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Effect of Using Steel Slag as Replacement to Coarse Aggregate in SMA

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Abstract

The utilization of steel slag in flexible pavement has recently gained attention due to its increasing availability. Steel slag is a by-product material generated during the production of steel and is typically produced in large quantities. It is a dense and hard material that makes it applicable for use as a coarse aggregate in stone mastic asphalt (SMA). Using steel slag as an aggregate in SMA can help to reduce the environmental impact of construction activities. Steel slag is an industrial waste material that is commonly disposed of in landfills, which can cause environmental pollution. By utilizing steel slag in SMA, it can be given a second life and contribute to the development of sustainable infrastructure. The study aims to determine the optimal replacement percentage of steel slag that achieves the desired mechanical properties and overall performance of SMA. Based on experimental results in this paper, Marshall stability of SMA mixtures increased with the increase in the percentage of steel slag. the results demonstrate that the use of steel slag as a partial replacement of natural aggregates in SMA can enhance the mechanical properties of the mixture and enhance pavement performance. Therefore, the use of steel slag as a sustainable alternative to natural aggregates can be an efficient way to reduce the environmental impact and promote sustainable construction practices.

Keywords

Stone mastic asphalt, Steel slag, Marshall stability, Mechanical properties, Pavement performance, Nanomaterial mineral fiber

Introduction

SMA is a type of asphalt mixture that has been gaining popularity in road construction due to its superior performance in terms of durability, stability, and noise reduction and it's composed of coarse aggregate, fine aggregate, binder, and additives. One of the unique properties of SMA is the high degree of stone-on-stone contact within the mixture, which contributes to its excellent rutting resistance. The aggregate interlocking property of SMA plays a vital role in enhancing its structural performance and durability [1]. The tightly packed coarse aggregates in SMA create a stable framework, promoting load transfer and reducing deformation under traffic loads, thereby contributing to its superior rut resistance and improved pavement longevity [2]. The gradation of aggregates in SMA significantly influences its mechanical properties and performance. Properly designed gradations with a balanced distribution of course and fine aggregates enhance the stone-on-stone contact, leading to improved load transfer and resistance against rutting and fatigue cracking [3]. However, deviating from the optimal gradation can result in reduced stability, increased voids, and decreased resistance to distresses, emphasizing the importance of precise control over aggregate gradation in SMA mix design [4]. Also, it has been found that the gradation of the aggregate and the bitumen content can have a substantial impact on the performance of SMA which was approved by Qiu and Lum [5]. By optimizing these factors, engineers can create materials that are better suited for specific applications. Also, Asi [6], found that the SMA has shown improved durability due to increased bitumen content and reduced air voids content. However, the main disadvantage of SMA mixture is its higher primary cost and binder drainage [7]. Adding a small quantity of 0.3 percent of cellulose fiber by total weight of mix is recommended by MORTH specification to prevent drainage of binder during placement and transportation [8].

In general, there are typically two primary types of aggregate used for construction purposes: natural and artificial. However, in recent years, there has been a push to use artificial aggregates instead of natural ones due to the need to conserve natural resources and mitigate environmental concerns. This has resulted in increased encouragement for material scientists and engineers to explore and utilize artificial aggregates in construction projects.

Steel slag is an industrial byproduct generated from the steel-making process and has been used in various construction projects. According to statistics 500 million tons of steel slag is produced annually in United States, North America, and Asia [9]. In the United States, Europe, and other developed countries, steel slag is being used at a rate of 70 - 80%, which means it is being utilized extensively [10]. The utilization rate of steel slag in China is only 29.5% [11]. Every year, steel industries in India generate approximately 12 million tons of steel slag, as stated in the FICCI report of 2018. Sadly, a significant portion of this steel slag is currently discarded as waste in nearby landfills and remains unused. However, in recent years, researchers have explored various innovative approaches for utilizing steel slag. Such as the mixture of fly ash, steel slag powder, and cement clinker was used to make composite cement, and it was discovered by Shih et al. [12] that a certain amount of steel slag admixture in cement could reduce porosity, improve pore distribution, and enhance cement consistent behavior. A suitable amount of steel slag can reduce the required firing temperature for clay bricks [13].

Steel slag application in industrial wastewater treatment has received a lot of attention in recent years. Steel slag is becoming a lucrative resource after formerly being considered garbage. Utilizing its complex makeup at the nanoscale, which is abundant in oxides such as iron, calcium, silicon, and magnesium, could have enormous benefits. These tiny soldiers' hold extensive potential to strengthen the road construction industry's future. These nanoparticles offer extreme strength and durable reinforcements to the concrete mixes. Consider the nanoparticles made of steel slag as microscopic builders that bridge the tiny spaces in the concrete matrix. This increases the overall strength and longevity of concrete by resulting in a denser, more robust structure. These are structures that are not just towering but also resilient to deterioration, cracking, and wear and tear throughout time. The inherent heat-resistant properties of steel slag nanomaterials add another layer of protection to concrete. These "heat-proof warriors" within the concrete matrix can withstand higher temperatures for longer durations, significantly improving the heat tolerance of asphalt concrete. This translates to safer spaces for people and reduced risk of catastrophic damage in case of high temperature. Steel slag in the form of nanomaterials offers very high durability as well. Harnessing waste steel slag as a construction material advocates sustainability on various fronts. This approach lessens dependence on fresh resources such as sand and gravel, consequently mitigating environmental repercussions. Furthermore, it advocates for effective waste management by diverting slag away from landfills and repurposing it into a valuable construction material.

However, our focus on this paper is utilization of steel slag in asphalt mixture. The results indicate that the surface of steel slag aggregate is characterized by a dense network of tiny pores with a high adsorption capacity for asphalt binder material. Ahmedzade and Sengoz [14] investigated the mechanical properties of asphalt mixtures containing steel slag. The mechanical properties of the asphalt mixtures were specifically examined by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength. The study's findings suggested that using steel slag as a coarse aggregate improved the mechanical properties of asphalt mixtures. In another same study, the mechanical properties of pavement bitumen mixture can be significantly improved by using steel slag as a coarse aggregate especially in terms of stability and durability [15, 16]. Also, it was found that the use of steel slag as a replacement for coarse aggregate in SMA resulted in higher tensile strength, higher resistance to rutting, and better water stability [17]. In another study conducted by Han et al. [18] it was found that the use of steel slag as a replacement for coarse aggregate in SMA resulted in improved mechanical properties, such as higher stability, higher resistance to deformation, and better fatigue performance. In summary, utilization of steel slag as coarse aggregate in asphalt mixes can increase the durability, strength, water damage resistance and rutting resistance. However, few studies have been conducted to determine the optimal amount of steel slag incorporation for SMA. This study investigates the use of steel slag as a partial or full replacement of natural aggregates in SMA. The objective of this research is to evaluate the performance of SMA mixtures containing five different percentages (20%, 40%, 60, 80%, and 100%) of steel slag as a coarse aggregate. The study also aims to assess the mechanical properties of the SMA mixtures containing steel slag. The experimental program consists of preparing and testing SMA mixtures with five different steel slag contents. Granite powder, which is a fine-grained material that's produced by crushing granite rocks, has been used as filler. The remaining components of the SMA mixture were kept constant. The mechanical properties of the mixtures were evaluated by conducting Marshall stability.

Materials and Methodology

Materials

Asphalt binder

The binder is commonly used in pavement construction due to its excellent performance in high-temperature environments. It contains a polymer additive that improves its elasticity and resistance to rutting and cracking. In this study VG-40 bitumen which was obtained from Bathinda Refinery is used. The binder was tested for its physical and rheological properties to ensure that it met the specifications required for the study. The infusion of steel slag nanoparticles into asphalt binders enhances their mechanical characteristics, resulting in roads that are more robust and enduring. These modified binders exhibit increased resilience against cracking, rutting (deformation), and wear, thereby prolonging the road's lifespan and lowering maintenance expenses. Table 1 shows the test values of virgin VG-40 bitumen.

Coarse aggregate

Jyoti Steel Amloh corporation is the source of steel slag used in this paper. The physical and chemical properties are examined to ensure its suitability. The natural aggregate was a high-quality aggregate from a quarry close to Patiala, Punjab (India). Various tests performed on both steel slag and natural aggregate and the specific indices are shown in table 2, table 3, and table 4. The gradation composition steel slag SMA is shown in table 5. Once considered waste, steel slag is now being recognized as a useful resource. When used at the nanoscale, its complex composition—rich in oxides such as iron, calcium, silicon, and magnesium—holds enormous potential. Nanoparticles function as "anchors," establishing a stronger connection between asphalt and aggregate (crushed rocks), enhancing their adhesion, and thwarting the formation of potholes. This results in a sturdier pavement structure capable of withstanding heavy traffic and adverse weather conditions.

Mineral filler and additive

Granite powder which consists of finely divided mineral matter is used as filler in this paper, The filler was graded within the limits indicated by MORTH specifications (Fifth Revision) as shown in table 6. As SMA contains a high percentage of coarse aggregate there's chances of bitumen drainage, MORTH specifications recommend a minimum 0.3% of lose cellulose fiber by weight of total mix to prevent bitumen drainage. Also, cellulose fiber is a vital part of asphalt mastic due to its ability to adsorb and stabilize asphalt mixtures through adsorption, physical infiltration, and chemical bonding [19, 20]. Embedding nanoparticles in concrete serves as self-healing agents. In the presence of microcracks, these nanoparticles react with water or carbon dioxide, effectively sealing the cracks and halting any potential further damage. This substantially enhances the durability and resilience of concrete pavements. Utilizing steel slag

Table 1: The results of tests performed on bitumen.

Tests	Results	Standards	Specifications
Penetration (mm)	54 mm	IS 1203	50 - 70
Softening point (°C)	56 °C	IS 1205	Min. 47
Specific gravity at 25 °C	1.013	IS 1202	0.98 - 1.02
Ductility (cm)	Greater than 100	IS 1208	Min. 75
Flash point (°C)	228 °C	IS 1209	Min. 220

Table 2: Physical properties of natural aggregate.

Tests	Units	Results	IRC:SP:79:2008
Crushing value	%	18.54	< 30
Los angles abrasion value	%	22.8	< 25
Impact value	%	15.9	< 18 specific gravity
Water absorption	%	1.1	< 32
Flakiness and elongation index	%	28.5	< 30

Table 3: Physical properties of steel slag.

Tests	Results %	Specifications of aggregate as per MORTH
Los Angles abrasion value	19	< 35%
Impact value	16.2	< 18%
Specific gravity	3.01	2.5 - 3.2
Water absorption	1.6	< 2

Table 4: Chemical test result of steel slag.

Parameters	Test method	Units	Results
SiO_2	Gravimeter method	%	72.38
Al_2O_3	Digestion followed by AAS	%	5.52
Fe_2O_3	Digestion followed by AAS	%	1.55
CaO	Digestion followed by AAS	%	3.95
MgO	Digestion followed by AAS	%	1.14

Table 5: SMA steel slag gradation composition design.

Type of mix	Coarse aggregate (76%)		Fine aggregate (14%)	Mineral powder (10%)	Optimum bitumen content (%)
CM	Natural aggregate		Natural aggregate	Natural aggregate	5.75%
SG0	0% steel slag	100% natural aggregate	Natural aggregate	Granite powder	6%
SG2	20% steel slag	80% natural aggregate	Natural aggregate	Granite powder	5.6%
SG4	40% steel slag	60% natural aggregate	Natural aggregate	Granite powder	6.05%
SG6	60% steel slag	40% natural aggregate	Natural aggregate	Granite powder	5.66%
SG8	80% steel slag	20% natural aggregate	Natural aggregate	Granite powder	6.08%
SG10	100% steel slag	0% natural aggregate	Natural aggregate	Granite powder	5.8%

Table 6: Gradation required for mineral filler.

IS sieve (micron)	Cum. percentage passing by total weight of aggregate
600	100 %
300	95 - 100 %
75	85 - 100 %

nanoparticles can reduce the porosity of concrete, thereby decreasing its vulnerability to frost damage. This is particularly vital in regions experiencing freezing temperatures, where the occurrence of freeze-thaw cycles can lead to substantial cracks and deterioration. Mineral filler which is a nano material as shown in table 6 is used in preparing SMA.

Methodology

Mid gradation

Gradation of SMA is typically determined through laboratory testing, where the aggregates are sieved, and their particle sizes are measured. Various tests, such as the sieve analysis, aggregate crushing value, and aggregate impact value, are conducted to evaluate the quality and suitability of the aggregates for SMA. Also, its gradation involves carefully selecting and combining aggregates of various sizes to create a dense and stable asphalt matrix. The aggregates used in SMA typically consist of crushed stone, gravel, or sand, and they are classified into different size fractions based on their particle size distribution (Figure 1).

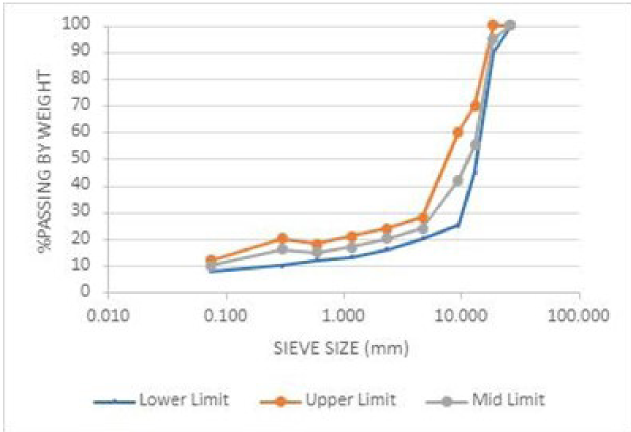

Figure 1: Gradation limits for stone mastic asphalt mixture.

Preparation of samples

In this paper, six different SMA mixes were prepared using [21], standard specifications for designing stone mastic asphalt, and then compared to control mix which labelled as CM. SMA and steel slag gradation composition is shown in table 5. for determining optimum bitumen content Marshall method is used. Samples with four different bitumen ratios (5.5% - 6.25%) were prepared at 0.25% increments. HMA process involved combining the selected aggregates, natural aggregate and steel slag in specific proportions based on the determined gradation and heated at 180 °C temperatures. Bitumen which was preheated at 160 °C was add to aggregates. The mixture is thoroughly mixed in a hot mix asphalt plant to achieve a homogeneous mixture. 50 blows on each side suggested by asphalt institute MS-2 (Sixth Edition), also previous studies by [6] showed 75 blows cause break down in aggregates and didn't show any rise in density. The SMA mixtures were prepared to produce a minimum VMA of 17% and 4% of air voids to meet the AASHTO-MP8 regulations (Figure 2).

Figure 2: Prepared samples.

Testing program: Marshall stability, flow, and Marshall quotient (MQ)

Marshall stability is a measure of the maximum load-bearing capacity of an asphalt mix used to determine optimal steel slag with asphalt binder in SMA. Marshall flow which measures deformation when subjected to stress and Marshall stability tests were carried out on compacted specimen with different binder content, according to (ASTM D1559, 2015). MQ, also known as stability-to-flow ratio, is the ratio of Marshall stability (Kn) to flow (mm). It is calculated by dividing the Marshall stability by the Marshall flow. The MQ is used as an indicator of the quality of the asphalt mix, with higher values indicating a stiffer and more stable mix. A higher MQ is generally desirable as it suggests a mix with good load- bearing capacity and resistance to deformation (Figure 3) [22].

Figure 3: Marshall stability test apparatus.

Results and Discussion

Marshall properties of typical SMA mix

Table 7 shows the result of Marshall test which have obtained from an average of three specimen prepared with four different bitumen content from 5.5% to 6.25% with an increment of 0.25%. Marshall test was conducted according to MORTH Specification (Fifth Revision) and [23], and the aim was to determine the optimal bitumen content in SMA. A stability value of 9.25 kN is obtained for the SMA mix containing 5.50% bitumen. With a slight increase in the bitumen content to 5.75%, the Marshall stability slightly improves to 9.41 kN. At 6.00% bitumen content, the stability remains high at 9.35 kN. However, when the bitumen content is further increased to 6.25%, the stability decreases noticeably to 8.12 kN. These results suggest that the SMA mix with 5.75% bitumen content has the highest Marshall stability among the tested mixtures. It indicates that increasing the bitumen content beyond this point (6.00% and 6.25%) may result in reduced stability. All other quantitative characteristics like flow, bulk density and etc, meet the requirements outlined in the IRC:SP:79:2008 [24].

Marshall properties of SMA mix with steel slag

The CM had the highest stability value of 9.41 kN. However, the use of steel slag in SMA resulted in improved mechanical properties (Figure 4). The higher percentage of steel slag in SMA led to increased stability with the highest value obtained at 80% replacement with a value of 15.11 kN. This could be attributed to the angular shape and rough texture of steel slag, which enhances the interlocking and frictional resistance among the aggregate particles, resulting in improved load-bearing capacity. Further increase in percentage of steel slag reduced the stability to 13.84 kN. All other important parameters such as minimum 17% (VMA), 4% air voids, VFB, bulk density and flow values were satisfying MORTH specification of Marshall mix requirements shown in table 8. Also, MQ values have been observed to fall within a specific range. MQ defines the resistance of asphalt mixture against deformation, A high MQ value denotes a mixture with a high degree of stiffness and excellent resistance to creep deformation. Therefore, steel slag proves to be a beneficial additive in SMA by enhancing its overall performance.

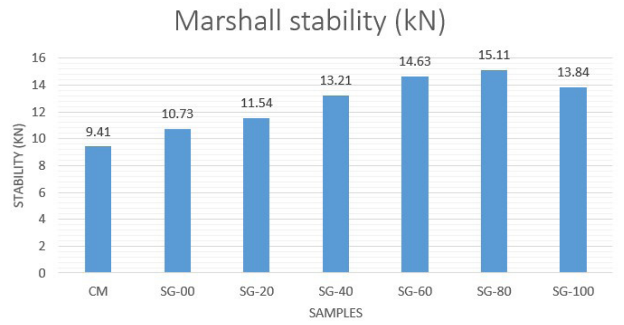

Figure 4: Summary of Marshall test results.

Conclusion

The study aimed to evaluate the feasibility of using steel slag as a sustainable alternative to natural aggregate in SMA mixtures and to assess the mechanical properties of SMA mixtures containing steel slag as a coarse aggregate, including Marshall stability, MQ, indirect tensile strength, and retained stability. These tests provide important indicators of the performance and durability of asphalt mixtures under traffic loads, and aging.

The Marshall stability test, which measures the resistance of the asphalt mixture to deformation under traffic loads, showed that the SMA mixtures with 80% steel slag replacement exhibited the highest stability value (15.11 kN). This indicates that the addition of steel slag as coarse aggregate at this percentage resulted in improved structural stability and resistance to deformation, which is a crucial factor in ensuring the long-term durability and performance of asphalt pavements.

The MQ, which is calculated as the ratio of stability to flow, also showed favorable results for SMA mixtures with 80% steel slag replacement. Higher MQ values indicate better resistance to rutting and deformation, which is an important consideration for pavement design in heavy traffic areas.

Steel slag contains a significant amount of reactive sili-

Table 7: Marshall properties of typical SMA mix.

Bitumen content (%)	Wt. in air (gm)	Wt. in water (gm)	SSD (gm)	bulk density (gm/cm³)	Marshall stabilitys (kN)	flow (mm)	Vv (%)	VMA (%)	VFB (%)
5.50%	1265	740	1280	2.41	9.25	2.6	4.86	18.42	73.64
5.75%	1280	750	1292	2.42	9.41	3.1	3.78	18.73	79.81
6.00%	1265	740	1250	2.41	9.35	3.8	3.6	19.15	81.18
6.25%	1255	739	1247	2.43	8.12	3.9	2.31	18.61	87.58

Table 8: Summary of Marshall test results.

Samples	Optimum binder content (%)	Marshall stability (kN)	Flow (mm)	VMA (%)	Air voids (%)	MQ (kN/mm)
CM	5.75%	9.41	2.17	18.73	4.38	4.33
SG0	6%	10.73	2.31	21.16	3.68	4.67
SG2	5.6%	11.54	2.85	9.91	5.11	4.04
SG4	6.08%	13.21	3.01	21.52	3.71	4.38
SG6	5.66%	14.63	3.35	21.99	5.42	4.36
SG8	6.08%	15.11	3.59	22.50	3.69	4.24
SG10	5.8%	13.84	3.97	23.01	4.75	3.48

cate minerals, such as calcium silicates (e.g., dicalcium silicate, tricalcium silicate). These silicates can react with the bitumen binder during the mixing and compaction process. The chemical reaction between the silicates and bitumen results in the formation of a durable bond, enhancing the stability and cohesion of the asphalt mixture. Although using steel slag as a recycled material is environmentally beneficial, there can be concerns related to leaching of potentially harmful substances. Proper testing and quality control measures should be implemented to ensure that the steel slag meets regulatory requirements and does not pose any environmental risks.

The use of steel slag waste in nanomaterials diminishes environmental impact by decreasing dependence on new materials such as sand and gravel. This advocates for circular economy principles and reduces the amount of waste sent to landfills. Certain nanomaterials originating from steel slag demonstrate thermal insulation characteristics. Their incorporation into road construction materials has the potential to reduce energy consumption for infrastructure cooling or winter de-icing. Specific nanoparticles derived from steel slag showcase antibacterial and antifungal attributes. Integration of these nanoparticles into road surfaces can mitigate the dissemination of bacteria, enhancing hygiene, particularly in urban settings. Nanomaterials could be employed in the creation of smart de-icing systems that react to temperature variations, dispensing de-icing agents solely when necessary. This approach minimizes salt usage and lessens environmental impact.resent sustainable solutions for the textile processing sector.

Acknowledgments

None.

Conflict of Interest

None.

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