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Research Article

Performance Evaluation of Semiplastic Recycled Cold Asphalt Using Noncement Binders

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The optimal mixing conditions for semiplastic recycled cold asphalt, which recycled waste asphalt and used noncement binders (NCB), were assessed through verification of the performance. The NCB of 6% desulfurization gypsum mixing was found to have the most outstanding properties. For the Marshall stability, 4% (NCB) filler mixing brought about a 1.92-time strength increase effect compared to OPC (2%) and was improved when using modified asphalt and SBR. The flow test results showed that although an increase dosage of filler and SBR decreased the flow value of the semiplastic recycled cold asphalt, an increase dosage of asphalt emulsion improved the flow value. The indirect tensile strength and liquid immersion residual stability for the condition with greatest Marshall stability were most outstanding with 0.95 MPa and 83.6%, respectively. Evaluation of the recycled cold asphalt abrasion durability revealed that for the case of mixing more than 4% NCB the mass loss rate was lower than 20%. The abrasion durability was found to improve when using modified emulsified asphalt and SBR substitution. From the test results, it was found that the optimal mixing proportion of semiplastic recycled cold asphalt satisfied mechanical properties and durability is NCB with 4%, emulsified asphalt with 3%, and SBR substitution with 20%.

1. Introduction

The total length and percentage of paved roads in Korea are 105,931 km and 80.4% (9.0% unpaved and 10.6% unopened), respectively. Among the paved roads, a significant portion (86.8% or 73,874 km) used asphalt pavement [1]. Such asphalt paved roads have the disadvantage of having a short service life in contrast to concrete pavement and repair work is frequent. In addition, the reconstruction of asphalt pavement is required due to installation and replacement work for infrastructure such as electric, gas, water supply, and sewage. The amount of resulting waste asphalt concrete is currently on the rise, resulting in demand for by-product recycling research [2].

Among types of construction waste, waste concrete has typically been recycled into secondary concrete products, subbase layer materials, and structural backfill materials as the quality standard for recycled aggregates has been established. However, because asphalt emulsion is attached to the aggregate surface in the case of reclaimed asphalt pavement, unlike waste concrete, reclaimed asphalt pavement cannot be used for structural backfill and subbase layer materials. In order to increase the effective recycling of reclaimed asphalt pavement, it has to be used as hot-mixed or cold temperature recycling asphalt [3–5]. Hot-mixed asphalt, which requires high degrees of heat, is targeted for having high CO_2 emissions. Thus, efforts to lower the temperature have recently been made. Specifically, research on warm asphalt pavements is actively being pursued as a part of the goal towards low-carbon environmentally friendly roads, and interest in recycled cold asphalt which can be constructed at room temperature is increasing [4–6].

These recycled cold asphalt application studies reported the application of Ordinary Portland Cement (OPC) as

Table 1: Reclaimed asphalt pavement recycled aggregate properties.

Density (g/cm^3)	Water absorption (%)	Contents of reclaimed asphalt (%)	Penetration of reclaimed asphalt (1/10 mm)	Loss content of washing test (%)	Amount of foreign material (%)	
					Organic	Inorganic
2.62	1.45	4.43	21	1.0	0.07	0.11

Table 2: Reclaimed asphalt pavement recycled aggregate size distribution.

Type	Percentage passing (%)									
	25 mm	20 mm	13 mm	10 mm	5.0 mm	2.5 mm	0.6 mm	0.3 mm	0.15 mm	0.08 mm
Recycled aggregate										
13~25 mm	55	46.8	39.9	30.0	21.8	15.0	8.75	6.33	4.02	1.54
8~13 mm	28	28	28	22.8	8.65	6.64	4.28	3.28	2.18	0.95
≤8 mm	15	15	15	15	14	11.18	6.29	4.44	2.87	1.04
Aggregate gradation (≤25 mm)	98	89.8	82.9	67.8	44.4	32.8	19.3	14.0	9.06	3.53

Table 3: Emulsified asphalt MSC-2 properties.

Viscosity (25°C)	Sieve fraction (1.18 mm, wt%)	Charge of particle	Mass of evaporation residue (wt%)	Evaporation residue			Settlement (24 hr, wt%)
				Penetration (25°C, 1/10 mm)	Ductility (25°C, cm)	Toluene solubility (wt%)	
7.6	0.02	Positive (+)	60.1	128	120 over	99.7	0.39

the filler material to partially supplement the ductility disadvantage of asphalt and facilitate the binding of the mixture at low temperatures. However, OPC produces a large amount of CO_2 during production, so research to find a suitable alternative material is called for [7].

Therefore, in this study, the optimal mixing conditions for semiplastic recycled cold asphalt using noncement binders (NCB) and recycled reclaimed asphalt pavement were derived and the performance was evaluated.

2. Materials and Testing Methods

2.1. Materials

2.1.1. Reclaimed Asphalt Pavement Recycled Aggregate. The reclaimed asphalt pavement recycled aggregate used in this study was processed and manufactured by company G of Korea and Table 1 shows the product specifications. Table 2 and Figure 1 show the size distribution results.

2.1.2. Noncement Binder (NCB). In order to secure strength of recycled cold asphalt, mixing conditions such as blast furnace slag, high-calcium fly ash, desulfurization gypsum, quicklime, hydrated lime, and high range water-reducing AE agent were derived. Additionally, this research aimed to deduce optimal mixing conditions for noncement binders by adjusting desulfurization gypsum substitution ratio [8–11].

2.1.3. Asphalt Emulsion. In this study, modified emulsified asphalt (HS-S.P COAT) was used, which is improved from the emulsified asphalt (MSC-2) commonly used in the conventional asphalt fabrication process in terms of plastic deformation and crack resistance [12–16]. Tables 3 and 4 show the properties of the modified emulsified asphalt.

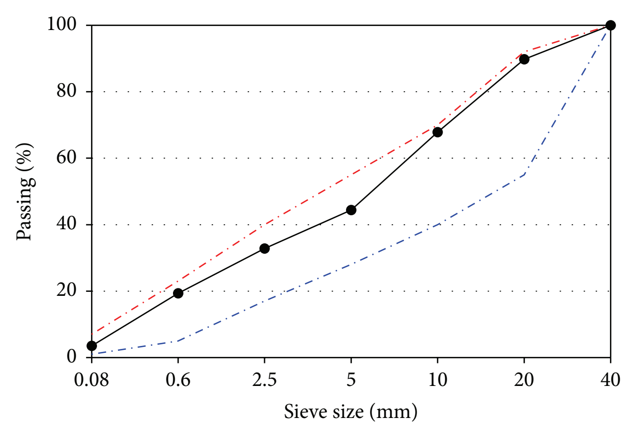

Figure 1: Reclaimed asphalt pavement recycled aggregate size distribution curve.

2.1.4. Polymer (SBR). In this study, SBR latex (Synthetic Rubber Latex) was used to improve adhesion, tensile strength, flexural strength, and waterproofing. Table 5 shows the properties of SBR latex.

2.2. Method

2.2.1. Noncement Binder (NCB) Performance Evaluation. In order to assess the optimal mixing conditions for the binder to be used as the filler, mortars were fabricated in accordance with KS L ISO 679 and compressive strength, flow, and setting tests were conducted [17].

2.2.2. Marshall Stability and Flow Value. The Marshall stability and flow value tests of the semirigid pavement were measured and analyzed according to ASTM D6927 “Standard

Table 4: Modified emulsified asphalt HS-S·P COAT properties.

Viscosity (25°C)	Sieve fraction (1.18 mm, wt%)	Charge of particle	Mass of evaporation residue (wt%)	Evaporation residue			Settlement (24 hr, wt%)	Toughness (N·cm)
				Penetration (25°C, 1/10 mm)	Ductility (25°C, cm)	Softening point (°C)		
3.4	0.00	Positive (+)	55.2	64	≥150	51.8	0.4	1,109

Table 5: SBR latex properties.

Viscosity (Engler degree, 25°C)	pH (25°C)	Solid content (%)
62.0	9.86	46.15

Test Method for Marshall Stability and Flow of Bituminous Mixtures."

2.2.3. Porosity. The porosity testing for the recycled cold asphalt was measured according to ASTM D3203 "Standard Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures" and calculated using

$$\text{Porosity}\,(\%) = \left(1 - \frac{\text{bulk specific gravity}}{\text{Theoretical maximum specific gravity}}\right) \times 100. \quad (1)$$

2.2.4. Indirect Tensile Strength. Tensile strength was evaluated according to ASTM D6931 "Standard Test Method for Indirect Tension (IDT) Strength of Bituminous Mixtures" with the load applied at a rate of 50 mm/min, and measurement was conducted until the load was reduced after reaching the maximum load.

2.2.5. Liquid Immersed Residual Stability. The liquid immersed residual stability testing for the recycled cold asphalt was conducted according to KS F 2369 "Cold Mix Asphalt for Patching Materials" and the test specimen was manufactured in accordance with ASTM D6927. The specimens were immersed in a $25 \pm 1^\circ$C constant temperature water tank for 48 hours and then the Marshall stability testing was performed.

2.2.6. Abrasion Resistance. Abrasion resistance of the test specimen according to the mixing condition was measured and evaluated following KS F 2492 "Standard Test Method of Cantabro Test for Porous Asphalt Mixtures" where the test specimen for Marshall stability testing was used in the LA abrasion test which measured the rate of mass change after 300 rotations using a steel ball.

2.3. Mixing. For the optimal mixing condition and performance evaluation of the recycled cold asphalt using noncement binders, this study was conducted in two parts depending on the test condition. In Series I, compressive strength, flow, and setting tests were conducted according to the desulfurization gypsum substitution ratio with regard to the ground granulate blast furnace slag with the aim of crack reduction at the optimal mixing condition presented in literature during noncement binder fabrication. In Series II, the mechanical properties and durability of the recycled cold asphalt for each mixing condition were verified. The mixing conditions are shown in Tables 6 and 7.

In Series I, mixing was conducted with the binder and fine aggregate ratio of 1 : 3 and W/B of 50% in order to derive the optimal mixing condition of the noncement binder for recycled cold asphalt. Setting, flow, and strength tests were conducted for the mortar [17].

To analyze the flow value, Marshall stability, and indirect tensile strength of the recycled cold asphalt mixture, a cylindrical test specimen with dimensions of Ø101.6 × 63.5 mm was manufactured in accordance with ASTM D6927 "Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures." The specimen was mixed into 1 mold at a time followed by compaction on both surfaces 50 times each and then curing for 24 hours in a 60°C thermostatic bath and finally demolding. Testing for each specimen was conducted after an additional curing under room temperature and moisture environment. Figure 2 shows the base recycled cold asphalt mixing, compaction, and demolding.

3. Test Results

3.1. Noncement Binder Mixing Ratio Evaluation

3.1.1. Setting Time according to the Desulfurization Gypsum Mixing Ratio. Figure 3 shows the setting test results for the ground granulated blast furnace slag according to the substitution ratio of the desulfurization gypsum. It was found that there was a tendency for the initial and final setting times to become shorter as the substitution ratio of the desulfurization gypsum increased, which acts as an expansive admixture for shrinkage reduction. This was thought to be due to the increased quicklime content, which constitutes desulfurization gypsum, resulting in early setting and the reduction of the initial and final setting times.

3.1.2. Flow Value and Compressive Strength according to the Desulfurization Gypsum Mixing Ratio. Figure 4 shows the mortar flow and compressive strength results according to the desulfurization gypsum content. Investigating the mortar flow according to the desulfurization content, which is used as a shrinkage reducing admixture, determined that an increase of the desulfurization gypsum substitution ratio resulted in a decrease of the flow, similar to the setting test results. In particular, for the case of mixing ratio of 8% where the amount of quicklime increased significantly due to the excessive mixing of desulfurization gypsum, the flow was reduced drastically [9].

Table 6: Noncement binder mixing ratio.

Mix number	Mixing condition	Mixing weight (wt.%)					
		BFS	FA	DG	QL	SL	SP
I-1	DG: 0%	66	20	0	8	6	0.002
I-2	DG: 2%	64	20	2	8	6	0.002
I-3	DG: 4%	62	20	4	8	6	0.002
I-4	DG: 6%	60	20	6	8	6	0.002
I-5	DG: 8%	58	20	8	8	6	0.002

BFS: blast furnace slag, FA: high-calcium fly ash, DG: desulfurization gypsum, QL: quick lime, SL: slaked lime, and SP: superplasticizer.

Table 7: Recycled cold asphalt mixing ratio chart.

Mix number	Mixing condition			Mixing weight (wt.%)					
	Filler	Emulsifier	Water	Filler	Emulsifier	Water	Aggregate		
							13~25 mm	8~13 mm	≤8 mm
II-1 (plain 1)	OPC	Normal	W-100	2	1.5	3.5	55	28	15
II-2	NCB	Normal	W-100	2	1.5	3.5	55	28	15
II-3	NCB	Normal	W-100	3	1.5	3.5	55	28	14
II-4 (plain 2)	NCB	Normal	W-100	4	1.5	3.5	55	28	13
II-5	NCB	Normal	W-100	4	1.5	3.5	55	28	13
II-6	NCB	Modified	W-100	4	3.0	3.5	55	28	13
II-7	NCB	Modified	W-90, SBR-10	4	1.5	3.5	55	28	13
II-8	NCB	Modified	W-80, SBR-20	4	1.5	3.5	55	28	13
II-9	NCB	Modified	W-80, SBR-20	4	3.0	3.5	55	28	13

Also, when the desulfurization gypsum substitution rate increased to 6%, the compressive strength increased, but for 8%, the strength decreased. This decrease in compressive strength was thought to be due to overexpansion, which reduces the compactness of the composition. This was due to the increase in products produced from the transition of quicklime to hydrated lime through hydration and reaction with C_3A among the minerals that compose the binder due to the minerals constituting the desulfurization gypsum being composed of $CaO\text{-}CaSO_4$ combinations.

3.2. Property Evaluation of Recycled Cold Asphalt according to the Mixing Condition

3.2.1. Marshall Stability and Flow Value. The Marshall stability test results for each mixing condition of the base recycled cold asphalt mixture are shown in Figure 5. Looking at the results for the noncement binder and conventional OPC according to the mixing condition, it can be observed that the Marshall stability increases with increase in content regardless of the type of filler. This increase in Marshall stability was thought to be due to the enhancement of cohesion with the reclaimed asphalt pavement, caused by the increase in filler content which has strong cohesion. The Marshall stability for the recycled cold asphalt using noncement binders was similar to or slightly lower than that of OPC.

However, mixing noncement binders with more than 3% as a filler resulted in a Marshall stability greater than that of the OPC 2% content mixture, and the Marshall stability for 4% mixture showed an increase of approximately 1.92 times.

The Marshall stability according to the asphalt emulsion condition showed that the Marshall stability increases by approximately 8.0~18.8% when regular modified emulsified asphalt is used, in comparison to when regular emulsified asphalt is used, regardless of the emulsion mixing content. This was thought to be due to the improvement of segregation resistance, aggregate scaling resistance, and crack resistance produced by the increase in interfacial adhesion between aggregates when mixing a polymer into the modified emulsified asphalt more so for asphalt than regular emulsified asphalt, resulting in a shorter curing time needed than hardening. The Marshall stability somewhat increased with the increase of emulsion mixing and the increase of emulsion mixing reduced delamination of the binder during failure of the test specimen.

When the substitution ratio of SBR increased, for the case of noncement binder and modified emulsified asphalt, the Marshall stability also increased. This behavior was deduced to be caused by the SBR resin polymer, which has become a functionalized polymer composition, filling the air gaps between the aggregates by forming a reticular structure [15]. This results not only in the suppression of expansion cracks by enhancing adhesion and tensile strength but also in the improvement of low temperature tolerance and binder (asphalt emulsion) strength [16]. It also enhances elasticity by being distributed evenly within the asphalt mixture.

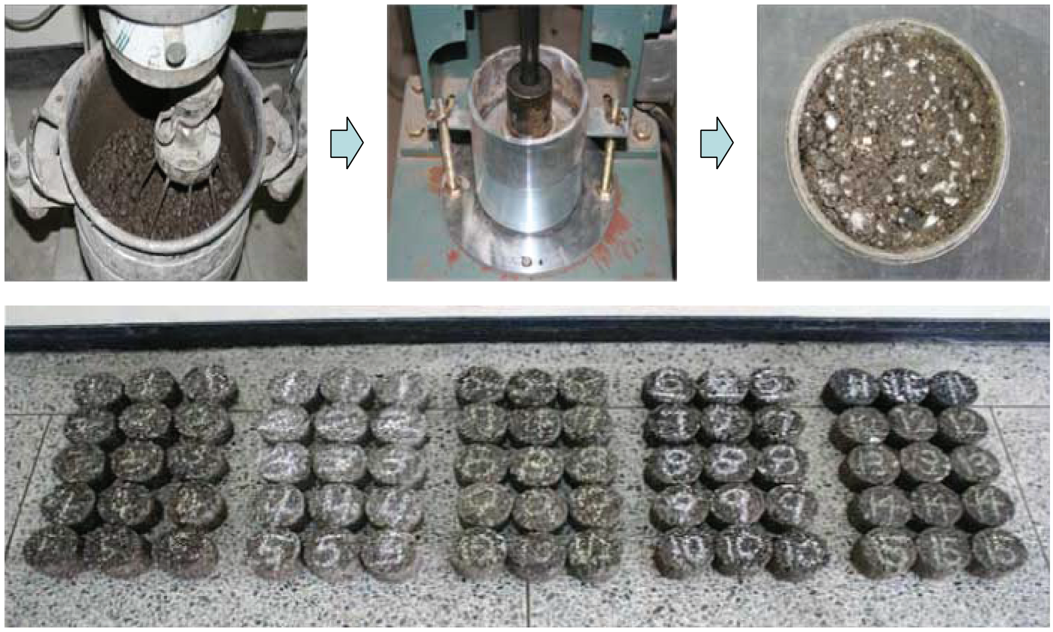

FIGURE 2: Fabrication process and final manufactured test specimen.

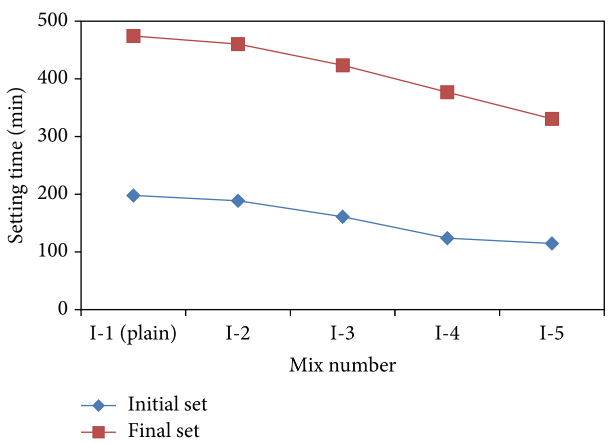

FIGURE 3: Setting time.

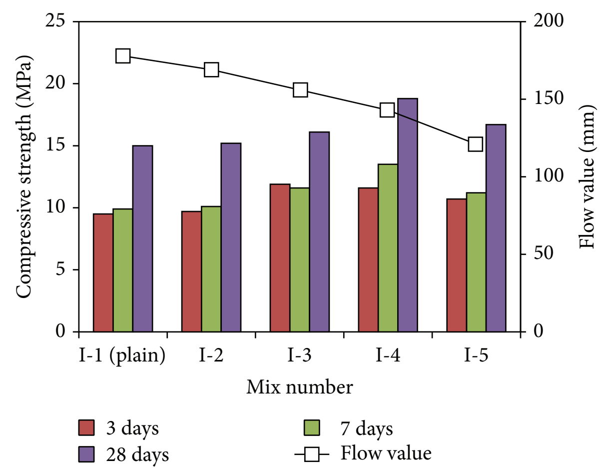

FIGURE 4: Compressive strength and flow value.

The flow value test result for the base recycled cold asphalt mixture according to the filler, asphalt emulsion and SBR substitution ratios, and mixed amount was measured to be approximately 20.3~31.4 mm.

Inspection of the flow value test results of the base recycled cold asphalt mixture according to each mixing condition revealed contrasting trends for the Marshall stability depending on the filler and SBR conditions. However, the flow value according to the amount of mixed asphalt emulsion showed an increase when the mixed amount was increased, regardless of the asphalt type. The observed decrease in flow value for the mixing condition of increasing Marshall stability was thought to be due to the improvement of the internal cohesion of the recycling asphalt and aggregate adhesion. The increase in asphalt emulsion mixed amount, which is a binder that facilitates plastification of the asphalt mixture, increases both the Marshall stability and the flow value.

Overall inspection of the above discussed Marshall stability and flow value test results reveal that they satisfy the requirements for the base mixture quality regulations of KS F 2369 (Cold Mix Asphalt for Patching Materials) and GR F 4026 (Recycled Cold Asphalt Paving Mixtures) for all mixing conditions.

3.2.2. Porosity. The asphalt mixture porosity affects the pavement sliding effect which is due to the asphalt pavement plastic deformation and penetration of water and air, so the porosity is a critical factor that influences the quality of the asphalt mixture. In this study, to further investigate the properties of the base recycled cold asphalt mixture,

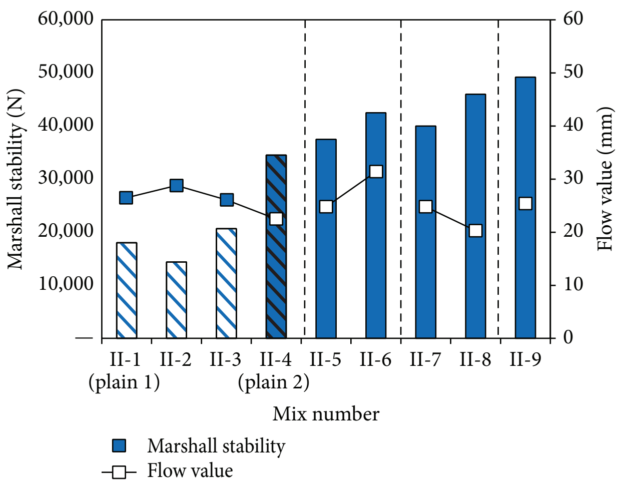

FIGURE 5: Marshall stability and flow value.

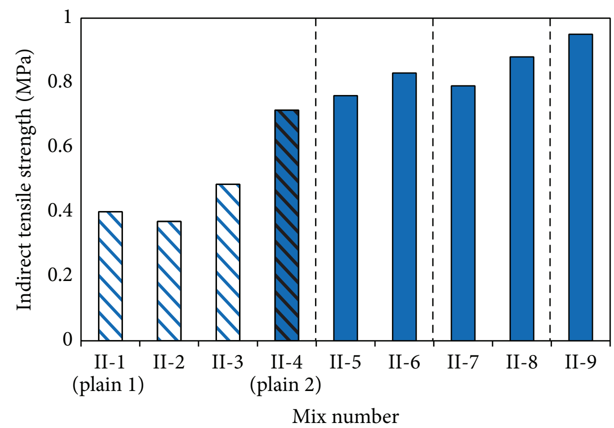

FIGURE 7: Indirect tensile strength.

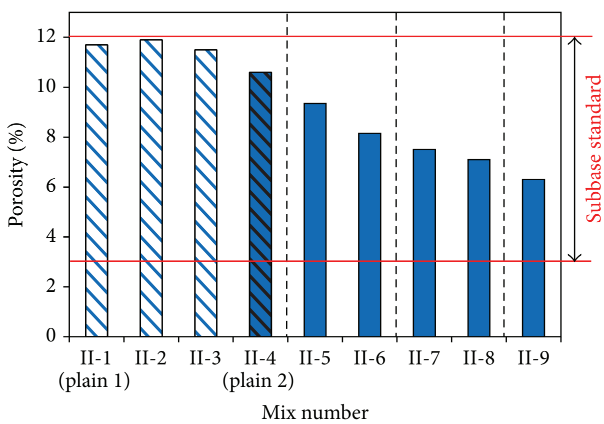

FIGURE 6: Porosity.

the porosity of the base recycled cold asphalt mixture was measured according to the substitution ratio and mixed amount of the used filler, asphalt emulsion, and SBR. The test results are shown in Figure 6.

The porosity results for each mixing condition show that although the difference depending on the filler type is not significant, the effect of the mixed amount is quite apparent. In particular, when 4% filler and 3% emulsion were mixed simultaneously, the porosity was 8.15%. The increases in the filler and emulsion mixed amounts were thought to have filled the air gaps of the mixture, thereby making the internal matrix structure denser, reducing the porosity. Moreover, when mixing latex, the porosity was superior, with a maximum 7.1%, to when modified asphalt was used. When implementing the optimal mixing condition within the scope presented in this study, the porosity was reduced down to 6.3%.

In the current domestic KS and GR standards, the base recycled cold asphalt porosity is given as 3~12% and the results of this study show a porosity near the maximum 12% when the filler mixed amount is 2%, but all the other mixing conditions were found to satisfy the regulation.

3.2.3. Indirect Tensile Strength. In order to evaluate the applicability and possibility of crack formation in recycled cold asphalt, the indirect tensile strength of the asphalt mixture was measured for each mixing condition and the results are shown in Figure 7. The results showed that the indirect tensile strength of the recycled cold asphalt had similar trends with Marshall stability for all conditions (Figure 9). The highest strength of approximately 0.95 MPa was obtained for the condition with the most superior Marshall stability. This trend can be attributed to increased mixing of the filler leading to increased adhesion between the binders and emulsion as the modified emulsified asphalt and SBR resin polymer are included. This resulted in an enhanced resistance to compressive loading, which is applied parallel along the plane perpendicular to the test specimen.

On the other hand, while the increase in filler content increases the indirect tensile strength, there were cases where the pressure from the loading head caused splitting at the center of the test specimen. However, when the asphalt emulsion mixed amount was greater than 3.0%, this splitting phenomenon did not occur, due to improvement of the cohesion between the aggregate particles by the increased emulsion.

In the current domestic KS and GR standards, there is no standard regarding the indirect tensile strength of base recycled cold asphalt. This study set the goal of indirect tensile strength value at 0.11 MPa in order to fabricate mixtures with superior performance in comparison to the conventional recycled cold asphalt being manufactured today. This regulation was satisfied for all mixing conditions conducted in this study.

3.2.4. Liquid Immersed Residual Stability. The liquid immersed residual stability test results of the recycled cold asphalt are shown in Figure 8. The results for each mixing condition reveal similar trends for all conditions to that of the Marshall stability test results, which evaluated mechanical performance (Figure 9). This result is affected by the cohesion of the internal structure and between the mixtures of the recycled cold asphalt. It was found that as the stability value increased, the reduction in stability measured after 48 hours of immersion at 25°C value decreased.

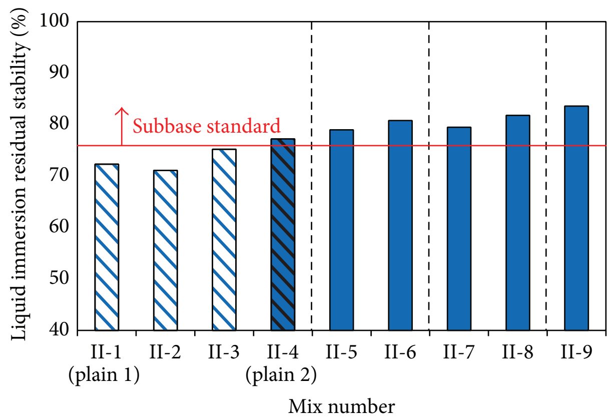

Figure 8: Liquid immersion residual stability.

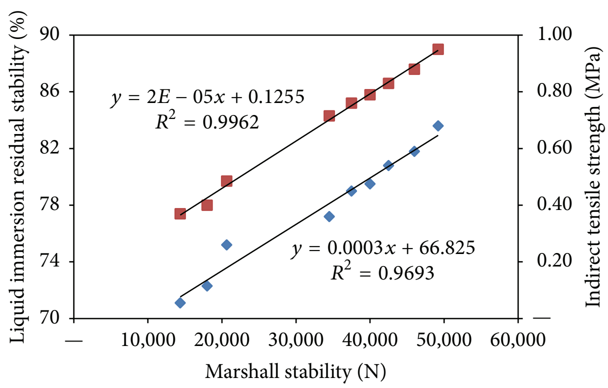

Figure 9: Correlation between Marshall stability, indirect tensile strength, and liquid immersion residual stability.

Currently, the domestic GR F 4026 standard only presents a standard for surface layer recycled cold asphalt, but KS F 2369 (Cold Mix Asphalt for Patching Materials) requires the liquid immersion residual stability target to be above 75%. In this study, the liquid immersion residual stability target was satisfied for the mixing conditions with filler mixing above 3%, and the liquid immersion residual stability was found to be highest at 83.6% for the condition of 4% noncement binder, 1.5% modified emulsified asphalt, and 20% SBR substitution.

3.2.5. Abrasion Resistance. Abrasion resistance was evaluated using the Cantabro test which evaluates the aggregate resistance towards scattering, due to automobile traffic over recycled cold asphalt. The fabricated Marshall test specimen was placed in the LA abrasion test equipment which rotated 300 times at a rate of 30~33 rpm and then measured the rate of mass loss.

The evaluation results, as shown in Figure 10, showed that the mass loss rates were 15.4~26.2% for all mixing conditions, while the mass loss rate for noncement binder and 4% filler was below 20%. When using the modified asphalt with asphalt emulsion, there was an abrasion resistance increase effect of about 3~15% compared to that of the regular asphalt.

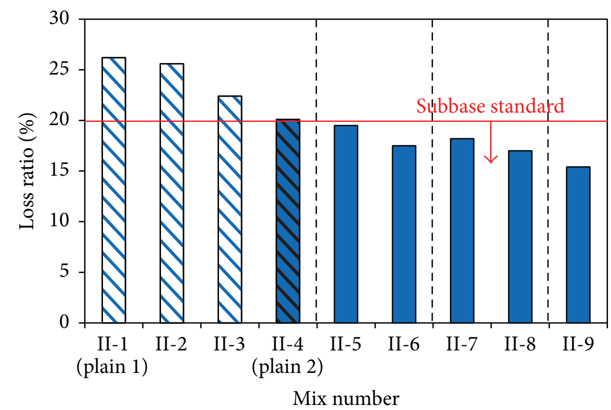

Figure 10: Abrasion resistance.

Also, the mass loss rate was found to decrease for the 20% substitution mixture of SBR resin polymer compared to the mixing condition without the mixture, which led to the determination that the use of SBR resin polymer has an increasing effect on the cold pavement durability of abrasion [12, 15].

For the II-9 condition, which was set as the optimal test condition for this study, the mass loss rate was 15.4%, which was a 70% decrease compared to that of the regular recycled asphalt (II-1).

Although there is no regulation regarding the evaluation standard on abrasion durability for recycled cold asphalt, when compared to the Cantabro loss rate quality standard of less than 20% for porous asphalt pavement, the abrasion durability of recycled cold asphalt can be considered outstanding.

4. Discussions

4.1. Optimal Mixing Ratio of Noncement Binders. Setting time, flow value, and compressive strength were estimated for optimal mixing ratio of noncement binders under the conditions of this research. As a result, appropriate desulfurization gypsum substitution ratio for blast furnace slag was indicated as about 6% [10].

4.2. Optimal Mixing Condition of Recycled Cold Asphalt. From the overall test results regarding marshal stability, flow value, porosity, indirect tensile strength, and liquid immersed residual stability of recycled cold asphalt, it was found that the optimal mixing proportion satisfied quality requirements are NCB with 4%, emulsified asphalt with 3%, and SBR substitution with 20%.

5. Conclusion

In this study, optimal mixing conditions were derived, and the performance was validated, of semiplastic recycled cold asphalt with recycled waste asphalt and noncement binders. These evaluations were conducted as basic tests for a field applicability investigation. The following are the conclusions obtained from this study.

(1) Regarding the noncement binder mixing ratio, the physical and mechanical properties results based on the substitution ratio of desulfurization gypsum revealed that blast furnace slag provided the most superior properties with 6% desulfurization gypsum substitution ratio.

(2) Regarding Marshall stability as a function of mixing condition, results showed that 4% mixing of filler brought about a 1.92-fold strength increase effect compared to that of OPC. Modified asphalt and SBR 20% substitution ratio resulted in a Marshall stability improvement. For the flow value testing, the increase in asphalt emulsion usage resulted in an increase of the flow value, while the flow value showed a decreasing trend with increasing filler and SBR substitution rate.

(3) With regard to the porosity testing, increasing the mixed amount led to a decrease in porosity and the lowest porosity of 6.3% was obtained for the mixing condition of 4% filler, 3% asphalt emulsion, and 20% SBR substitution. However, the domestic and international standards were satisfied.

(4) The indirect tensile strength and liquid immersion residual stability for recycled cold asphalt showed trends similar to the Marshall stability for all conditions. The correlation was found to be above 95%. For the condition of highest Marshall stability, the indirect tensile strength and liquid immersion residual stability were highest, at 0.95 MPa and 83.6%, respectively.

(5) Evaluation of the recycled cold asphalt abrasion durability revealed a mass loss rate lower than 20% when mixing more than 4% noncement binders, and the abrasion durability was improved when using modified emulsified asphalt and SBR substitution.

(6) For the test conditions assessed in this study, the condition of 4% filler mixing, 3% emulsified asphalt usage, and 20% SBR substitution was found to be appropriate as the optimal mixing condition to satisfy mechanical performance and durability.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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