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Laboratory Investigation of Microwave Healing Characteristic of Hot Mix Asphalt Incorporating Steel Slag and Fly Ash

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Abstract: This research aims to analyze the usage of fly ash (FA) as filler and Steel slag as coarse aggregate in hot mix asphalt concrete to monitor its healing characteristic under microwave heat. Both fly ash and steel slag are the industrial by-products. Using Marshall, Hot mix asphalt (HMA) mixtures were prepared for control and three different modified specimens having 10%, 20% and 30% steel slag as coarse aggregate, and 75% optimum fly ash content (OFC) as filler. Then thermal distribution and optimum healing time of test specimens were recorded using infrared thermometer. A three-point bending (TPB) tests were applied to the samples before and after the microwave healing procedures. Test results demonstrated that adding steel slag and fly ash in asphalt concrete mixtures increases the heating rates and improve the healing performance of hot mix asphalt using microwave heat.
The replacement of natural coarse aggregate by 30% steel aggregate is extremely promising since it has not only improved healing results but also enhance the load-displacement relationship of the HMA mixtures with more ductile behavior. Overall, the use of steel slag and fly ash in hot mix asphalt is a significant option that helps to the sustainable pavement construction as it improves healing and cracking resistance.
Keywords: Fly ash, Steel slag, Hot mix asphalt, Microwave heating, Three-point Bending

I. INTRODUCTION

Pakistan steel production capacity is nearly 8.5 to 9 million metric tons per annum in accordance with National Steel Advisory Council (National Steel Advisory Council, 2019) among which the steel slag generation is 13% to 20% of total steel production. Therefore, a reasonable amount of Steel slag is generated which should be utilized instead of discarding it in landfill. Over the last ten years, the use of steel slag has been increased significantly in road construction industry. Hence use of steel slag as a substitute for natural aggregate in hot mix asphalt is a potential strategy for conserving natural resources and managing environmental pressure.

Similarly Fly ash is a byproduct of coal combustion plants. Coal-burning and steam generating plants produces fly ash. The rapid increase in the production of fly ash and its environmentally friendly disposal is becoming a growing source of worry around the world. The use of recycled fly ash improves the physical and mechanical qualities of concrete and reduces the negative environmental effects, also lowers the cost of concrete production. Based on literature reviews (Amelian et al., 2018; Gao et al., 2017; Nguyen et al., 2018), evaluated the use of steel slag as a partial substitute of natural aggregate in flexible pavement surface course. In comparison to conventional aggregate, HMA containing steel slag has shown better skid resistance, moisture resistance, lower permanent deformation, and longer fatigue life.

The modified mixture with steel slag as fine aggregate performed better than mixture with natural fine aggregate in terms of deformation resistance, moisture resistance and crack resistance (Chen et al., 2015).The microwave heating method of mixture with 30% steel slag had a greater surface temperature and more uniform thermal distribution than the conventional aggregate mixture at all SWF level at the same heating duration (Phan et al., 2018). Microwave heating, healed fractures better than induction heating at the same temperature of the asphalt concrete surface (Norambuena-contreras & Garcia, 2016)(Gallego et al., 2013). Microwave oven can be used to heat asphalt mixes and to increase the energy efficiency of the microwave heating process steel wool must be added (Gallego et al., 2013).

According to previous study (Nayak, 2020) fly ash can effectively replace conventional fillers as a filler material in bituminous mix. The utilization of fly ash provides a solution to disposal issue as well as a mean of maintaining a clean environment. (Woszuk et al., 2019)(Abass, 2020) suggested that the replacement of limestone and cement fillers with fly ash filler in different proportions not only improved the indirect tensile strength and stability but also enhanced the water and frost resistance of asphalt mix. (Mistry & Roy, 2016) concluded that replacing of conventional mineral filler like hydrated lime with fly ash up to 4% in bituminous mix, results in reduction of OBC up to 7.5% compared to the control mix, which provide significant bitumen economy in the resultant mixtures. (Yıldız & Atakan, 2020) indicated that fly ash improves the heating rate, and healing potential of asphalt concrete at a certain threshold of damage. (Atakan, 2020) concluded that fly ash rather than being utilized as a binder modifier, it can be employed in asphalt mix as filler to improve self-healing through microwave heat.

The aim of this research is to investigate the self-healing characteristic of asphalt concrete under microwave heat by using steel slag as a replacement of natural coarse aggregate in proportion of 10%, 20% and 30%, along with optimum fly ash content (OFC) as filler.

II. MATERIALS AND METHODS

A. Materials

In this research, Pak Arab Refinery Ltd (PARCO) 60/70 binder was used. The physical properties of binder are presented in Table 1. Aggregate used in asphalt mix was supplied from Khattar Stone Crusher plant, Taxila. The steel slag was provided by Pak Iron Re-Rolling Mill Plot 24 Service Road I-9, I-9/2 Islamabad, with coarser gradation listed in Table 2.

National Highway Authority (NHA-B) gradation was adopted with nominal maximum aggregate size of 19mm for the preparation of asphalt mixtures of control and modified specimens. The gradation curve used for the preparation of specimens of the aggregate mixture is shown in Figure 1. Different fillers such as stone dust and class F fly ash were utilized in this research work. Stone dust was obtained from the same quarry as fine and coarse aggregate. While Class F fly ash was obtained from B1 Fly Ash Bricks Company, Model Village Sudran, Islamabad, with chemical composition listed in Table 3. The optimum fly ash content (OFC) was used along with different proportions of steel slag coarse aggregate for the purpose of enhancing heating rate and healing characteristic of asphalt specimens.

Table 1. Parco binder 60/70 properties

S. No	Tests	Results	Specification limits	S. No	Tests	Results	Specification limits
1	Penetration (□C)	65	60-70	4	Flash point (□C)	280	250 min
2	Softening point(□C)	50.5	49-56	5	Fire point (□C)	305	> 250
3	Ductility test (cm)	120	≥ 100	6	Specific Gravity	1.03	1.01-1.06

Table 2. Steel slag gradation

Sieve sizes (mm)	25	19	12.5	9.5	4.75	2.38	1.18	0.075
Percent passing %	100	100	23	5	4	1	0	0

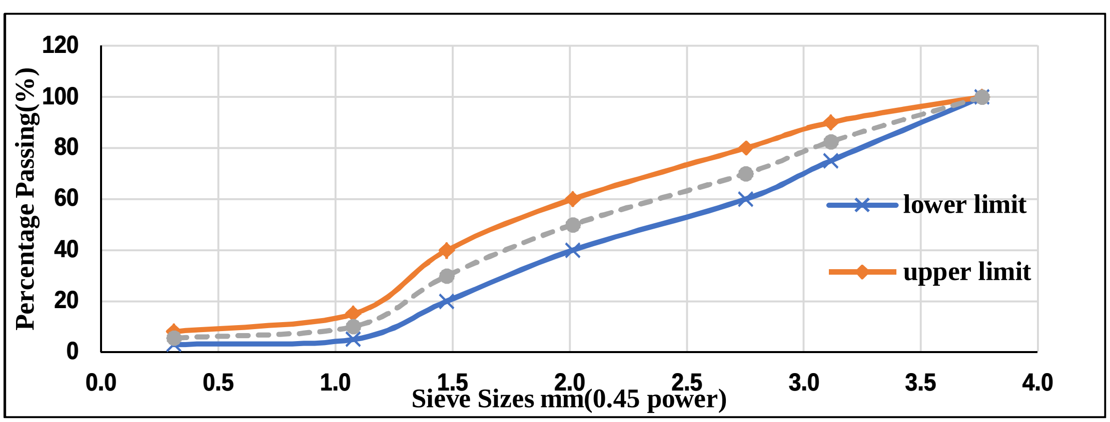

Figure 1: NHA-B gradation curve for asphalt-mix design

Table 3. Fly ash chemical composition

Components	Percentages (%)	Components	Percentages (%)
SiO_2	48.49	K_2O	0.84
Al_2O_3	27.81	SO_3	0.37
Fe_2O_3	10.65	TIo_2	1.67
CaO	4.47	P_2O_5	0.63
MgO	2.3	Mn_2O_3	0.18
Na_2O	0.61	LOI	1.48

B. Mix Design

In this research work the Marshall Mix design was adopted throughout the study for the preparations of laboratory tests specimens. First Marshall mix design was carried for the determination of optimum binder content (OBC) corresponding to 4% air voids, which was found to be 4.8% by the weight of aggregate as shown in Figure 2. Then modified Marshall was carried out for the determination of optimum Fly ash Content (OFC) as a replacement of natural filler i.e., stone dust. At 4.8% binder, upon maximum stability and satisfying the Marshall Mix design criteria optimum fly ash content was chosen to be 75% as shown in Table 4.

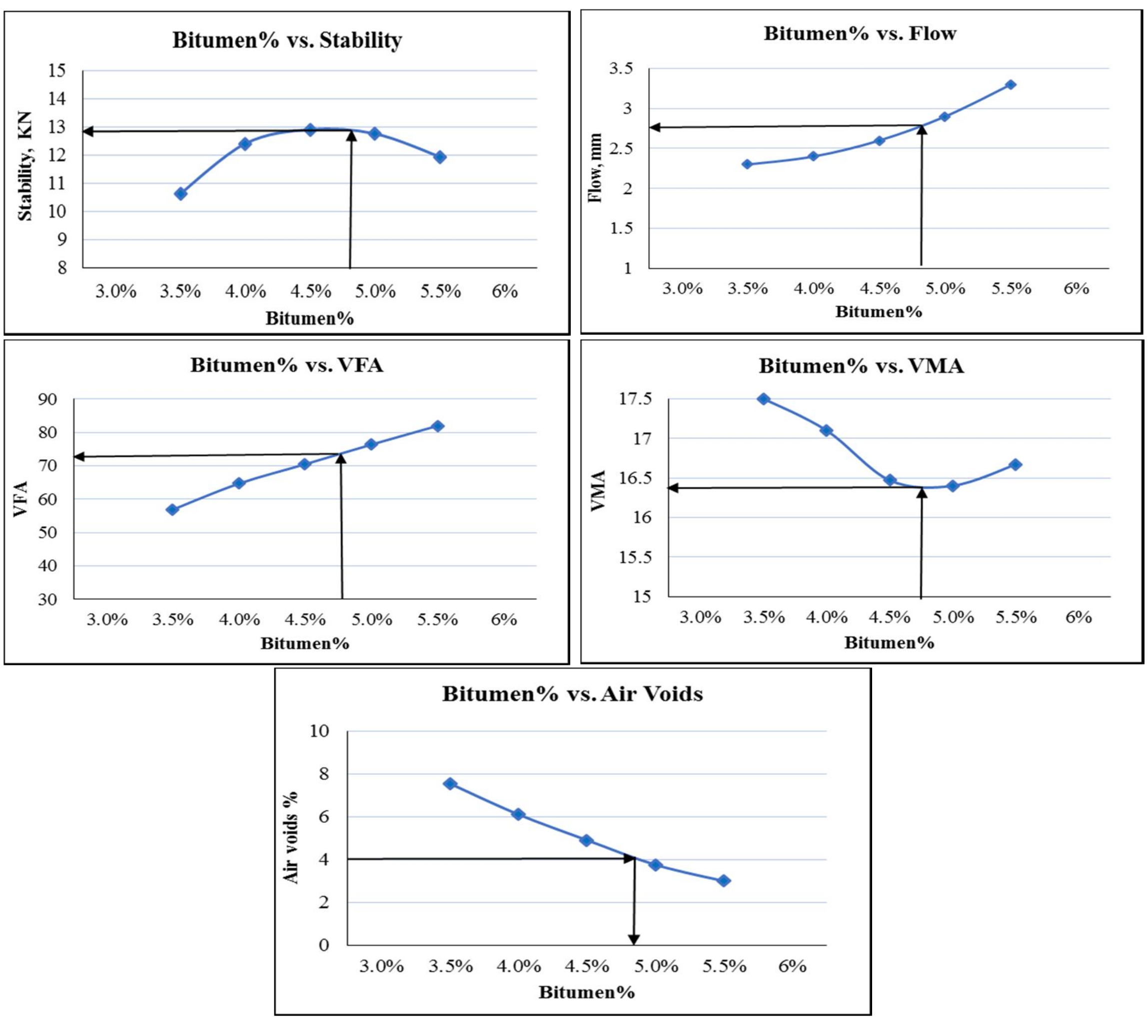

Figure 2: Graphical representation of Marshall Test results for optimum binder content (OBC)

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Table 4. Modified Marshall Test results for Optimum Fly ash Content (OFC)

S. No	Fly Ash (%)	Stone Dust (%)	Binder (OBC %)	Flow (mm)	Stability (KN)	Air Voids (%)	VMA (%)	VFA (%)
				2-3.5	≥8.006	3-5	≥13	65-75
Marshall Mix Design Criteria (MS-2 Manual)								
1	25	75	4.8	2.15	10.3	6.49	17.59	62.90
2	50	50	4.8	2.35	11.8	5.58	17.00	67.19
3	75	25	4.8	2.65	13.0	4.27	16.30	73.78
4	100	0	4.8	3.20	10.6	3.76	17.21	78.15

Using optimum binder ratio, four different cylindrical Marshall Specimens were produced with mixture formulation presented in Table 5. First control specimens consist of conventional aggregate with stone dust filler while remaining three modified Marshall specimens contain optimum fly ash content (OFC) as filler along with different proportion of steel slag i.e., 10%, 20% and 30% as a coarse aggregate by weight. For each mixture, 2 cylindrical Marshall Specimens were produced with dimensions of 101.6mm diameter, and 65mm height approximately. To adopt three-point bending (TPB) test requirement, four semi-circular specimens of dimensions 30 mm thickness and 100 mm diameter, were generated from each cylindrical specimen using saw cutter. A notch of 10 mm depth, and 5mm height was introduced to each semi-circular specimen to guide cracking during TPB test (Figure 3). From each mixture four semi-circular specimens were used for thermal distribution test and four semi-circular specimens were used for TPB for average purpose.

Table 5. Formulation of mixtures

Mix	Binder	Conventional Coarse aggregate	Steel Slag (Coarse aggregate)	Fly Ash (Filler)
Control	4.8%	100%	0%	0%
SF1	4.8%	90%	10%	75%
SF2	4.8%	80%	20%	75%
SF3	4.8%	70%	30%	75%

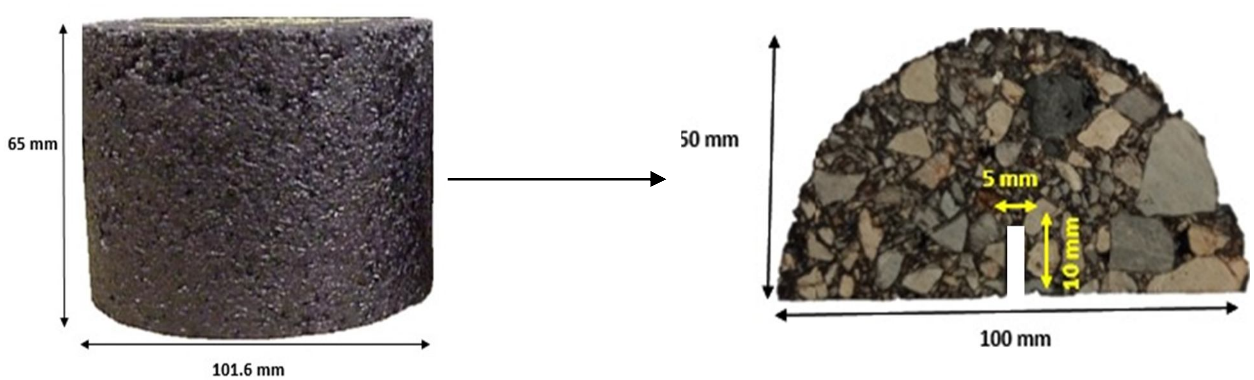

Figure 3: Preparation of semi-circular sample using Saw cutter

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C. Thermal Distribution

The goal of this experiment is to determine the surface temperature of HMA samples heated using a Microwave (700W output). The infrared thermometer was used to take measurement on the surface of samples as surface temperature in every 10 seconds (Figure 4) until they reached the required temperature of 90 degrees Celsius. Based on prior study (Norambuena-contreras & Garcia, 2016)(Gallego et al., 2013) and laboratory experience, the test specimen will provide good healing performance without overheating at this stage. To get the best healing results, the surface temperature should be kept at around 90 degrees Celsius. All temperature readings were taken three times and the average value was calculated.

Figure 4: Surface temperature monitoring using infrared thermometer

D. Three-point Bending test (TPB)

To produce the brittle state, the test samples were stored for two hours in the refrigerator at -18□C prior to completing the TPB test (Figure 5). The initial TPB strength of the samples was measured using universal testing machine UTM 25 kN (Figure 6). The distance between the two supporting rollers was adjusted to 8 cm in this test, a loading roller was placed in the central top of the semicircular sample. The loading UTM device has a capacity of 25 kN and 0.5 mm/min loading rate. The entire testing procedure took place at 25□C. Due to applied load specimens fails because of the formation of cracks. The failed specimens were thoroughly covered with napkins and allowed to rest for three hours at room temperature due to excessing moisture from the freezing procedure. After completing the drying process, the test specimens were exposed to an electromagnetic microwave (700W output) to obtain 90□C healing temperature. The heating duration was determined by the benefits of trial heat test by thermal distributions. After that, a three-hour resting time was administered to all test samples to reestablish the stable state as well as the average room temperature. The healed specimens were stored for two additional hours in the refrigerator to return to brittle condition before second TPB test. Finally, the condition specimens were exposed to another TPB test to complete one healing cycle (Figure 7). All the samples were examined for three healing cycles.

Figure 5: Brittle condition -18^{o}C

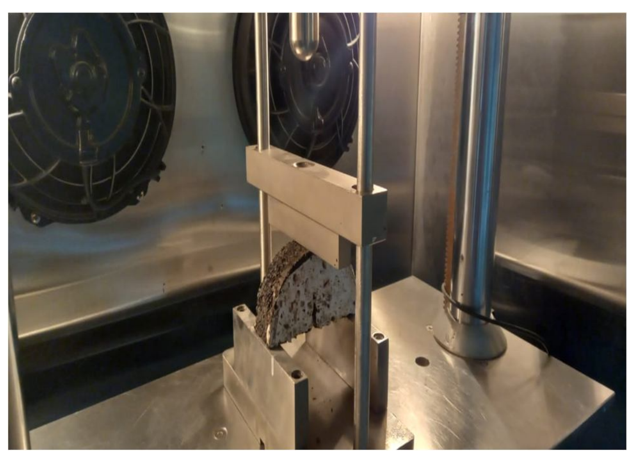

Figure 6: Three-point bending test

Figure 7 : Healing Cycle

E. *Healing Performance*

The initial bending strength and the bending strength of the healed specimen were used to determine healing performance. The specimen's geometry was believed to be the same before and after healing, therefore healing level was determined as the ratio of maximum force of healed specimen and maximum force of original specimen as shown in equation below.

$$Sh = \frac{F2}{F1} * 100$$

Where:

Sh is the healing index in percentage.

F1 is the maximum force before the damage-healing cycle of the test sample.

F2 is the maximum force after the damage-healing cycle of the test sample.

III. RESULTS AND DISCUSSION

A. *Thermal Distribution Evaluation*

Figure 8 shows the comparison of thermal distribution of conventional specimen and modified specimens having optimum fly ash as filler along with 10%, 20%, and 30% steel slag coarse aggregate. It is observed that more heat distribution occurs in modified specimens as compared to control specimen. As the percentages of steel slag increase the surface temperature increases more faster with time. At the same heating time i.e., 60 s, the SF3 specimen with 30% steel slag achieved 1.3 times higher surface temperature as compared to control specimen. To avoid overheating and for good healing level, the optimum healing surface temperature should be controlled at 90□C. Optimum healing temperature by the modified specimens SF1, SF2, and SF3 were achieved in 10%, 14%, and 20% lesser time correspondingly than that of control specimen. Optimum heating time (sec) by each specimen are listed in Table 6. Figure 9 shows the strong correlation between heating time and surface temperature of the modified specimens. It means that if heating time increases the surface temperatures of the specimens also increases because of the sensitive behavior of fly ash and steel slag to microwave heat.

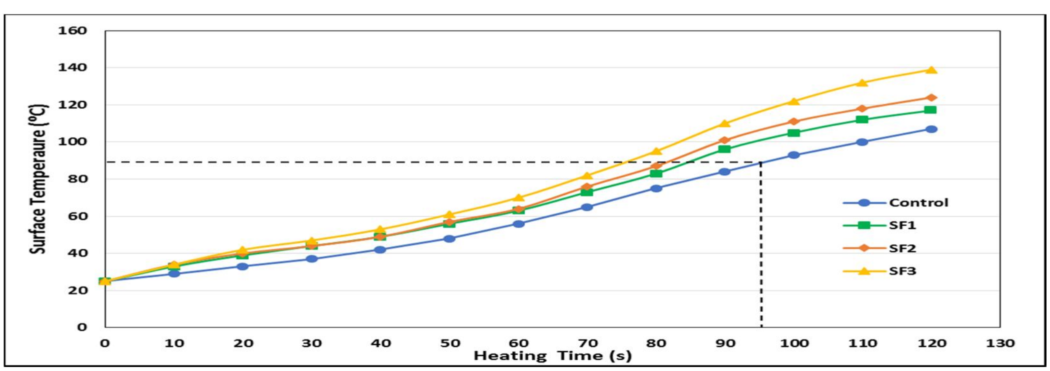

Figure 8: Thermal distribution of control and modified specimens

Table 6. Optimum heating time of test specimens

Mix	Control Specimen	SF1	SF2	SF3
Time	95 sec	85 sec	82 sec	76 sec

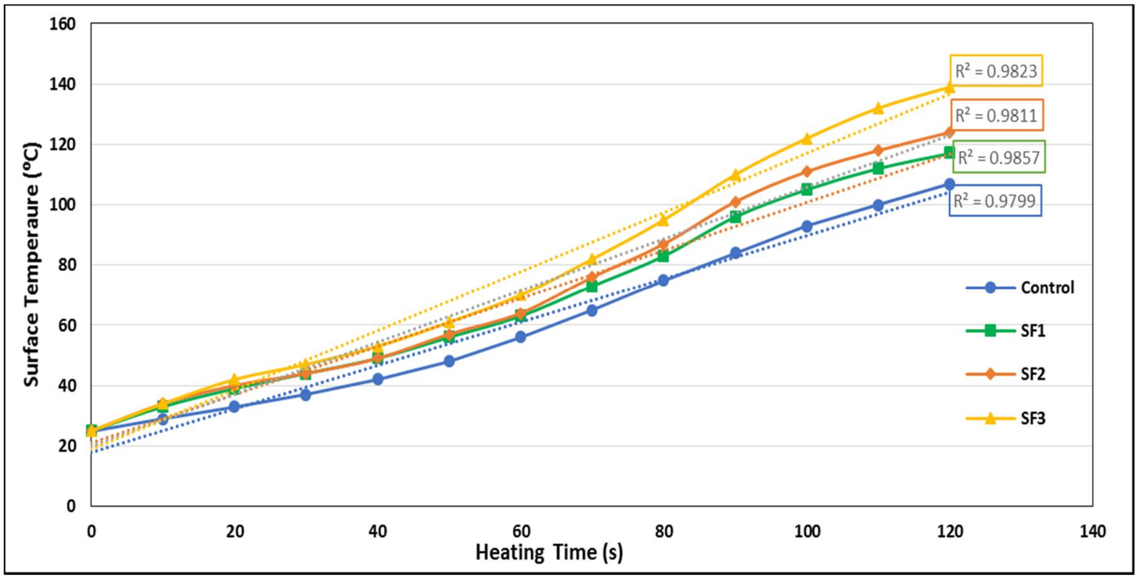

Figure 9: Relation of heating time and surface temperature

B. Bending Strength Behavior

Initial bending strength of modified specimen increases as the percentages of steel slag increases. The SF3 specimen with 30% steel slag has higher initial bending strength of 16% and 11% than control and SF1 modified specimen (Figure 10). The control specimens load resistance to cracking almost reduces by 40% after second healing cycle (H2), whereas the SF1, SF2, and SF3 modified specimens, the load resistance to cracking reduces by 41%, 38% and 30% respectively after last healing cycle (H3). This result indicates that the reaction of fly ash particles with free lime present in steel slag increases binding strength of asphalt concrete.

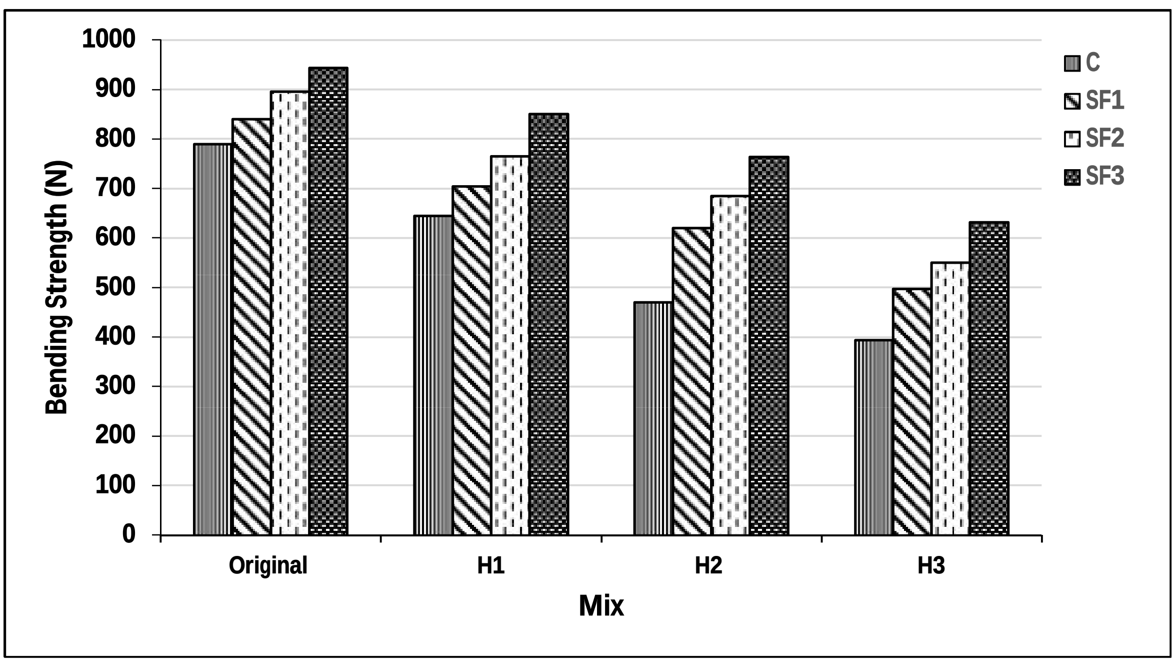

Figure 10: Bending strength of control and modified specimens

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C. Healing Performance

For each mixture the ideal heating time from Table 6 was used to the corresponding mixtures in the following assessment to reach optimum healing surface temperature of about 90 ^{0}C under microwave heat. As previously stated, this temperature will provide satisfactory healing efficacy for HMA samples while reducing the risk of overheating. Figure 11 shows the healing index of the control and all three modified specimens. The healing performance of all the mixture decreases gradually after each damaging cycle but healing level of most of the samples remains higher than 50% at last cycle. After first healing cycle, the control specimen healed back up to 82% of their original condition whereas the modified specimens SF1, SF2, and SF3 healed up to 84%, 85% and 90% respectively of their original state. Until the second healing cycle the SF3 modified specimen restored the healing performance more than 80%, while such value of control specimen with natural aggregate dropped below 60%. After last healing cycle the modified sample with 30% steel slag and optimum fly ash filler (SF3) had the highest healing performance of 67% which is 17% higher than the sample with conventional aggregate. Such enhancement occurs due to expansion and sensitive metallic properties of steel slag and fly ash and also their potential strengths to transfer heat and healed the crack under microwave heat.

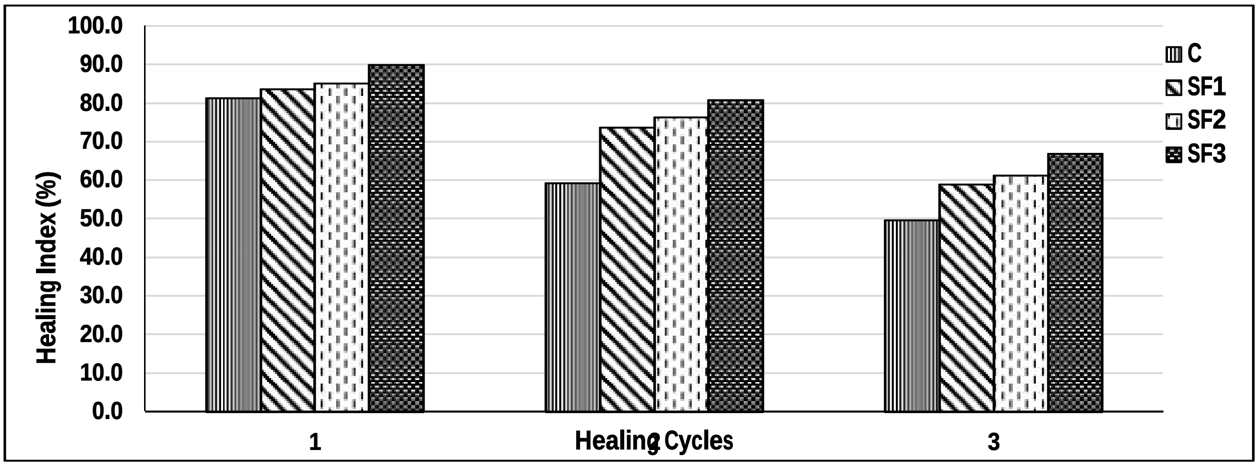

Figure 11: Healing Index of control and modified specimens

D. Cost Comparison of Control Vs Modified HMA

Material costs are the most expensive factor among all the other elements that influence road construction costs. In this research work the economic comparison of control and modified mixes including steel slag aggregate and fly ash filler, was carried out for one-kilometer road section with a width of 3.6 meters and thickness of 50 millimeters. (Figure 12) shows the graphical representation of cost comparison between control and all three modified specimens. By using 20% steel slag with optimum fly ash filler can save 2% cost per kilometer approximately, while using 30% waste steel slag with fly ash filler can provide saving up to 3%.

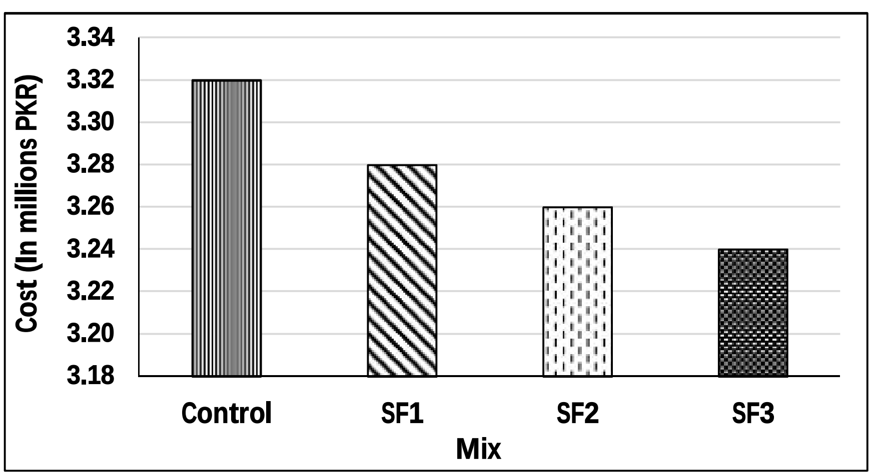

Figure 12: Cost comparison of control and modified specimens

IV. CONCLUSION

This paper evaluated self-healing characteristic of hot mix asphalt by using steel slag coarse aggregate and fly ash filler under microwave heat. Thermal distribution test was performed for each mixture to determine optimum healing time and then samples from each mixture were introduced to three damage healing cycles for the investigation of healing performance of each mixture. From this research work the following conclusions can be carried out:

1) At 4.8% OBC, the mix with 75% fly ash replacement as filler, the volumetric properties and stability of such mixture satisfy the requirements of asphalt concrete as well as Marshall Design criteria.
2) It is valid to use steel slag as coarse aggregate and fly ash as filler to increase the heating rates of asphalt concrete and to enhance the healing performance of modified HMA using microwave heating method.
3) At the same heating period i.e., 60 sec, the combination of 30% steel slag and 75% fly ash in modified specimens had 20% higher surface temperatures with uniform thermal distribution than the original aggregate mixture. It can be explained by the chemical composition of fly ash and sensitive metallic behavior of steel slag particles to microwave radiations.
4) During 3 damage-healing cycles, the healing performance of both modified and unmodified mixes steadily decreases to a specific level. The test results indicated that SF3 specimen with combination of 30% steel slag and 75% fly ash generated more than 17% healing efficacy than control mix after last cycle.
5) After the second damage-healing cycle, the healing index of the traditional aggregate combination was less than 60%. In the meantime, the value of modified SF3 sample remained above 80%. Hence such conclusion can be drawn that using 30% steel slag with optimum fly ash content improves healing properties of HMA.
6) Initial costs were compared between control mix and modified mixes including steel slag and fly ash. When only the cost of laying down an HMA wearing course for 1-km section was considered, it is determined that replacing coarse aggregate with 30% steel slag and filler with 75% fly ash content can save cost up to 3%.
7) It is also concluded that usage of steel slag and fly ash, which are the industrial byproducts can conserve our national resources of aggregates and significantly suitable for long-term sustainability of the environment.

V. CONFLICT OF INTEREST

There is no known conflict of interest.

VI. ACKNOWLEDGEMENT

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Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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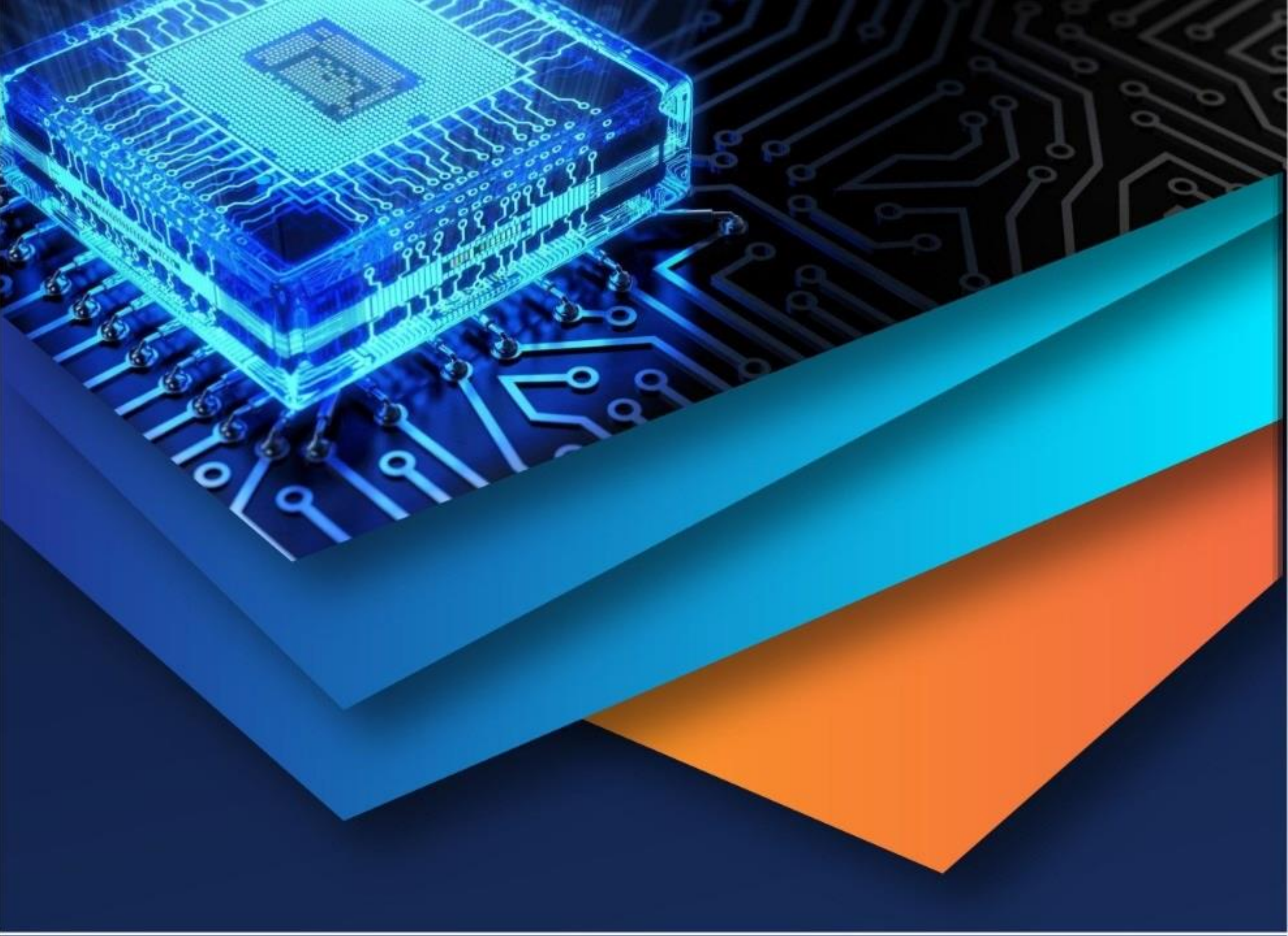

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