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THE EFFECT OF STEEL SLAG POWDER ON HMA STABILITY

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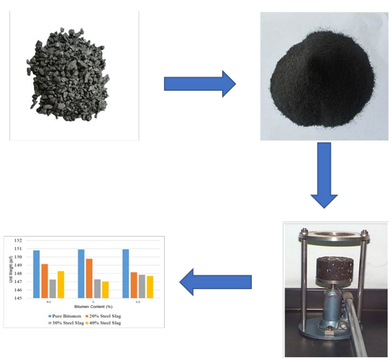
Graphical abstract



Abstract

The goal of the study is to evaluate the improvements of the stability of the hot mix asphalt (HMA) after the addition of ground steel slag. Steel slag was grounded into finer 75µm particles at Bangladesh Road Research Laboratory (BRRL). Then the ground steel slag powder was added to asphalt binder for penetration and softening point tests. Three modified HMA mixes were prepared with 20%, 30% and 40% of steel slag powder and 2% of cement for the Marshall test with a control mix containing 2% of cement only. The Marshall stability result shows increased stability and decreased flow. Marshall stability reached to maximum at the level of 30% of steel slag powder. The flow values obtained showed a slightly decreasing pattern with the increase in steel slag. The density of the mixes slightly decreases with the increase of steel slag content in the asphalt binder. It was found that the ground steel slag has a negligible effect on air voids (Va), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). A designed mix was also achieved the best possible result for all parameters in this experiment setup. Ground steel slag can be used in HMA and asphalt pavement construction, which can result in reduced maintenance work and minimize the frequency of rehabilitation and contributes to economic and environmental development.

Keywords: Flexible Pavement, Steel Slag, Hot Mix Asphalt, Penetration, Marshall.

1.0 INTRODUCTION

Surface course or wearing course is the topmost layer of the flexible pavement directly exposed to traffic. For flexible pavements, it normally contains multiple layers. This should be weather-resistant and fatigue-resistant. Pavement surfaces are constructed using asphalt binder to bond mineral aggregates, such as sand, gravel, and crushed rock, which create the road surface. A wide range of conditions, including temperature fluctuations, sun radiation, oxidation, and prematurely average daily traffic (ADT), impact asphalt binder therefore the pavement performance (Ahmedzade and Sengoz, 2009). The asphalt binder begins to lose its life due to wheel load, environmental condition and resistance. Rejuvenation of the asphalt binder is required. There are different types of fresh asphalt binder that must be modified to meet the pavement specifications. In recent years, Engineers have turned their attention to non-conventional materials (i.e., COVID-19 single used facemasks, steel slag) with the considerations of the environment, economy, technology, natural resource conservation, and insufficient building materials (Giesekam et al., 2015; Wang et al., 2022). Steel slag is a strong, dense, and abrasion-resistant co-product of steelmaking. The steel slag can be used as an aggregate in hot mix asphalt paving due to its high strength, excellent binder adhesive, and high frictional and abrasion resistance (Zhang et al., 2020). The use of steel slag in pavement construction lessens the number of natural resources used in highway construction, therefore less steel slag-storing areas are required (Nazarinasab et al., 2018). Steel slag can also be used as an aggregate in unbound bases and subbases (Motz and Geiseler, 2001). Normal hot mix asphalt or Stone Mastic Asphalt (SMA) incorporating steel slag were found to have a high skid-resistant number, rutting resistance, and stability (Mahmoud and Mahmoud, 2019). Steel slag was formerly used as a road construction material in South Yorkshire in England in the 1960's. Comparing Road surfaces with steel slag to those with natural aggregate under equivalent traffic circumstances revealed that steel slag provides superior traction and used in HMA to decrease premature discomfort. When treated to the desired grain size, the steel slag aggregate (SSA) produces the most interlocking, which is necessary for creating internal friction for increased stiffness and making the aggregate more resistant to permanent deformation. The use of steel slag can reduce pollutants, save occupied land and prolong the service life of the pavement (Aziz et al., 2014; Jones, 2000). In Japan and Europe, high percentage of steel slag is used in road construction (Al-Kinani et al., 2015). In the late 1990s, in Germany, test roads employing steel slag as an aggregate for unbound base and asphalt mixtures were constructed (4). Research work in Qatar was initiated in 2011 to recycle electronic arc furnace slag and use it in road construction and in concrete (Fronek, 2012). From 1993 to 2008, the Japanese Slag Association has researched and reported the use of steel slag as a material for ground improvement in port and harbors construction (Alsadig and Wagialla, 2018). Steel slag also can be used in a variety of ways. Recycling of these wastes is important in conserving natural resources, minimize the extraction of primary aggregates thereby protecting more of natural resources, and manufacturing new products to protect people and the environment. American Society for Testing and Materials (ASTM) classifies steel slag as a non-metallic substance, which is made up of primarily calcium silicates and ferrites and other iron, aluminum, manganese, calcium, and magnesium-containing fused oxides (Rezaul et al., 2018). Because of its high strength, good adhesion, and high resistance to wear and tear, steel slag is expected to increase the performance of asphalt mixtures, increasing its strength and stability and the likelihood of having increased voids decreases bleeding of the asphalt, which in turn decreases the amount of bleeding the pavement exhibits. Because of improvement of stability, strength, durability etc., it also ensures that a thinner layer can be applicable saving materials and cost, same thickness and longer life span is achieved, decreasing maintenance and reconstruction cost. In Bangladesh together with the whole world, Steel slag is considered debris and ends up in landfills near steel manufacturing facilities (Wang, 201[illegible]). Steel slag was pulverized into finer than 75-micron particles by the Bangladesh Road Research Laboratory (BRRL) in order to investigate the feasibility of improving the stability of hot mix asphalt by adding steel slag. In this study steel slag powders were added with asphalt binder for penetration and softening point tests. Three modified HMA mixes were prepared with 20%, 30% and 40% of ground steel slag powder with 2% of ordinary Portland cement to perform the Marshall test. In addition, Section 3.5.2 of the Road and Highway Department's (RHD) "Pavement Design Manual" is followed during study which specifies that Marshall stability and flow test shall consist of mineral aggregates combined with 2% hydrated lime powder or Portland cement, as needed, and coated with the asphalt binder (Roads and Highway, 2011). To predict how well this asphalt mixture will perform and the maximum load it can support. In the crisis period of Hyperinflation, developing projects in particular the road construction needs to be more sustainable for developing countries like Bangladesh along the underdeveloped counties to meet sustainable Development Goal (SDG 2030), is the principal concern of the Study.

2.0 METHODOLOGY

2.1 Materials

Steel slag is a by-product from the steel manufacturing process. It is created when molten steel is separated from impurities in steel-making furnaces. After cooling, the slag solidifies as a molten liquid composed of a complex solution of silicate and oxide. To begin, the steel slag is ground to ≤75μm at BRRL.

2.2 Preparation

In this study 60-70 grade asphalt binder (AASHTO M20-70 & ASTM D946) is used, and 2% Portland cement is added into the mixes as an anti-stripping agent, including the control mix. The 2% cement was added to all the mixes since it is a requirement of Roads and Highway Department (RHD) of Bangladesh to use 2% cement to prepare hot mix asphalt mixtures (HMA). The physical properties of the steel slag used in this study is in the range of the Table [illegible]. The percentage ground steel slag powder is 20%, 30% and 40% for the tests. Three groups of specimens for each combination were prepared. Each batch was oven dried before experiment. 50% of coarse aggregate, 45% of fine aggregate and 5% of mineral filler proportion chosen for the mix design. In order to ensure a theoretical density of 2.4-2.5 grams/cc, ground steel slag, cement and asphalt were used in the sample preparation of 1,216 gm (with 5% asphalt binder content). In addition to coarse aggregate, fine aggregate, and bitumen, ground steel slag was added as a modifier in the modified mixes. This same process was also done for other mixes. Several laboratory tests on the hot mix asphalt were conducted to evaluate the performance of HMA used on highways. Most of the tests were carried out in the laboratories of the various highway agencies. The testing methods developed by the American Association of State Highway and Transportation Officials and the American Society for Testing and Materials, i.e., ASTM D5, ASTM D1559, ASTM E28-67 or ASTM D36 or ASTM D6493-11. The properties asphalt binder (penetration and softening point) and HMA (Marshall stability and flow) were conducted in this study.

2.3 Binder Testing

Penetration test

Penetration test is a basic and standard asphalt binder test. The distance (in centimeters) to which a standard needle penetrates an asphaltic substance under known conditions of time, load, and temperature. This test measures high-temperature viscosity and low-temperature stiffness. This test measures asphaltic materials' consistency. The standard penetration test uses a 100-gm needle for 5 sec. at 77^{o} F. (25^{o} C). Straight-run asphalt binder grades include 30-40, 40-50, 50-60, 60-70, 70-85, and 80-100.The standard penetration test procedure involves use of the standard needle [Needle 50 mm (2 in) length and 1 to 1.02 mm (0.039 to 0.040 in.) diameter] under a load of 100 gm for 5 sec. at a temperature of 77ºF (25º C).

Softening point test

Softening Point Test, as per ASTM D36-89, a standard ball passes through a sample of asphalt binder in a mold and falls through a height of 25 mm, when heated under water or glycerin at specified conditions of test. The binder should have sufficient fluidity before its applications in pavement construction. Softening point denotes the temperature at which the HMA attains a particular degree of softening under the specifications of test.

Percentage of modifier for Penetration and softening point test (by weight): Ground steel slag: 10%, 20%, 30%, and 40%, Cement: 2% (anti-stripping agent).

Table 1 Physical properties of steel slag produced in RSRM steel mill.

Physical Property	Value
Specific Gravity	3.2 - 3.6
Unit Weight, kg/m3 (lb/ft3)	1600 – 1920 (100 - 1[illegible])
Absorption	up to 3%

2.4 HMA Testing

Marshall Stability Test

Marshall stability and flow test is the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) has standardized ASTM-D6927, AASHTO T 245 and AASHTO T283 for the Marshall test procedures and published them (Jamal, 2017). The method is applicable only to hot mixtures containing aggregates with a maximum size of 1 inch (25 mm) or less. Marshall test was used to determine the performance of steel slag mixed with standard HMA. This method most accurately replicates the field conditions encountered while wearing course. To simulate moderate traffic volume and heavy compaction, a medium type design (50 blows per side of specimen) was used. The maximum deformation at which a Marshall specimen fails is termed as the flow value. It is a measure of deformation. For a good design, always a lower value of flow is expected, and as higher flow value of asphalt pavement indicates lower rigidity and indicates too much deformation under specific load and weather condition. A compound's stability is quantified as the greatest load that a compacted specimen can carry before it decays. Deformations of 0.25 mm in unit load of the specimen in the range of no load to maximum load during stability testing (flow value may also be measured by deformation units of 0.1 mm). This test is designed to measure the optimal aggregate mixed binder content for a specific traffic intensity (Design, 2001). Void in Mineral Aggregate, or VMA, is defined as the inter granular void space between the aggregate particles in a compacted paving mixture. It's expressed as a percentage of the total volume. Based on aggregate bulk specific gravity, VMA is expressed as a percentage of the compacted paving mixture's bulk volume. So, subtract the bulk specific gravity of the aggregate from the bulk volume of the compacted paving mixture to find the volume.

Superpave Volumetric Test

Superpave volumetric test is the Superpave mix design approach was one of the primary outcomes of the Strategic Highway Research Program (SHRP). The Superpave technique of mix design was developed to take the role of the Hveem and Marshall systems. The Superpave mix design approach is based on the volumetric analysis used in the Hveem and Marshall procedures. The Superpave technology integrates the selection of asphalt binder and aggregate into the mix design process, while also taking traffic and climate into account. The Hveem and Marshall methods' compaction devices have been replaced with a gyratory compactor, and the compaction effort in mix design is proportional to predicted traffic (Roberts et al., 2009). When the HMA samples were prepared in the laboratory, they were tested to evaluate their performance in a pavement construction. The investigation focused on five parameters of the HMA (i.e., mix density, air voids, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and binder percentage) and the effect those characteristics are anticipated to have on HMA behavior.

3.0 RESULTS AND DISCUSSION

3.1 Binder Testing

Penetration test

The penetration test was conducted to determine the appropriate percentage for the bitumen modifier. The test was done with different percentages of additive to find out the best possible results at the beginning. Table 2 shows that with the addition of steel slag, the penetration value is changed from 72-52. The asphalt binder used for the test had a penetration grade of 60-70, which was alternated by the bitumen modifier. Figure 1 shows that 30 percent of steel slag with 2 percent of cement gives a penetration value of 47 mm, which may be the optimum steel slag content. Steel slag content increases the consistency and stiffness of asphalt binder. Asphalt binder helps the mixture to maintain cohesion or tensile strength. Tropical countries require asphalt binder with higher penetration values to prevent bleeding in pavement due to local climate conditions (Hoque et al., 2019). However, as asphalt binder ages or oxidizes, its penetration value steadily decreases over time. This binder's characteristic causes bleeding and cracking on fresh pavement, and cracking and breakage on aged pavement. In this case, the steel slag binder modified with particles from the blast furnace could be the solution. Since Steel slag is a byproduct, it has the potential to decrease of penetration of bitumen (Penetration value shown in Table 2 decreases from 72mm to 47mm). Thus, it enhances the performance of pavement.

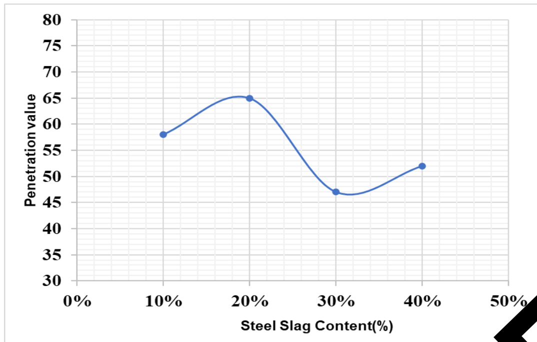


Figure 1 Penetration test results

Table 2 Penetration value of different [illegible]

Test	Cement	Ground Steel Slag	Penetration Value (mm)
1	-	-	72
2	2%	-	69
3	2%	10%	58
4	2%	20%	65
5	2%	30%	47
6	2%	40%	52

Softening Point Test

The results of the softening point test are shown in Table 3 and Figure 2. As illustrated in Figure 2, the softening point decreased at a steel slag content of 20% and then increased as the steel slag content increased. Table 3 shows that with an increasing amount of Steel slag, increase T(°C) from 50°C up to 51°C whereas test specimen without any modified was also 49.5°C. This indicates that the additive had no noticeable effect on the binder's temperature susceptibility as there is no such variation in the result of softening Point test for sample with or without additive.

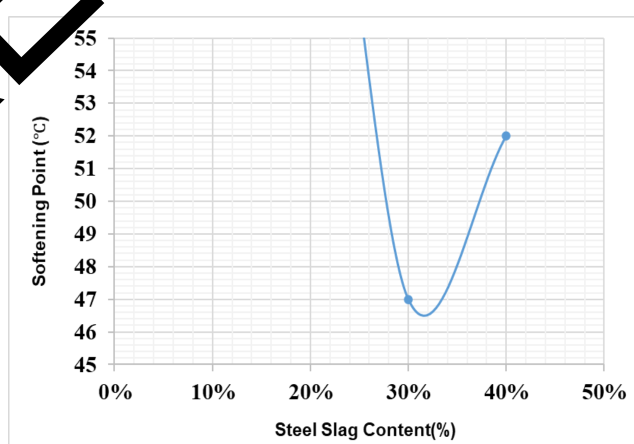


Figure 2 Softening test results

Table 3 Softening of different mixes

Test	Cement	Ground Steel Slag	Softening Point (°C)
1	-	-	49.5
2	2%	-	50
3	2%	10%	50
4	2%	20%	48
5	2%	30%	50
6	2%	40%	51

3.2 HMA Testing

Marshall Stability and Flow Test

From Table 4, it was observed that the flow decreases 26.88% to 72.19% compared with the maximum value. From the comparison graph of control mix and different percentage of steel slag it seems that steel slag gives better result at 5.5% of asphalt content where flow value is minimum is 4.45 units. It can also be observed that for 4.5% and 5% of asphalt content, the flow values decrease; with the increase of steel slag and that for 5.5% of asphalt content, the flow values increase with the increase of steel slag percentages. Marshall Stability is utilized to determine the maximum load resistance of the HMA mix design. Observing the result data mentioned in Table 4, it is visible that stability increases in every case. It is evident that the presence of the Steel Slag in the mixture effectively improves the Stability value which will result in an improvement of mixture toughness. As the additive content increase, the stability value increase initially, reaches a maximum and then decrease. Especially for 30% steel Slag at 4.5% of Asphalt Binder gives the best result. Considering the minimum and maximum values of stability obtained from the design, it increases 1.72% to 490.3% from standard. Figure 3 shows the comparison between control mix and different mixes with different percentages of steel slag in terms of stability.

Table 4 Different parameters of marshall test

Specimen no	Asphalt Binder (%)	Cement (%)	Steel slag (%)	Stability (lbs)	Stability (KN)	Flow (units)
1	4.5		-	2990	13.30	5.40
2	5	2	-	2350	10.45	6.30
3	5.5		-	1800	8.01	6.70
4			20	3051.11	13.57	11.70
5	**4.5**	**2**	**30**	**7083.68**	**31.51**	**6.20**
6			40	3118.08	13.87	6.30
7			20	1221.80	5.43	6.85
8	5	2	30	4649.53	20.66	5.90
9			40	1767.42	7.86	4.64
10			20	1473.20	6.56	4.45
11	5.5	2	30	3678.4	16.36	4.50
12			40	1726.32	7.68	4.57

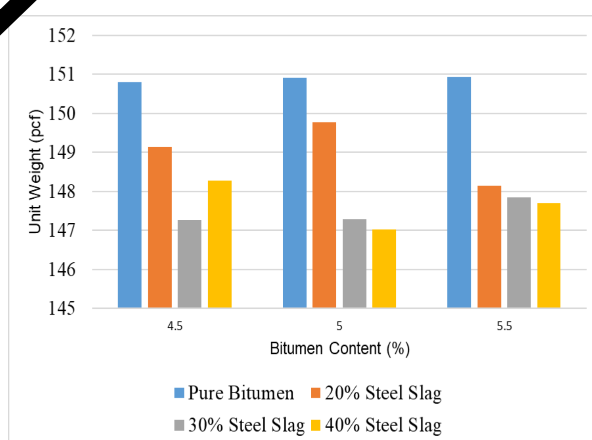


Figure 3 Comparison of stability between control mix and mixes with different percentages of steel slag

Superpave Volumetric Test

Following Table 5, the VMA value decreases significantly from the maximum standard value to 15.3%, which is not satisfactory at all. VMA collapse can occur during HMA pavement production. It occurs when the VMA in an HMA produced is lower than the VMA set during mix design. There is a need to investigate the reasons for the collapse and find methods to mitigate the effects. To have a successful market, the causes of VMA decline must be controlled. Some of the modified samples have VMA values below the standard minimum value of 15%, so adjustments can be made to adjust the VMA value, such as gradation, asphalt content, and particle angularity (Daniel and Lachance, 2005). VFA parameters help avoid creating mixes with low VMA. The VFA analysis aims to limit maximum levels of VMA and binder content. Air void, %VMA, and, %VFA values in this experiment were satisfactory for 4.5% asphalt binder, as indicated in Table 5. All the values are above the minimum specific requirement by 3.95% to 20.03%. This shows that most holes were properly filled. VFA limits the amount of air voids in compacted mixtures. So VFA is significant in bitumen mix design. The VFA criteria helps to prevent mixtures that are prone to rutting in high traffic situations and adds another level of performance safety to the design and construction process. After several years of traffic, the design range of air voids (3-5%) is desired. The amount of air voids in the mix is a critical design factor. The pavement mix should have enough air voids so that the binder can properly coat the aggregate without bleeding at high temperatures. The mix should not have too many or too few air voids. Pavement rutting, brittleness, premature cracking, raveling, or stripping can occur. More air voids mean more water and air permeability, causing serious waterproofing damage. Again, if the air void is below the minimum value, future compaction is impossible, resulting in rutting. Table 5 shows that the air void did not exceed or fall below the prescribed limits. The experiment also reduced air voids by up to 34%, though some results show values as low as [illegible]. On average, 5% of the asphalt binder had less than the minimum specific value of air voids. Placement of mixtures with less than 3% air voids in high traffic areas has been shown to rut and shove. This can be caused by an increase in asphalt binder at the mixing facility or an increase in fine particles that act as asphalt binder extenders

Table 5 Superpave volumetric properties of HMA

Specimen No	Asphalt Binder (%)	Cement (%)	Steel Slag (%)	Unit Weight (lb/cft)	Air Void (%)	VMA (%)	VFA (%)
1	4.5		-	[illegible]	4.67	14.39	67.57
2	5	2		150.91	4.60	14.78	68.87
3	5.5		-	150.93	4.59	14.77	68.94
4			[illegible]	149.136	4.45	14.96	70.26
5	4.5		[illegible]	147.26	4.84	16.03	69.81
6			40	148.28	4.18	15.45	72.92
7			[illegible]	149.76	3.31	15.05	78.02
8	5	2	30	147.28	4.83	16.46	70.63
9			40	147.03	4.99	16.60	69.95
10			20	148.15	3.61	16.41	77.97
11	5.5		30	147.85	4.46	16.58	73.10
12			40	147.69	4.56	16.67	72.63

4.0 CONCLUSIONS

In this study, ground steel slag with 2% Portland cement were added into asphalt binder to verify if there were any changes in the properties of the asphalt binder and HMA. The addition of ground steel slag into the hot mixes increased the stability of the HMA to a considerable amount. Although the experiment was designed based on medium traffic, the higher stability suggests more traffic load can be carried. Also, the flow of the design was decreased up to 72.19% within the standard maximum limits but not within the minimum limit. The smaller the flow values, the better the resistance to deformation. However, the smaller flow values also limit the expansion of asphalt content to some extent when temperatures rise. Additionally, the air void was within a standard limit (3%-5%) that prevents too much water penetration, is less permeable, and is less brittle. Therefore, premature hardening and early cracking will be avoided. Nonetheless, the VMA value is lower than the unsatisfactory lower limit of 15.0%. Adapting the aggregate size may result in the desired results for VMA, however, in this case, care must be exercised, because insufficient mixtures can cause rutting. The overall analysis gives an indication to an optimal design which is 5% of asphalt content with 30% of ground steel slag with 2% of cement content. Most of the good results were observed at 5% asphalt content. Moreover, the additives decreased the penetration grade, making it more suitable for warmer weather. Therefore, the selected additives have some positive effects. In addition, it is possible that rutting could be improved; nevertheless, more rutting testing will be required. Continued study will focus on long-term volume stability, which will ensure that free lime and periclase in steel slag do not cause any net volume expansion.

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Madani; analysis and interpretation of results: Ajoy Karmakar, Md. Hasibul Hasan Rahat, Md. Aminuzzaman Madani; draught manuscript preparation: Ajoy Karmakar All authors evaluated the results, and the final version of the manuscript was approved by all of them.

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