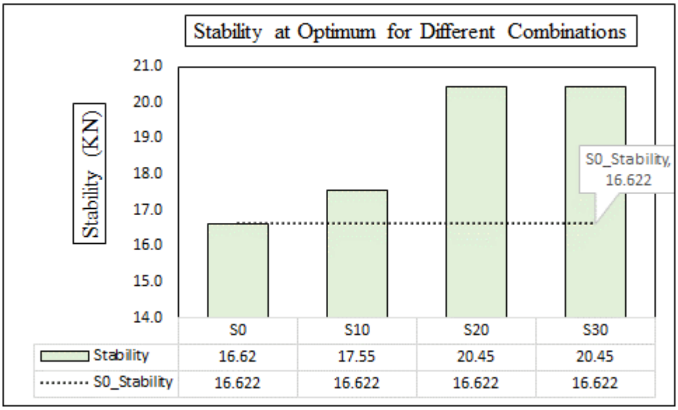

Fig. 8. Stability at optimum for different slag percentages.

3.6 Indirect Tensile Strength

The Indirect Tensile Strength (ITS) Test was performed on both conditioned (wet) and unconditioned (dry) specimens to determine the Tensile Strength Ratio (TSR) for all previously mentioned combinations, following AASHTO T 283 standards.

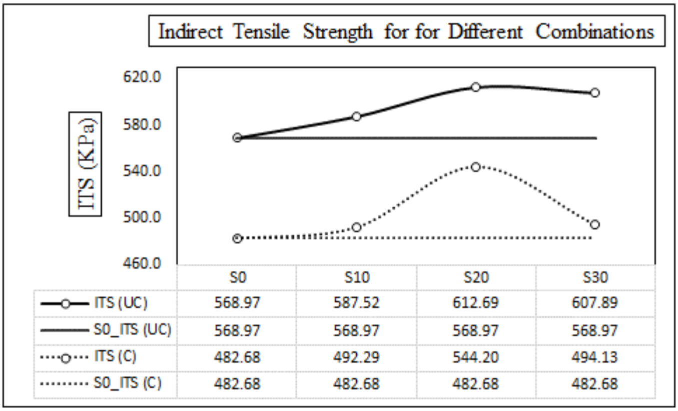

Fig. 9. Indirect tensile strength for different slag percentages.

The above figure shows the Indirect Tensile Strength (ITS) values for both conditioned (C) and unconditioned (UC) specimens at varying slag percentages. Unconditioned specimens are represented by solid lines, while conditioned ones are shown with dotted lines. The straight lines indicate the virgin AC mix (S0_ITS). Both ITS values for unconditioned and conditioned specimens exceeded those of the virgin AC mix, with unconditioned specimens displaying greater strength than their conditioned counterparts, as anticipated. The unconditioned specimen for S20 exhibited the highest ITS, demonstrating better resistance to fatigue, thermal cracking, and rutting.

3.7 Tensile Strength Ratio (TSR)

The tensile strength ratio (TSR) was determined from the Indirect Tensile Strength (ITS) values of both conditioned and unconditioned samples.

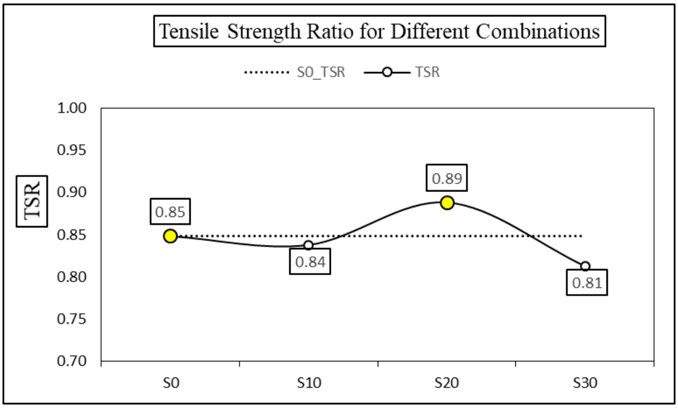

Fig. 10. Tensile strength ratio for different slag percentages.

The TSR for S20 was the highest at 0.89, showing greater resistance to moisture damage. For the virgin asphalt concrete (AC) mix, the ratio of conditioned to unconditioned ITS was found to be 0.85. As noted by Sun (2016), the standard TSR value typically falls between 70% and 80%, making all the combinations mentioned acceptable [20]. For Superpave mix design, a TSR above 80% is considered suitable for hot mix asphalt (HMA).

3.8 Cost Analysis

The figures below show the material cost savings for the surface layer of the hypothetical roadway. Savings generally increased with higher slag content, except for S10. Estimated savings per kilometer for material costs, compared to the Virgin AC mix, were 0.7% for S20 and 3.2% for S30.

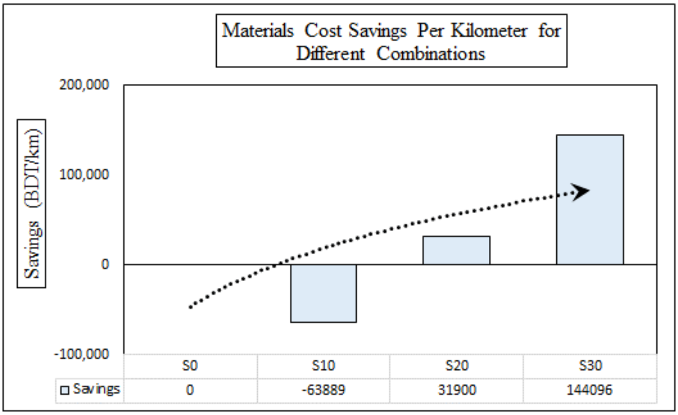

Fig. 11. Materials cost savings (BDT)/km for different combinations.

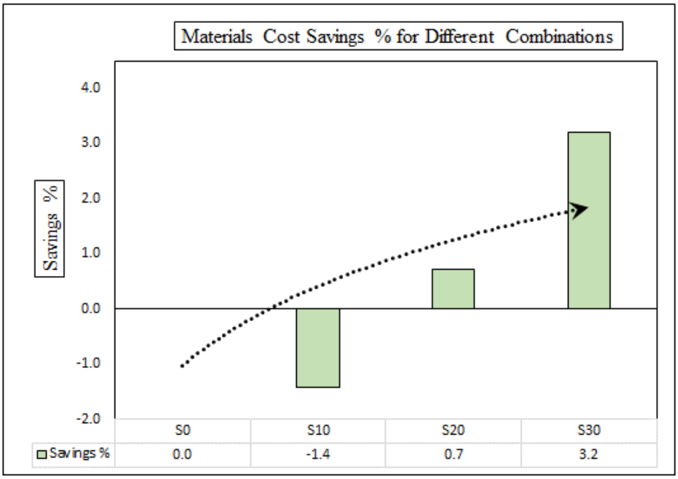

Fig. 12. Materials cost savings (%) for different combinations.

4 CONCLUSION

From the results obtained through various experiments on individual components and different AC mixtures, the following conclusions can be made:

1. As slag content rose, AIV and ACV values increased but stayed below 30, indicating that a 30% slag replacement is suitable for meeting the criteria for the wearing course.
2. Steel slag had a higher specific gravity than traditional stone aggregate, with less difference in coarse aggregate due to porosity. Steel slag coarse aggregate also showed higher water absorption, while fine aggregate had lower due to breakdown

of pores. All measured values were below the 3.0% maximum absorption limit for road construction.

3. The optimum binder content (OBC) increased as slag content rose, due to the porous structure of slag necessitating more binder. The greatest stability was achieved at 30% slag content, with higher slag percentages consistently leading to improved stability.
4. The ITS values for both unconditioned and conditioned samples surpassed those of the virgin AC mix, with unconditioned samples showing higher strength than conditioned ones, as expected. Among them, the unconditioned S20 specimen displayed the highest ITS, indicating superior resistance to fatigue, thermal cracking, and rutting.
5. TSR value of all the combinations are higher than 80% demonstrating them acceptable for superpave mix design. The TSR for S20 was the highest at 0.89, showing greater resistance to moisture damage.
6. The projected savings in material costs per kilometer, in comparison to the Virgin AC mix, were 0.7% for S20 and 3.2% for S30, with S10 being the exception. Incorporating 20% slag into the AC mix can enhance stability and improve resistance to fatigue, rutting, and moisture damage, while also facilitating cost savings and effective waste disposal.

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