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Effects of Partial Substitution of Styrene-butadiene-styrene with Granulated Blast-furnace Slag on the Strength Properties of Porous Asphalt

S. Shahba[a], M. Ghasemi*[a], S. M. Marandi[c]

[a] *Department of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran*
[c] *Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran*

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ABSTRACT

The present experimental research investigates the feasibility of partial substitution of styrene-butadiene-styrene (SBS) with ground granulated blast-furnace slag (GGBS) for the modification of bitumen and porous asphalt mixtures. The control asphalt mixture and the seven modified porous asphalt mixtures have been analyzed separately and their performance was compared. Modified bitumen and asphalt mixtures were evaluated based on the penetration test, softening point, ductility, Marshall stability, indirect tensile strength (ITS), moisture susceptibility, uniaxial compression test, porosity, and permeability. According to the results, a blend of GGBS and SBS can be used to modify porous asphalt mixtures since it either improves or does not change their properties. The results show that using these additives have decreased penetration and ductility of bitumen and also there is an increase in softening point, so that the additives have strengthened asphalt mixture properties such as Marshall strength, ITS and Uniaxial compression strength. Furthermore, in the current research work, artificial neural networks (ANN) are used to estimate the permeability of modified porous asphalt mixtures. Sensitivity analysis was discussed for the measurement of the importance of different input parameters. The laboratory experiments and proposed ANN model indicated that a new method can be developed for permeability control.

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1. INTRODUCTION

In recent decades, porous asphalt has been extended for surface drainage in various regions through world such as European countries, Japan, the Unites States, and China. Due to their high air void content (18-25%), these mixtures have the potential of plummeting pavement noise. To provide surface drainage, open aggregate gradation with nominal aggregate sizes of 9.5, 12.5, 19 and 25.4mm are being applied. Porosity is the crucial component of the porous asphalt in sound reduction and water drainage in the rainy weather [1, 2]. Friction improvement, reduction of slash and spray, minimizing pavement noise levels and dangers of hydroplaning, and visibility improvement are the special purposes of using porous asphalt mixtures [3, 4]. The most remarkable problem related to the porous asphalt is its short service time (roughly 11 years) compared with the dense-graded asphalt concrete [5].

To accommodate the ever-increasing traffic loading varying climatic environments, a major emphasis has been placed on improving the performance of asphalt mixtures. Particular performance enhancers have been investigated to improve the bitumen characteristics, including additive, polymer, and chemical reaction modifications [6-8].

Considerable efforts have been made to enhance the lifespan and mechanical properties of porous asphalt, such as imroving the mixtures with fibers and thermoplastic binder modifiers [1, 9]. The most commonly used polymer for bitumen modification is the styrene–butadiene–styrene (SBS). Various studies have shown that using SBS in bitumen modification will increase the resistance of bituminous mixtures in permanent deformations, moisture-induced damage, and

*Corresponding Author's Email: m.ghasemi@kgut.ac.ir (M. Ghasemi)

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fatigue crack [6, 7]. From pervious experimental works, the most efficients performance of bitumen modification with SBS indicated a considerable decrease in the penetration value and softening point temperature at the polymer contents of 3% and 5% respectively. The results show that the more the polymer conduct increase up to 5%, the more Marshall stability and indirect tensile strength of asphalt mixture rise. After that, by adding more polymer content, the resistance decreases [10-12].

SBS polymer boosts the elasticity of bitumen and is probably the best polymer in bitumen modification. Although it rises the flexibility at low temperatures, some researchers believe that it lead to a decline in resistance and an increase in penetration at higher temperatures [13]. Employing the SBS polymer increases the resilient modulus of the asphalt mixture. A high modulus asphalt concrete makes pavements more rigid and hence persistent against fatigue process [14, 15].

The use of waste from various industrial processes preserves irreplaceable resources, reduces environmental pollution, and recovers the energy spent during the production of waste. In particular, GGBS contains 15-20% of the iron output of the steel production process [16]. The enormous storage of GGBS has various outcomes. It occupies large areas of land, and its leach liquor results in water pollution and land destruction during rainy seasons. Envrionmental reuse GGBS will solve these problems [17].

Among the materials used in road construction, GGBS is one of the most popular, because the amounts of natural aggregates applied in the road construction industry can be reduced and fewer areas would be required for storing GGBS, and thus has a lower environmental impact. If GGBS is not recovered, it will be disposed of in landfills. Reuse of GGBS as recycled materials can limit the amount of discarded waste materials and reduce the consumption of natural aggregates [18-22].

ANN approach is a numerical methodology attempting to simulate quite a few important features of the human nervous system; in other words, it is the ability to solve problems by applying the information gained from past experiences to contemporary problems. ANN area is a sort of mathematical tools, which establish a mapping between a set of input and output numbers. ANN are widely used in civil engineering for finding the patterns between the input and output results [23-30].

The main objective of the present study is to conduct laboratory tests on porous asphalt mixtures containing GGBS and SBS to evaluate their performance for producing a modified porous asphalt that is more resistant, economical, and environmentally friendly.

2. MATERIALS AND METHODS

2. 1. Aggregates The required aggregates were provided from Hossein Abad, a mine near Kerman, Iran. Most of the materials include coarse aggregates passed through sieve 3/4". The amount of filler materials (passing sieve No. 200) in porous asphalt is 1% of aggregates. The aggregate gradationis presented in Table 1.

2. 2. Bitumen The 60/70 penetration grade bitumen used in this study has been taken from Shiraz Oil Refinery. The standard laboratory test results for bitumen are presented in Table 2.

2. 3. Modifiers SBS was produced by Yueyang Petrochemical Co. Ltd., China. The GGBS was prepared from a steel factory near Kerman and powdered by a ball mill. The obtained powder was passed through sieve No. 200 to be mixed with SBS in bitumen specimens. The density of GGBS passing through sieve No. 200 was measured to be 2.14 g/cm^3. The chemical composition of GGBS is presented in Table 3.

TABLE 1. Aggregate gradation

Mesh	Sieve size (mm)	%Passing
¾”	19	100
½”	12.5	94
3/8”	9.5	69
No. 4	4.75	19
No. 8	2.36	6
No. 30	0.6	4
No. 100	0.15	2.3
No. 200	0.075	1

TABLE 2. Properties of bitumen

Properties	Standard Method	Value
Penetration at 25°C (dmm)	ASTM D5	70
Softening point (°C)	ASTM D36	46-59
Ductility at 25°C (cm)	ASTM D113	76
Flashpoint (°C)	ASTM D92	>302

TABLE 3. Chemical composition of GGBS

CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3
39.4%	32.1%	16.9%	7.1%	3.75%

2. 4. Specimen preparation While modifying the base binder, different percentages of solid-formed SBS and GGBS were mixed at 160-180°C using a high-speed stirrer rotating at 2000 rpm. Blending was perform for one hour in order to acquire a homogeneous binder. Marshall samples were prepared according to ASTM D1559. In the present study, all porous asphalt samples were compacted using 75 blows of the Marshall hammer per side. The GGBS and SBS were combined and added to the bitumen for a total of 5% according to other reaserchers [10-12], as presented in Table 4.

3. TESTING AND RESULT ANALYSIS

3. 1. Penetration Test The penetration test was performed according to ASTM-D5 at 25°C, and its results are shown in Figure 1.

Penetration test is used to determine the relative hardness of pure and modified bitumen. According to the results illustrated in Figure 1, the penetration values of SBS modified bitumen decrease on increase of the GGBS content. The decrement is about 6- 22% with the addition of GGBS, as compared to the control bitumen. The results also show that the addition of GGBS makes the modified bitumen harder and more consistent than control bitumen which results in improvement in the rutting resistance of the mix. This mix can be suitably used in the regions where temperature differential is substantially higher and roads with heavier traffic.

3. 2. Softening Point The softening point of unmodified and modified bitumen was measured according to ASTM-D36. The softening point is the temperature at which bitumen passes from the solid state to thefluid state. Figure 2 shows that softening point increases with increasing GGBS content. The results clearly show that the addition of GGBS in the bitumen increases the softening point value from 43° C for control bitumen to 60° C for GGBS modified bitumen.

TABLE 4. Percentages of modifiers in specimens

Specimen No.	SBS content (wt.% of bituman)	GGBS content (wt.% of bituman)
1	0	0
2	5	0
3	4.5	0.5
4	3.5	1.5
5	2.5	2.5
6	1.5	3.5
7	0.5	4.5
8	0	5

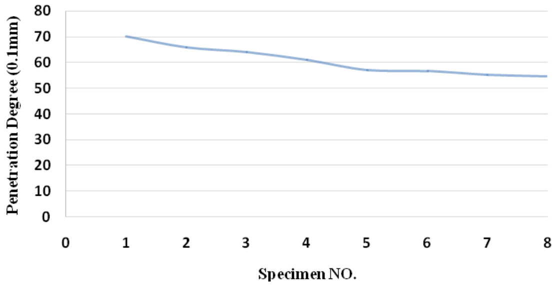

Figure 1. Penetration test results of unmodified and modified specimens

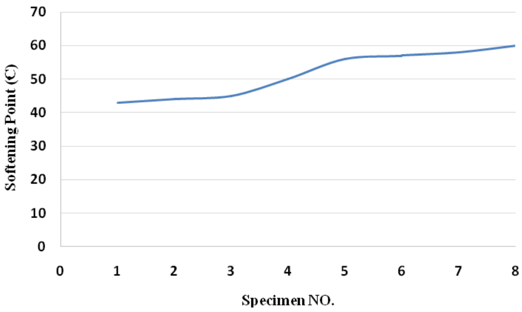

Figure 2. Softening point test results of unmodified and modified specimens

It has also been observed that the increase in the softening point of control bitumen was significant when GGBS is added in percentages from 2.5 to 5%. The increment in the value indicates that the resistance of the binder to the effect of heat is increased and it will reduce its tendency to soften in hot weather. Thus, with the addition of GGBS the modified binder will become less susceptible to temperature changes.

3. 3. Ductility Test This test method provides one measure of tensile properties of bituminous materials. Ductility test can give an idea about low temperature properties of the bitumens. Bitumens with lower softening points become less harden as the temperature decreases, and thus show a more ductile behaviour. These types of bitumens (softer bitumens) are more favorable in terms of low temperature cracking resistance [31]. This test was performed according to ASTM-D113. Figure 3 shows the effect of GGBS on ductility value of bitumen. The observation data shows that ductility of control bitumen decreases with the addition of GGBS. The decrease in the ductility values were observed as 6.5- 21% on addition of GGBS, as compared to the control bitumen.

The decrease in the ductility value may be due to decrease SBS content and therefore decrease interlocking of polymer molecules with bitumen.

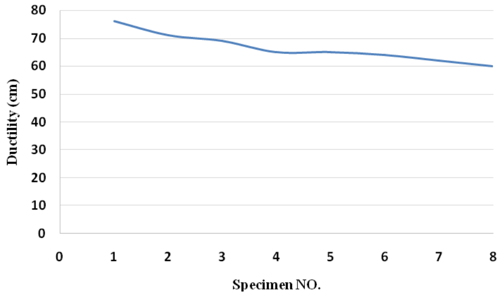

Figure 3. Ductility test results of unmodified and modified specimens

3. 4. Flash Point Test The flash point of unmodified and modified bitumens were measured according to ASTM-D95. The flash point is the lowest liquid temperature at which the application of the test flame causes the vapors of the test specimen to ignite. The results of flash point tests were more than 300°C for all unmodified and modified bitumen samples.

3. 5. Penetration Index (PI) The thermal sensitivity of the modified bitumen samples, which is the change in the consistency parameter as a function of temperature, was evaluated by a PI as well as the results of the penetration degree and softening point tests (Equation (1)).

$$PI = \frac{1952 - \log Pen_{25} - 20SP}{50 \log Pen_{25} - SP - 120} \quad (1)$$

where Pen_{25} is the penetration grade of bitumen at 25°C, and SP is the bitumen's softening point temperature. According to the results shown in Table 5, an increase in the GGBS content led to a rise in PI.

3. 6. Marshall Strength The Marshall strength tests were performed on compacted specimens with various modified binders according to ASTM D1559. The Marshall quotient (MQ) represents an approximation of the ratio of load to deformation under particular conditions, and may be used as a measure of the material's resistance to permanent deformation in service [32].

TABLE 5. PI of unmodified and modified specimens

Specimen No.	PI
1	-2.395
2	-2.225
3	-1.99
4	-0.734
5	0.525
6	0.721
7	0.873
8	1.247

According to the Marshall stability test results given in Table 6 and Figure 4, the highest strength is achieved by omitting the polymer content. The increase of Marshall stability is due to the high angularity and friction angle of GGBS which lead to excellent stability and load bearing capacity. As represented in Table 3, the MQ increases between 5- 165% by addition of GGBS, as compared to the control bitumen.

3 .7. ITS Test Marshall specimens were used for the ITS test based on AASHTO T283. The tensile strength of a specimen is calculated according to Equation (2).

$$ITS = \frac{2000 P_{max}}{\pi D L} \quad (2)$$

where P_{max} is the peak load (N), and D and L are the diameter (mm) and the thickness (mm) of the specimen, respectively. As shown in Figure 5, the average ITS of modified specimens ranged between 174 kg.f and 350 kg.f. All the values of the strengths were greater than the ITS value of the unmodified specimen (149 kg.f). It can be clearly seen that the addition of the additives seems to have a positive effect on the strength of the samples. The unmodified sample had the lowest strength.

3. 8. Uniaxial Compression Test The uniaxial compression test was conducted by the universal testing machine.

TABLE 6. Marshall test results

Specimen No.	Flow (mm)	MQ (kg/mm)
1	10.76	13.104
2	11.89	13.793
3	4.08	32.843
4	7.19	21.001
5	5.49	27.869
6	5.92	26.142
7	5.69	34.798
8	13.23	21.920

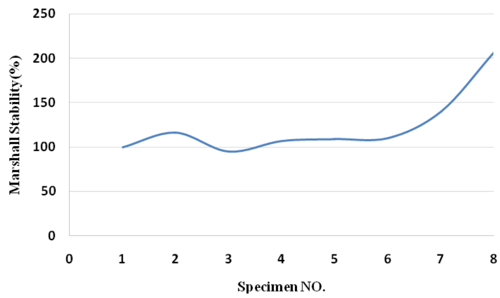

Figure 4. Marshall stability results of unmodified and modified specimens

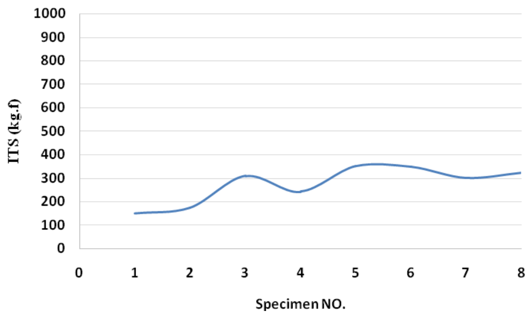

Figure 5. ITS test results of unmodified and modified specimens

Figure 6 shows the effect of GGBS on compressive strength value of porous asphalt. The observation data shows that compressive strength of unmodified sample increases with the addition of GGBS. The increase in the compressive strength values were observed as 77-154% on addition of GGBS , as compared to the unmodified sample. The unmodified sample had the lowest compressive strength.

3. 9. Porosity The primary purpose of executing a porous surface is water drainage in porous media. Porous asphalt should have enough thickness to pass the volume of rain through itself. Identification and selection of parameters play an important role in achieving this aim. In this study, effective porosity was computed using Equation (3). The effective porosity is taken into account as water-accessible air voids, while the total porosity (or air void content) accounts for all the air voids within a specimen. The effective porosity was used in this study because only the accessible voids contributes to the permeability of the specimens [33].

$$Porosity\ (\%) = \left[1 - \frac{\frac{M_{dry} - M_{sub}}{\rho_w}}{V_T}\right] \times 100 \quad (3)$$

These dimensions were used to calculate the total volume (V_T) of the cylindrical specimen.

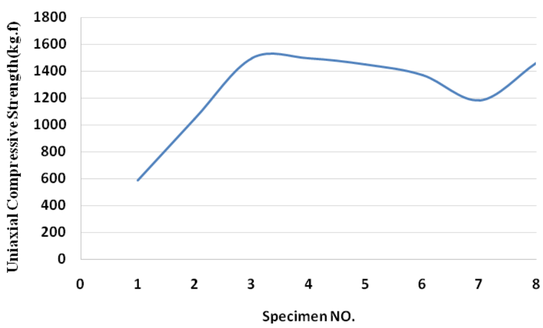

Figure 6. Compressive strength of unmodified and modified specimens

Moreover, the dry mass of the specimen was recorded (M_{dry}), and then the specimen was submerged in a 25°C water bath. After 30 min, the specimen was inverted 180 degree and tapped on the bottom of the water bath five times to release the air entrapped in the specimen. The taping was done such that it was firm enough to release the entrapped air while taking care not to damage the specimen. After tapping, the specimen was inverted 180 degree again and the submerged mass was recorded (M_{sub}).

Vertical and transverse drainage in porous asphalt promotes the excretion of water from the pavement, reducing water dispersion in the air. To this end, a porosity test was conducted. Figure 7 shows that all modified samples had a higher porosity than samples made by conventional bitumen. The addition of SBS and GGBS to porous asphalt increased the effective porosity.

3. 10. Permeability This test was performed according to ASTM D2434-68 using the constant hydraulic head method. One of the advantages of porous asphalt is its high permeability which leads water to the edges of the road or water collection system and reduce car sliding. Coefficient of permeability was calculated using Equation (4).

$$K = \frac{QL}{Aht} \quad (4)$$

where K is the coefficient of permeability, Q is the quantity of discharged water, L is the distance between manometers, A is the cross-sectional area of the specimen, h is the difference in the head on manometers, and t is the total time of discharge. Figure 8 shows that all modified samples had a higher permeability than the unmodified sample.

4. DISCUSSION

According to the results, the strength of asphalt samples has increased in comparison with unmodified samples.

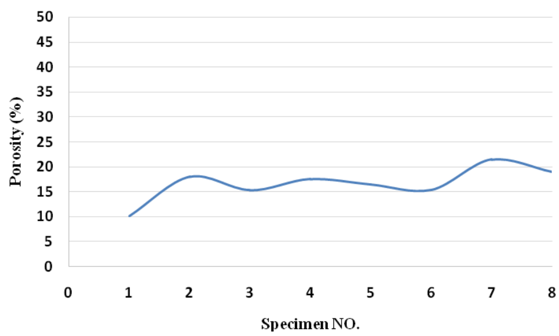

Figure 7. Porosity of the unmodified and modified specimens

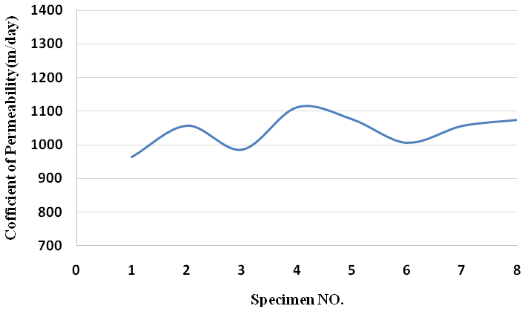

Figure 8. Permeability test results of the unmodified and modified specimens

The Marshall stability increased with increasing of GGBS content, and the ITS of modified asphalt samples increased compared with the unmodified sample. According to the results of compressive strength, all modified samples had a greater resistance than unmodified samples. The results of PI indicated that the modified samples became harder and less sensitive to the variations of temperature. Ultimately, the combination of 2.5% SBS and 2.5% GGBS was introduced as the optimum ratio of additives that have the greatest impact on engineering properties of bitumen and asphalt.

Figure 9 presents a comparison between the optimum results of the present study and those of the previous researches. It can be seemd that the combination of GGBS and SBS is an efficient modifier than RGP and SBS.

4. 1. ANN Modeling and Sensitivity Analysis

This study discusses the application of ANN in predicting the permeability of porous asphalt mixtures modified with SBS and GGBS. An ANN model was developed using eight independent input parameters including SBS content, GGBS content, penetration degree, softening point, ductility, porosity, PI and flash point. An ANN with 18 neurons in the hidden layer was considered as the most appropriate architecture for predicting the permeability of asphalt mixtures, as illustrated in Figure 10. Excellent conformity was observed between the predicted and the observed ones. The results indicated that the proposed model can be applied in predicting the permeability of modified porous asphalt mixtures.

Sensitivity analysis was employed to understand the effect and measure the importance of different input-modified porous asphalt parameters on various predicted permeability of specimens. In this way, eight different ANN models were developed and one of the inputs was eliminated in each of them. The effect of omitting each input in reducing the accuracy of the model indicates its importance.

The importance and relative ranking of different input variables of ANN are shown in Table 7. It may be observed that sensitivity analysis ranked porosity as the most important parameter whereas, the penetration degree and flash point as the least important ones were considered.

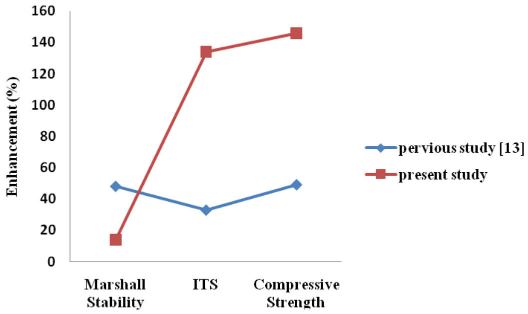

Figure 9. Comparisons between the results of this and the previous study

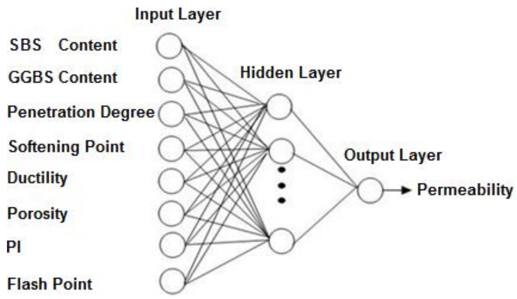

Figure 10. The ANN architecture used as a prediction model for permeability

TABLE 7. Sensitivity analysis results

Eliminated input	R	Relative ranking
-	0.994	-
SBS content	0.960	3
GGBS content	0.979	5
Penetration degree	0.991	7
Softening point	0.940	2
Ductility	0.990	6
Porosity	0.450	1
PI	0.976	4
Flash point	0.993	8

5. CONCLUSION

The following conclusions may be derived from the present study:
1. Fifty percent SBS being substituted by GGBS boosted the porous asphalt physical properties.
2. In addition to reducing production costs, the replacement of GGBS with a portion of SBS has positive environmental effects by returning a quantity of GGBS abundant in nature.
3. Partial substitution of SBS with GGBS in the modification of porous asphalt improved PI, the Marshall strength, ITS, compressive strength, porosity, and permeability by 22%, 14%, 135%, 146%, 65% and 12% respectively.
4. The ANN model was able to predict the permeability of modified porous asphalt with SBS content, GGBS content, penetration degree, softening point, ductility, porosity, PI and flash point as input parameters.
5. Porosity was taken into account as the most effective parameters on the permeability prediction, and remaining variables including the softening point, SBS content, PI, GGBS content, ductility, penetration degree and flash point gone through a downward impact, respectively.

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Effects of Partial Substitution of Styrene-butadiene-styrene with Granulated Blast-furnace Slag on the Strength Properties of Porous Asphalt

S. Shahba[a], M. Ghasemi[a], S. M. Marandi[c]

[a] *Department of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran*
[c] *Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran*

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چکیده

در تحقیق حاضر مطالعه آزمایشگاهی امکان جایگزینی بخشی از پلیمراستایرن-بوتادین-استایرن (SBS) با سرباره کوره ذوب آهن (GGBS) جهت اصلاح قیر و مخلوط آسفالت متخلخل انجام شده است. لذا مخلوط آسفالت اصلاح نشده و هفت مخلوط آسفالت متخلخل اصلاح شده مورد بررسی قرار گرفته و عملکرد آنها مقایسه شده است. قیر اصلاح شده و مخلوط-های آسفالتی بر اساس آزمایش‌های درجه نفوذ، نقطه نرمی، شکل پذیری، مقاومت مارشال، مقاومت کششی غیرمستقیم (ITS)، حساسیت در برابر رطوبت، مقاومت فشاری تک محوره، تخلخل و نفوذپذیری مورد بررسی قرار گرفتند. با توجه به نتایج آزمایشها، ترکیب GGBS و SBS می تواند برای اصلاح قیر و مخلوط های آسفالت متخلخل مورد استفاده قرار گیرد، زیرا یا خواص آن‌ها بهبود می‌یابد یا بدون تغییر باقی می‌ماند. نتایج نشان می‌دهند که استفاده از این افزودنی‌ها، درجه نفوذ و خاصیت کشسانی را کاهش داده و نقطه نرمی را افزایش داده‌اند، لذا افزودنی‌ها خصوصیات آسفالت مانند مقاومت مارشال، مقاومت کششی غیر مستقیم و مقاومت فشاری را افزایش داده‌اند. همچنین در این تحقیق از شبکه‌های عصبی مصنوعی (ANN) به منظور برآورد میزان نفوذپذیری مخلوط آسفالت متخلخل اصلاح شده استفاده شده است. آنالیز حساسیت برای تعیین اهمیت ورودی‌های مختلف مدل انجام شد. بررسی‌های آزمایشگاهی و مدلسازی‌ها نشان دادند که می‌توان یک روش جدید برای کنترل نفوذپذیری آسفالت متخلخل ارائه نمود.

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