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In-situ Temperature Effects in Basic Oxygen Furnace Slag Asphalt Concrete Pavement

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Abstract: Basic oxygen furnace (BOF) slag is a by-product of steel plants and is different from conventional natural aggregates. Studies have shown that BOF slag asphalt concrete is able to store heat. However, no quantitative research results have been presented. In this study, conventional natural aggregates and reclaimed asphalt pavement (RAP) are replaced by BOF slag in an asphalt concrete mixture. To observe the temperature variations in BOF slag asphalt concrete pavement during construction and after being opened to traffic, test roads with different levels of BOF slag and RAP were constructed in Kaohsiung City, Taiwan. The goal of this study was to provide information about the temperature differences between asphalt concrete pavement containing natural aggregates and those containing BOF slag aggregates.

The results of this research indicate that for the same transportation time and distance, the temperature of asphalt concrete pavement with 40% BOF slag was approximately 7℃ higher than that with 0% BOF slag. Because the internal heat energy of pavement with a large amount of BOF slag is not easily released, a longer curing time is needed after rolling compaction of the pavement, and thus, a longer time is needed before the BOF slag pavement can be opened to traffic. The temperature required to open the pavement to traffic was approximately 65℃. Furthermore, after opening the road to traffic, temperatures at depths of 3 and 5 cm in pavement with 40% BOF slag were 2 to 4℃ lower than at the same depths in pavement with 0% BOF slag.

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***Key words**: Basic oxygen furnace (BOF) slag; Durability, Reclaimed asphalt concrete; Temperature.*

Introduction

In Taiwan, the conventional asphalt concrete pavement strength becomes inadequate to support for the gradual increasing vehicle payloads and traffic volume. As a result, pavement rutting, depressions, and squeezing commonly occur due to the heavy traffic volume. Huang and Kang [1] combined portable falling weight deflectometer (PFWD) penetration tests with pavement stress analysis to study vehicle loading on pavement. They suggested that more than 70% of vehicle loading was transferred through contact of the vehicle tires with the asphalt concrete pavement. When the volume stability of the asphalt concrete was insufficient, horizontal stresses were produced by repeated vehicle loadings, and pavement rutting occurred.

Basic oxygen furnace (BOF) slag is a by-product of steel plants. In recent years, some coarse aggregates have been replaced by BOF slag in conventional asphalt mixtures. Shen et al. [2] investigated the performance of porous gradations by applying BOF slag to the mix design. They found that because the BOF slag had a rougher surface texture than other aggregates, the BOF slag developed a good interlocking mechanism, internal friction, and skid resistance between the aggregates. Xue et al. [3] used BOF slag as asphalt mixture aggregates and found that the adhesive forces between BOF slag and asphalt were improved because BOF slag had a coarser surface texture than natural aggregates. Wu et al. [4] studied the performance of stone mastic asphalt (SMA) gradations by applying BOF slag to the mix design. The test results showed that because of the characteristics of the porous material, BOF slag could efficiently adsorb asphalt, increase the resistance to high temperatures, and improve the performance of low-temperature cracking. Moreover, the BOF slag helped reduce the level of permanent deformation of asphalt concrete at high temperatures.

Asphalt concrete is a temperature-sensitive material. The temperature of asphalt concrete gradually decreases during pavement construction, including at manufacturing, transporting, paving, and rolling of the asphalt concrete. Asphalt binder, which can improve the strength of asphalt concrete, can tightly bind the aggregates only when it is at a high temperature and has a low viscosity. Control of the construction temperature of asphalt concrete is an important factor in obtaining and maintaining good-quality pavement. The long periods of time needed to transport the asphalt concrete mixture during pavement construction in cities results in lower temperatures of the mixture. Willoughby et al. [5] defined the cessation temperature for pavement construction and found that when the pavement cooled below the cessation temperature, the pavement could not be effectively compacted even with large amounts of compaction energy. In their simulation tests,

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Xue et al. [6] found that, when the BOF slag was heated to a high temperature, the effect of heat energy absorbed by BOF slag was increased. This result implies that BOF slag is capable of storing heat.

Huang and Lin [7] replaced aggregates by BOF slag to make asphalt concrete specimens in the laboratory. They found that BOF slag used as aggregate can reduce the rate of temperature drop, and can be compacted at lower temperatures as compared with those without BOF slag. However, this phenomenum of termeprature reduction was obtained in the laboratory conditions. Currently, few field studies of the effects of temperature on BOF slag asphalt concrete have been performed. Hence, the purpose of studying the application of BOF slag as an asphalt mixture aggregate is to develop practical pavement engineering applications. In this study, a BOF slag asphalt concrete pavement road was constructed in Kaohsiung City, Taiwan. Three different amounts of BOF slag were used to replace the natural aggregates in the asphalt concrete mixture. Field temperature measurements were carried out starting from the pavement construction and continuing until 24 hours after opening the road to traffic. Samples of the BOF slag asphalt concrete were collected for Marshall strength tests to evaluate the effects of BOF slag on the field pavement temperature and the pavement's engineering properties.

Method and Materials

Method

The road sections tested in this study are located in Kaohsiung City, Taiwan. The test road sections are 240 m long, and the pavement thickness is 5 cm. Three different combinations of aggregate were tested in the asphalt concrete test road, including (1) 20% recycled asphalt pavement (RAP) with 0% BOF slag, (2) 20% RAP and 20% BOF slag, and (3) 40% BOF slag. The remaining coarse and fine aggregates were natural aggregates. The aggregate gradations of these three asphalt concrete test roads were regulated by ASTM D3515. The nominal maximum aggregate size was 12.5 mm.

BOF Slag Asphalt Concrete Pavement

Samples of the slag asphalt concrete mixtures were randomly collected from the paver before the BOF slag asphalt concrete pavement was constructed in the field. The samples were analyzed under laboratory conditions, and nine sets of BOF slag asphalt concrete specimens were generated following the regulations of ASTM D1559 and AI MS-2. Moreover, these specimens were compacted according to a heavy traffic flow design. Before the Marshall test was carried out, each side of the specimen was compacted 75 times. The results of the sieve analyses, air voids, Marshall stability, and V.M.A. were then obtained.

Temperature Measurements

Before the test road with the RAP/BOF slag asphalt concrete pavement was constructed, temperature sensors were placed at different locations in the test road sections. One sensor was placed on the surface of the pavement, and the others were located 1, 3, and 5 cm below the surface. At each depth, two sensors were placed 10 m apart in the axial direction and were connected to automatic temperature measurement devices to record the data, which were then averaged as the final measured results. Atmospheric temperature was also measured. All data measurements were recorded every five minutes, starting from the beginning of the construction and ending when no temperature change was observed. The recording time was approximately 180 min.

To investigate the effects of natural light and atmospheric temperature on the temperature changes on the surface (0 cm) and at depths 1, 3, and 5 cm of the pavement, the temperatures were measured again after the test road was opened to traffic, starting in the early morning of the day after completion of construction and continuing for 24 hours.

Materials

Properties of Asphalt and Aggregates

The BOF slag samples used in this study were obtained from the China Steel Corporation, Taiwan, and AC-20 asphalt binder was applied. The properties of the BOF slag, the natural aggregates, and the asphalt binder are shown in Tables 1 and 2. The specific gravities of the natural aggregates and the BOF slag were 2.6 and 3.3, respectively. The higher specific gravity of the BOF slag may help improve the bearing capacity of the pavement. The relatively large difference in specific gravity between the BOF slag and the natural aggregates led to a smaller volume per unit weight for the BOF slag samples than for the natural aggregates. Hence, to obtain a better volume distribution for the natural aggregates and the BOF slag and to meet the aggregate gradation distribution requirements, the volume ratio method was applied for coarse and fine aggregates and BOF slag in the aggregate gradation for the BOF slag asphalt

Table 1. Properties of BOF Slag and Natural Aggregates.

Test		BOF Slag	Natural Coarse Aggregate	Natural Fine Aggregate	Filler	Specification Standard
Specific Gravity		3.31	2.61	2.59	2.59	-
Water Absorption (%)		2.60	1.69	-	-	＜3
Los Angeles Abrasion Test (%)		11.35	27.19	-	-	＜40
Fracture Surface	Less than 3% Surfaces (%)	2.74	20.19	-	-	-
	Greater or Equal 3% Surfaces (%)	97.23	79.84	-	-	-
Flat and Elongated Ratio Greater or Equal1：3 (%)		0.89	6.91	-	-	＜7
Sand Equivalent (%)		-	-	-	-	81

Table 2. Asphalt Binder Properties.

Test	Results
Specific Gravity	1.037
Softening Point (°C)	58
Ductility (cm)	100＋
Flash Point (°C)	230+
Viscosity (60 °C, poise)	1680
Mix Temperature (170±20cSt, °C)	157
Compaction Temperature (280±30cSt, °C)2	145
Penetration (25°C, 100 g, 5s 0.1mm)	68.7

concrete mix design.

Approximately 7% of the natural aggregates had flat and elongated shapes. When the elongation ratio is large, the aggregates can be easily broken, which can lead to a reduction in the aggregate's bearing capacity and an increase in the porosity and permeability of the aggregates. Nevertheless, because BOF slag was a rolling-controlled product with a bulky shape, a very small amount of flat and elongated shapes of BOF slag was observed. Therefore, the use of BOF slag aggregate in asphalt concrete pavement increased the degree of interlocking between the aggregates and improved the life cycle and rutting resistance of the asphalt concrete.

Aggregate Sieve Analysis

BOF slag with a uniform aggregate size was used to replace the coarse aggregates. Fig. 1 shows the aggregate gradation curves obtained from sieve analyses of three different combinations of aggregates. Fine aggregates were relatively rare in the asphalt concrete mix design. Hence, to meet the regulations specified in the standards, aggregate sizes of #50, #100, and #200 were decreased to the lower limit of the standard. The passing percentages of the #4 sieve were different for the three amounts of BOF slag. The passing percentage decreased with an increasing amount of BOF slag.

Results and Discussion

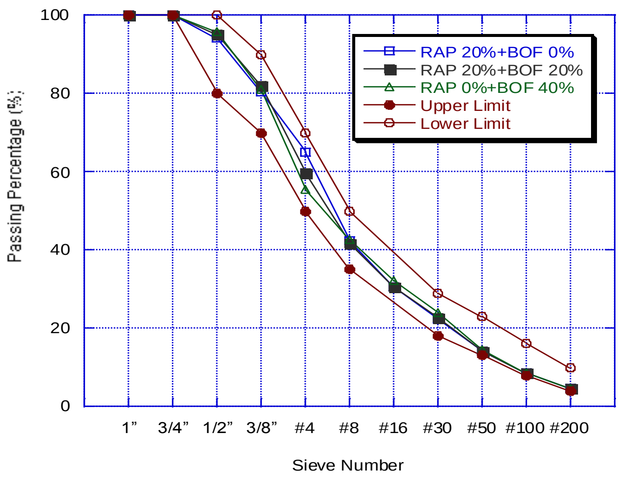


Fig. 1. Aggregate Gradation Curves Obtained from Sieve Analyses Concrete Mix Design.

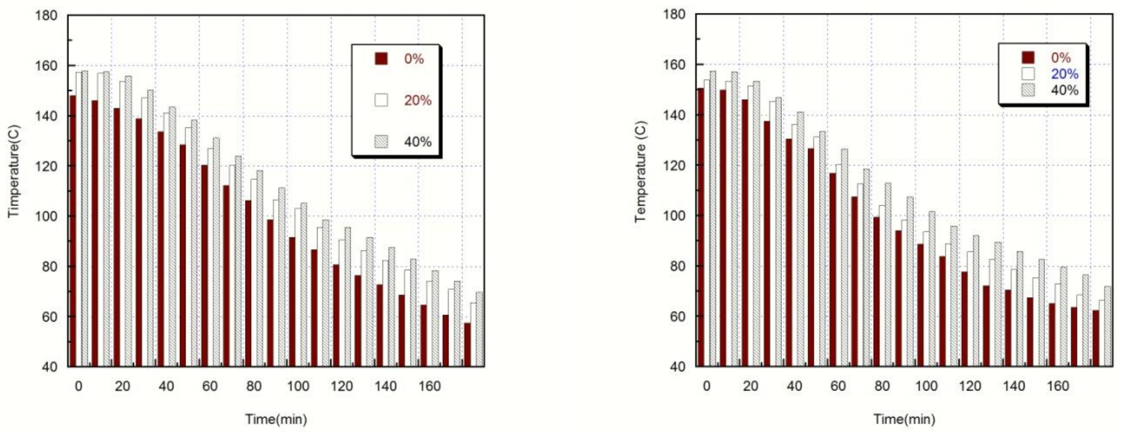
BOF Slag Asphalt Concrete Mix Design

The mix design parameters and their values and standard requirements are shown in Table 3. The BOF slag asphalt concrete samples were obtained from the paver before the pavement was constructed in the field. The specimens were manufactured from these in situ samples and analyzed under laboratory conditions. The results were compared with those obtained from the asphalt mixing plant to determine the properties and the related coefficients of determination. As shown in Table 3, the coefficients of determination for the three BOF slag aggregate replacements were greater than 0.9, which indicates that the quality of the BOF slag asphalt concrete obtained from the laboratory mix design was similar to that manufactured by the asphalt mixing plant.

The Marshall test values increased with increasing amounts of BOF slag. Other values, such as the optimum asphalt content, flow, V.M.A., and V.F.A., decreased with increasing amounts of BOF slag aggregate. However, these values were still higher than the

Table 3. Mix Designs of BOF Slag Asphalt Concrete.

Levels of BOF Slag Replacement	0% BOF Slag +20% RAP		20% BOF Slag + 20% RAP		40% BOF Slag + 0% RAP		Specification Standard
Test	Mix Design	Sampling from Paver	Mix Design	Sampling from Paver	Mix Design	Sampling from Paver	
Optimum Asphalt Content (%)	5.20	5.10	4.80	4.72	4.70	4.60	4.0~7.0
Viscosity (Poise)	2000	1780	2000	1850	2000	1890	2000±400
Compacted Specific Gravity (kg/m^3)	2.336	2.380	2.455	2.602	2.623	2.642	-
Theoretical Max. Specific Gravity	2.452	2.426	2.588	2.712	2.722	2.731	-
Stability (kgf)	1100	1490	1120	1620	1570	1780	＞681
Flow (0.25mm)	9.5	8.29	8.3	8.62	8.7	8.40	8~16
VA (%)	4.8	3.52	6.6	4.48	5.3	5.35	3~5
V.M.A (%)	15.2	17.4	14.7	16.5	14.2	15.4	＞13.0
V.F.A (%)	68	70	62	66	50	61	-
Average Aggregate Specific Gravity	2.613	2.621	2.763	2.758	2.778	2.785	-
Aggregate Oil Absorption (%)	0.569	0.945	0.499	0.921	2.636	2.697	-
Coefficient of Determination	0.977		0.974		0.995		



(a) (b)

Fig. 2. Temperature Changes for Three Levels of BOF Slag Aggregate Replacement at (a) Pavement Surface and (b) 3cm Below Surface.

13% that specified in the standard. Because the BOF slag is lipophilic and mixes easily with asphalt binder, it helps reduce the asphalt content.

Temperature Variations During Transportation and Construction of BOF Slag Asphalt Concrete

Fig. 2 shows the temperature changes for the three levels of BOF slag aggregate replacement. The temperature of the asphalt concrete mixture when it left the asphalt mixing plant was 163℃. As shown in Fig. 2(a), the temperatures at the surface of the pavement (0 cm depth) were 150℃, 154℃, and 157℃ for 0, 20, and 40% BOF slag replacement, respectively. Hence, the 40% BOF slag replacement pavement was approximately 7℃ warmer than the 0% BOF slag pavement for the same transportation time and distance.

The initial cooling rate for the reclaimed asphalt concrete pavement was fast, and it began to slow down to a temperature of 65℃. This implies that the reclaimed asphalt concrete pavement reached a steady-state temperature at 65℃. After 180 min, the surface temperature of the 0% BOF slag replacement pavement was 65℃; the surface temperatures of the 20 and 40% BOF slag replacements pavements, in which thermal equilibrium was not yet reached, were 73 and 80℃, respectively. This indicates that the heat inside the pavement takes longer to be released with larger amounts of BOF slag and that a longer stabilization time was needed to reach thermal equilibrium. As a result, asphalt concrete pavement containing a large amount of BOF slag requires a longer curing time after the pavement is rolled and compacted, so a longer time is required before opening the road to traffic.

As shown in Fig. 2(b), the temperature trends at 3 cm below the surface were similar for the 20 and 40% BOF slag replacements and were higher than that measured for the 0% BOF slag replacement. After 180 min, the temperature of the pavement with the BOF slag was approximately 10℃ higher than the temperature of the pavement without the slag.

The temperatures inside the pavement were approximately 5 to 6℃ higher than that at the surface of the pavement. The temperature difference between the pavement surface and the atmospheric temperature (approximately 25℃) at the time of construction led to heat convection between the atmosphere and the pavement surface. As a result, the surface temperature of the pavement decreased. However, the inside of the pavement was not exposed to the atmosphere, and heat convection did not occur. Hence, the heat energy remained trapped in the pavement, and the temperature inside the pavement did not decrease. This result indicates that when the surface temperature of the pavement and atmosphere temperature reached a steady-state value, the heat in the inside of the pavement did not supply energy to the surface and thus remained in the pavement. Hence, the temperature inside the pavement was higher than the surface temperature.

Variation in Cooling Rate of BOF Slag Asphalt Concrete

To compare the variations in the temperature gradient for the different levels of BOF slag replacement and based on the temperature reduction zones defined by Huang and Lin [7], the temperature rate changes for field asphalt concrete pavement measurement were also divided into three zones. They were the initial exothermic temperature, the cessation temperature, and the open-to-traffic temperature. The average temperature gradients at these three zones were calculated and the results are shown in Fig. 3. The initial exothermic temperatures were greater than 80℃, the cessation temperatures were between 60 to 80℃, and the open-to-traffic temperatures were less than 60℃. At the initial exothermic temperature, Huang and Lin [7] noticed that the initial exothermic temperature/time increased with the increasing amount of BOF slag replacement in the asphalt concrete specimens. However, in this study, the focus was on the effects of the amount of BOF slag replacement on the cooling rate for field asphalt concrete pavement. At the initial exothermic stage, the cooling rate for the pavement with 0% BOF slag was 1.29℃/min; the cooling rates were 1.14 and 1.12℃/min for the pavements with 20 and 40% BOF slag, respectively. Hence, the initial exothermic rate decreased with increasing amounts of BOF slag. Furthermore, in the initial

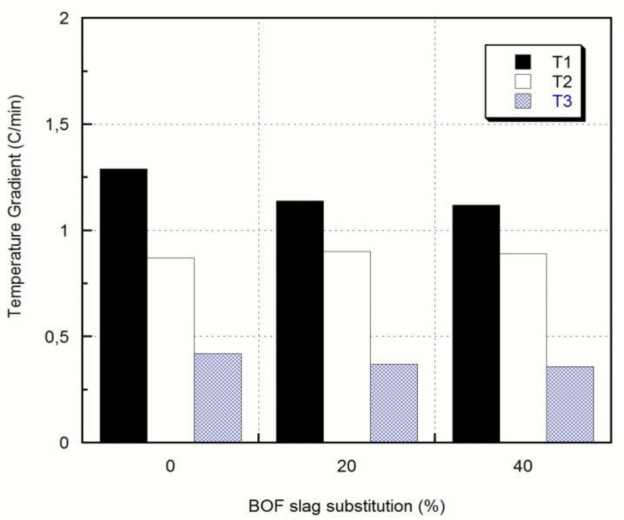


Fig. 3. Variations of the Temperature Gradient for Different Levels of BOF Slag Replacement at Three Temperature Stages (T1:initial temperature, T2:cessation temperature, T3:opening temperature).

exothermic stage, the reclaimed asphalt mixture with 0% BOF slag had a high temperature, and the temperature decreased through convection with the atmosphere. However, the cooling rates for the asphalt mixtures with BOF slag were lower, which implies that the mixture temperature was easier to be maintained and that the mixtures had longer working times. This result also suggests that the application of BOF slag to asphalt concrete can hold off the cooling rate when transported and extend the time needed for transportation.

As stated above, the cessation temperatures were between 60 and 80℃. The cessation temperature is the lowest temperature possible for rolling compaction. If the temperature of the asphalt concrete mixture is lower than the cessation temperature, the pavement is difficult to compact. In this stage, the cooling rates for the 0, 20, and 40% BOF slag replacements were 0.87, 0.90, and 0.89℃/min, respectively. The temperatures for the open-to-traffic stage were less than 60℃, and the cooling rates for the 0, 20, and 40% BOF slag replacements were 0.42, 0.37, and 0.36℃/min, respectively. The cooling rate decreased with increasing amounts of BOF slag. The heat energy in the asphalt mixture was gradually depleted as time passed, and the temperature decreased. As a result, the cooling rate decreased, although the BOF slag aggregate itself can store heat, the surface of the BOF slag was covered by asphalt. When the temperature of the asphalt mixture with BOF slag decreased, the asphalt gradually showed elastoplastic behavior and the energy of the mixture reached thermal equilibrium. Therefore, the heat-storing effect of BOF slag was strong in the initial exothermic temperature stage because both asphalt and BOF slag were at a high temperature. The BOF slag can develop a heat exchange mechanism to maintain heat during the transport of the asphalt mixture.

Variation in the Cooling Rate Inside the BOF Slag Asphalt Concrete Pavement

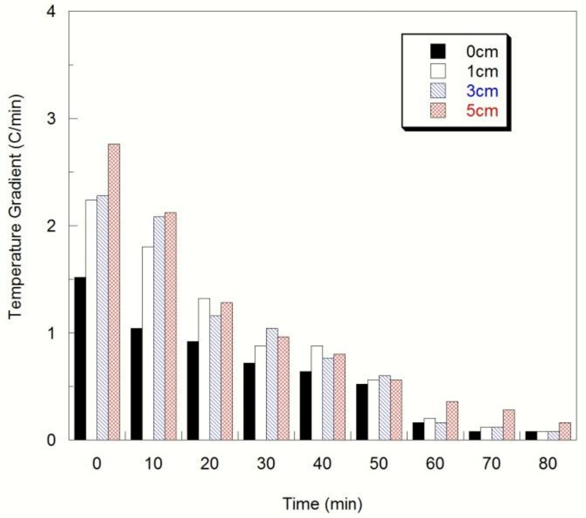
Fig. 4 shows the cooling temperature gradients for pavement with 0, 20, and 40% BOF slag at depths of 0, 1, 3, and 5 cm. The pavement surface (0 cm depth) had the smallest temperature gradient, followed by 3 and 5 cm below the surface. According to thermal equilibrium and energy conservation principles, the asphalt concrete mixture was at a high temperature just after being mixed. Because the pavement surface was in contact with the atmosphere and a large amount of energy was depleted by the temperature difference, the internal heat energy of the pavement would be convected toward the surface to replenish the energy loss at the surface. As a result, the temperature gradient at 3 cm below the pavement surface was higher than that at the surface in the initial exothermic temperature stage. Similarly, the temperature gradients at 5 cm below the surface were higher than those at 3 cm below the surface. As time progressed, the temperature gradients at the three depths gradually reached equilibrium and became similar.

As shown in Fig. 4, the temperature gradients for the mixture with 20% BOF slag were similar to those of the RAP mixture (0% BOF slag). For the mixture with 40% BOF slag in the initial exothermic temperature stage, the temperature gradients at 3 cm below the pavement surface were relative small. This indicates that the BOF slag was less likely to lose heat energy. Hence, less internal heat energy was needed to replenish the energy loss at the pavement surface. In the cessation temperature stage, the pavement surface temperature continued to fall, and energy was supplied from 3 cm below the surface. As a result, the temperature gradients at 1 cm below the pavement surface were higher.

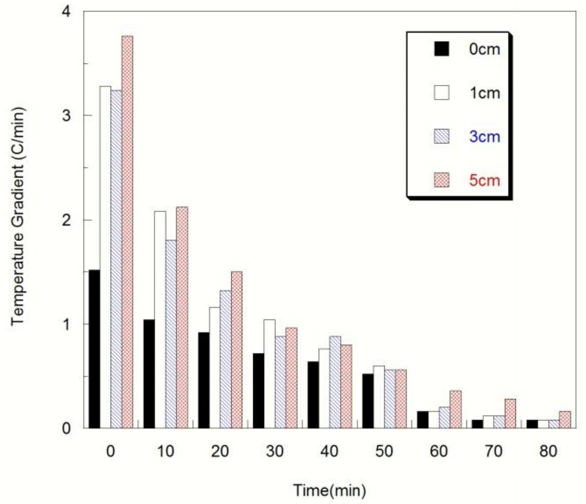
The initial exothermic temperature of the RAP mixture was maintained for only 5 min. This indicates that the pavement surface temperature fell quickly after it was mixed. However, the initial exothermic temperature of mixtures with different levels of BOF slag was maintained for 11 to 15 min. The time period of the initial exothermic temperature stage reflects the time to transport the asphalt mixture to the construction site after being mixed. The heat-storing effect of the BOF slag can extend the amount of time that can be used for transportation. Moreover, the times for the cessation and open-to-traffic temperature stages reflect the suitable times for beginning and completing the rolling compaction of the pavement, respectively. Because rolling compaction of the pavement must begin within 30 min after the asphalt mixture is mixed and must be completed within 60 min, there are no clear differences in the beginning and completion times for RAP asphalt pavement with or without BOF slag.

Effects of Air Voids in the Asphalt Mixture on the Cooling Rate

The effects of air voids in RAP asphalt mixtures with different levels of BOF slag on the pavement cooling rate were investigated. Fig. 5 shows the relationship between the air voids and the temperature for various levels of BOF slag at the three temperature stages. The air voids varied between 3 and 5% for mixtures with different levels of BOF slag replacement and increased with increasing amounts of slag replacement. However, the coefficients of determination, R^2, between the air voids and the three temperature stages ranged from 0.1 to 0.2. This implies that the air voids had no clear influence on the cooling rate of RAP asphalt concrete pavement with or without BOF slag.



(a)



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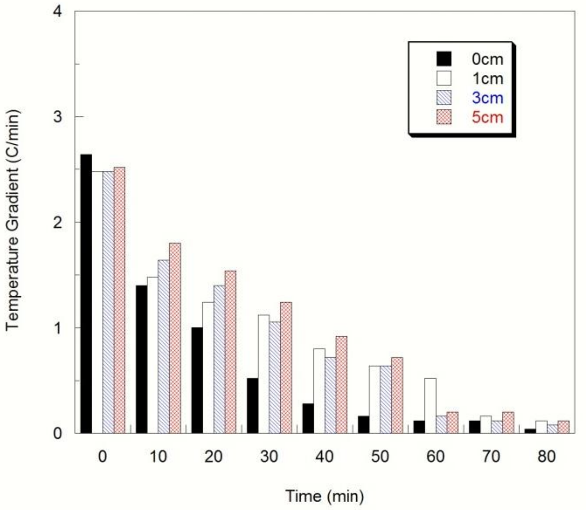


(c)

Fig. 4. Cooling Temperature Gradients for Pavement with (a) 0, (b) 20, and (c) 40% BOF Slag Replacements at Depths of 0, 1, 3, and 5 cm.

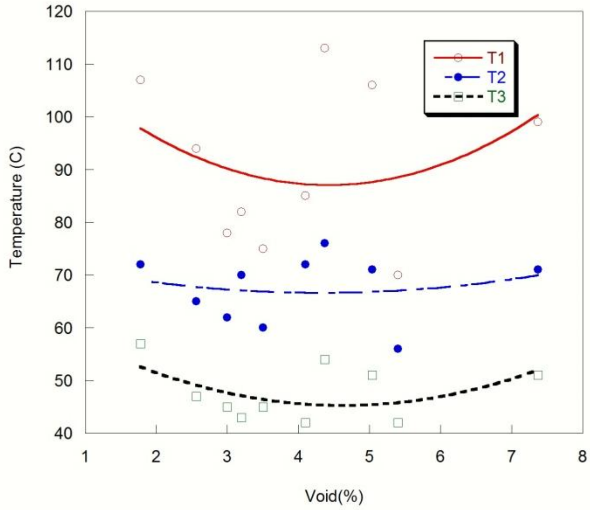


Fig. 5. Relationship Between Air Voids and Temperature for Various Levels of BOF Slag Replacement at the Three Temperature Stages (T1:initial temperature, T2:cessation temperature, T3:opening temperature).

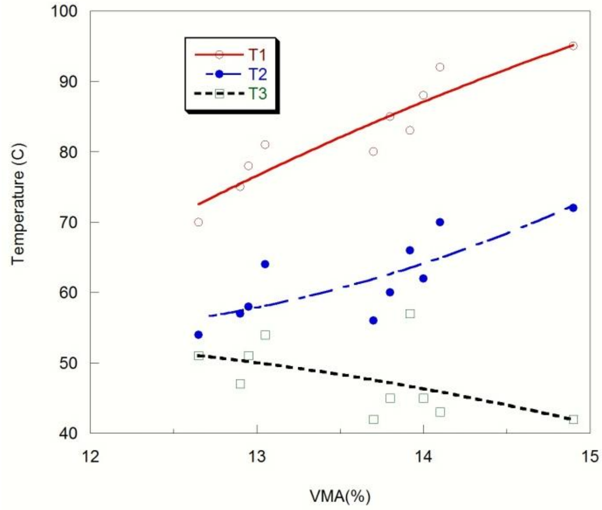


Fig. 6. Relationship Between V.M.A. and Temperature for Various Levels of BOF Slag Replacement at the Three Temperature Stages (T1:initial temperature, T2:cessation temperature, T3:opening temperature).

Mrawira and Luca [8] suggested that voids in asphalt pavement have no effect on heat dissipation. In this study, regression curves were constructed for V.M.A. and temperature for various levels of BOF slag replacement at the three temperature stages and are shown in Fig. 6. Note that the temperatures depicted in the figure are the lowest cooling rates at different stages. The V.M.A. values decreased with increasing levels of BOF slag replacement, which implies that the initial exothermic and cessation temperatures were lower in mixtures with higher amounts of BOF slag. This result may be caused by the heat-storing effect of the BOF slag replacement. Moreover, because the cooling temperature reached the stable temperature stage and heat dissipation was nearly completed for the

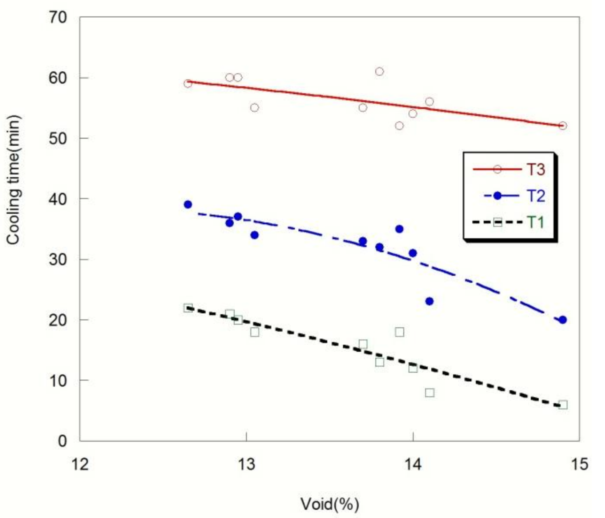


Fig. 7. Relationship Between V.M.A. and the Required Cooling Time for Various Levels of BOF Slag Replacement at the Three Temperature Stages (T1:initial temperature, T2:cessation temperature, T3:opening temperature).

asphalt mixture, the V.M.A. values had no clear influence in the stable temperature zone when thermal equilibrium was reached.

Fig. 7 shows the relationship between V.M.A. and the required cooling time for various levels of BOF slag replacement at the three temperature stages. The smaller the V.M.A. value, the longer the required cooling time. This phenomenon implies that because BOF slag can store heat, asphalt concrete mixtures with larger amounts of BOF slag replacement had lower cooling rates and required longer cooling times. Moreover, asphalt mixtures with higher levels of BOF slag replacement had smaller V.M.A. values. Because the inside of the asphalt pavement was not directly exposed to the atmosphere, it was difficult to reduce the internal heat energy through convection at the surface alone. Moreover, BOF slag is a porous material that can store heat. This accumulated heat is then convected to the upper layer of the asphalt pavement. As a result, the cooling rate slows down. The coefficients of determination, R^2, between the V.M.A. values and the initial exothermic, cessation, and open-to-traffic temperatures were 0.84, 0.80, and 0.40, respectively. Hence, the best energy dissipation effect was observed at the initial exothermic temperature stage, followed by the cessation temperature stage. The V.M.A. values were correlated with the cooling and energy dissipation effects. However, no clear cooling was observed in the open-to-traffic temperature stage. Therefore, the V.M.A. values had no effect on the cooling of the asphalt pavement.

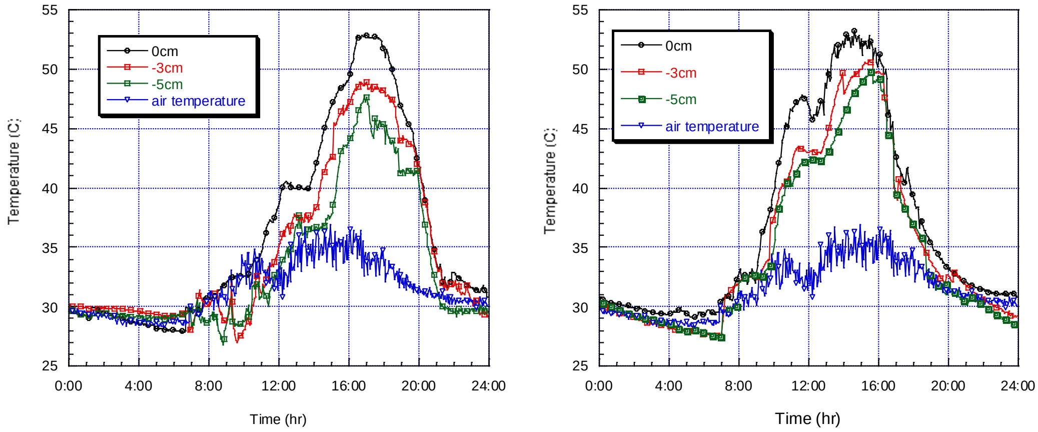
When the level of BOF slag replacement was 20%, the V.M.A. value was reduced by approximately 1%. The time for the asphalt mixture to cool to the initial exothermic temperature stage increased to approximately 8 min, and the time to cool to the cessation temperature stage increased to approximately 12 min. This suggests that BOF slag replacement extends the cooling time.

When the pavement surface temperature nears the atmospheric temperature, the asphalt concrete mixture is elastic and can support loading from vehicles. However, when the surface temperature is higher than the atmospheric temperature, the asphalt concrete mixture is viscoelastic, and permanent deformation can occur more easily. Because of these different characteristics of the pavement surface, conventional asphalt concrete pavement can absorb heat during the high temperatures of the summer season. When the pavement surface temperature is 20℃ higher than the atmospheric temperature, the pavement becomes viscoelastic and unstable. As a result, plastic deformation of the pavement occurs after being compacted by vehicles. In contrast, the surface temperature of pavement with BOF slag remains near atmospheric temperature, and the pavement stays in an elastic state. After being compacted by vehicles, elastic deformation occurs in the pavement, which allows the pavement to resist permanent deformation.

Variation of the in situ Temperature of BOF Slag Asphalt Concrete Pavement after Being Opened to Traffic

Fig. 8 shows the variation of the in situ temperature of BOF slag asphalt concrete pavement containing 0 and 40% BOF slag after being opened to traffic. Three periods of time were defined: 0 to 8 hours (midnight to early morning), 8 to 18 hours (daytime), and 18 to 24 hours (night). From 0 to 8 hours, the surface temperature of the pavement with 0% BOF slag reached a steady-state value when the average atmospheric temperature was approximately 30℃ (Fig. 8(a)). From 8 to 18 hours, the atmospheric temperatures were between 30 and 36℃, and the pavement temperature decreased with increasing depth from the surface. According to Dempsey and Thompson [9], the factors that affect the pavement cooling rate are heat convection and heat radiation. Because the pavement surface was in direct contact with the atmosphere and absorbed heat radiation from the sun, the surface temperature increased and reached a maximum of 53℃ at 14 hours. The heat absorbed by the surface was then transmitted to the inside of the pavement by heat convection. This heat convection gradually decreased with increasing pavement depth. From 18 to 24 hours, no heat radiation was obtained from the sun. The temperatures at different depths inside the pavement gradually decreased to atmospheric temperature, which implies that thermal equilibrium was reached again.

From 0 to 8 hours, the surface temperature of the pavement with 40% BOF slag reached 30℃ (Fig. 8(b)). Compared with the pavement with 0% BOF slag, there were no differences in surface temperature in this time period. However, the temperatures at depths of 3 and 5 cm were 2 to 4℃ lower in the pavement with 40% BOF slag than in the pavement with 0% BOF slag. The lower temperatures were related to the voids in the BOF slag itself. Chang et al. [10] investigated the cooling effects of asphalt concrete and noticed that the void ratio or porosity had no apparent effect on the cooling rate of asphalt concrete. However, if larger pores were located on the surface, internal heat would be removed by heat convection. Therefore, the pores had a clear effect on heat absorption and convection in asphalt concrete pavement while the temperature increased. The pavement with 0% BOF slag was designed to be a densely graded asphalt concrete with a small void ratio. When the temperature increased, heat convection occurred among the aggregates. As a result, the rate of temperature increase was rapid. However, in pavement with BOF slag, because of the many voids in the BOF slag itself, heat could be released from



(a) (b)

Fig. 8. Variation of the in Situ Temperature of BOF Slag Asphalt Concrete Pavement with (a) 0 and (b) 40% Replacement after Being Opened to Traffic.

inside the BOF slag while the temperature increased. Hence, the rate of temperature increase slowed.

Conclusions

In this study, the effects of BOF slag replacement on heat preservation in asphalt concrete pavement were investigated. We drew the following conclusions from the results:

1. The Marshall test values increased with increasing amounts of BOF slag. However, the optimum asphalt content, flow, V.M.A., and V.F.A. values decreased with increasing amounts of BOF slag aggregate. These values were similar to or higher than those specified in the standards.
2. For the same transportation time and distance, the temperature of the asphalt concrete pavement with 40% BOF slag was approximately 7°C higher than that with 0% BOF slag. Hence, a longer curing time is needed after rolling compaction, and a longer period of time is required before the asphalt concrete pavement with large amounts of BOF slag can be opened to traffic.
3. The asphalt concrete mixtures had high temperatures immediately after being mixed. Because the pavement surface was exposed to the atmosphere and a large amount of energy was lost because of the temperature difference, the internal heat energy of the pavement was convected upward to replenish the energy loss at the pavement surface. The temperature gradients inside the pavement were similar to those at the pavement surface. At a temperature of 65°C, the temperature gradients at the surface and inside the pavement would reach equilibrium.
4. Asphalt mixtures with higher levels of BOF slag had smaller V.M.A. values. Because the inside of the asphalt pavement was not directly exposed to the atmosphere, it was difficult to reduce the internal heat energy through convection at the surface alone. Moreover, BOF slag is a porous material that can store heat. This accumulated heat was then convected upward to replenish energy in the upper layer of the pavement. As a result, the cooling rate decreased in pavement containing BOF slag.
5. After being opened to traffic, the temperatures at depths of 3 and 5 cm in the pavement with 40% BOF slag were 2 to 4°C lower than at the same depths in the pavement with 0% BOF slag.

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