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Evaluation of Properties of Asphalt Concrete Mixture Using Basalt Aggregate from Jeju Island

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Abstract: In this study, the engineering properties of basalt aggregate used for asphalt road pavement on Jeju Island were evaluated, and the characteristics of the asphalt mixtures used were evaluated to assess the suitability of Jeju Island basalt as road construction material. Chemical composition and surface morphology analysis of the basalt and granite aggregate, engineering characteristics analysis, and filler property evaluation were performed. Mix design was performed, and the basic properties of three asphalt mixtures for the surface, intermediate, and base layers were evaluated. Permanent deformation resistance was evaluated through a wheel tracking test, and moisture resistance was evaluated through a dynamic immersion test and a tensile strength ratio test. The optimum asphalt contents of the asphalt mixture using low-porosity basalt aggregate and high-porosity basalt aggregate were determined to be 5.7% and 5.9% in the surface layer, 5.3% and 5.4% in the intermediate layer, and 4.7% and 5.1% in the base layer, respectively. It was found that the basic properties of the asphalt mixtures satisfied Korean quality standards. The dynamic immersion test results of low-porosity basalt aggregate and high-porosity basalt aggregate were 20% and 10%, respectively, which fall far below the quality standard of 50%. The tensile strength ratios of the basalt asphalt mixtures for the intermediate layer were 0.69 and 0.40, and they were found to increase significantly to 0.87 and 0.80 after the application of a suitable anti-stripping agent. Therefore, it was concluded that in order to apply Jeju Island basalt to asphalt pavement, an appropriate anti-stripping material must be applied.

Keywords: basalt aggregate; Jeju Island; hot mix asphalt; moisture resistance; anti-stripping agent

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Citation: Han, S.; Baek, C. Evaluation of Properties of Asphalt Concrete Mixture Using Basalt Aggregate from Jeju Island. *Buildings* **2023**, *13*, 3119. https://doi.org/10.3390/buildings13123119

Academic Editor: Dan Bompa

Received: 11 November 2023
Revised: 7 December 2023
Accepted: 12 December 2023
Published: 15 December 2023

1. Introduction

1.1. Background and Purpose

Recently, in South Korea, the risk factors that cause damage to road pavement have increased due to climate change, poor quality control, and continuous traffic growth. In particular, Jeju Island, the largest island located at the southern tip of the Korean Peninsula, is a region that is highly impacted by climate change, and the frequency and intensity of extreme weather events have recently increased [1]. Over the last 30 years, the population of Jeju Island has increased by approximately 165,000 people, and the traffic volume has also steadily increased. In addition, as summer precipitation and winter snow gradually increase, premature damage to road pavement and the occurrence of potholes are increasing [2,3].

Most asphalt road pavements in Korea use granite aggregate, and some limestone is used. However, due to its geographical characteristics, Jeju Island mainly uses basalt, which can be produced locally, for road pavement. Despite the use of basalt, there are few studies on asphalt road pavement using a basalt aggregate [4]. Jeju Island has higher precipitation than other regions in Korea; the average annual total precipitation on Jeju Island from 2010 to 2019 was 1834 mm/year, about 1.5 times higher than the national average of 1264 mm/year. Jeju Island exhibits the characteristics of an island region with high precipitation, which is expected to increase the likelihood of moisture-induced road pavement damage. Therefore, ensuring moisture resistance performance in pavement is considered to be crucial [5].

There are limited areas around the world where basalt is used for pavement, so there are not enough related research cases. Various studies on the engineering properties of basalt itself [6–8] or on performance evaluation by applying it to cement concrete [9–13] have been conducted. There is some research on replacing some portion of asphalt mixtures with basalt, but it is rare to use it for the entire composition of an asphalt mixture [14,15].

Ibrahim et al. conducted a study on Jordan's road pavement and found that limestone aggregate was mainly used, and a portion of the limestone aggregate was replaced with basalt aggregate. This was done to address the problems of premature cracking and poor skid resistance that can occur when poor-quality limestone aggregate is used. The study conducted experiments on the entire aggregate, coarse aggregate and fine aggregate, used in the asphalt mixture by replacing it with basalt aggregate. The experiments included tests for Marshall stability, indirect tensile strength, stripping resistance, resilient modulus, fatigue cracking, and permanent deformation. The analysis results showed that using basalt for coarse aggregate and limestone for fine aggregate was the best option, as this performed excellently in all tests [16,17].

Currently, the area where research on basalt aggregate is most active is Hawaii in the United States, and most quarries in Hawaii collect basalt rock. The Hawaii Department of Transportation (HDOT) studied the correlation of experiments to analyze aggregate properties that affect the performance of asphalt pavement, considering the characteristics of using basalt aggregate, which are completely different from those of other U.S. states. Then, the HDOT recommended the magnesium sulfate soundness test and the aggregate durability index test as alternative aggregate testing methods that best reflect local characteristics [18]. According to the guidelines of the Hawaii Asphalt Paving Industry (HAPI), the properties of basalt aggregate in Hawaii were generally well rated, but some of the aggregate may exhibit stripping and labeling problems due to excessive asphalt content as a result of high absorption rates and also showed high porosity and low durability properties [19].

Brandes conducted a performance evaluation of asphalt mixtures using basalt aggregate. In this study, the performance of asphalt mixtures using limestone was compared and analyzed through various experiments such as Marshall stability, permanent deformation and fatigue crack resistance, and moisture damage resistance. When the basalt asphalt mixture was compared to the limestone asphalt mixture, Marshall stability was found to be at an equivalent level, permanent deformation was found to be more than four times better, and fatigue cracking was found to be about two times better. As a result of conducting an indirect tensile strength ratio (TSR) test to evaluate resistance to moisture damage, it was found that the asphalt mixture using limestone exceeded the general standard of 80%, but for the asphalt mixture using basalt, it was 64%. Therefore, it was analyzed that asphalt mixtures using basalt aggregate may be very vulnerable to moisture damage [20].

Most road pavements on Jeju Island use asphalt mixture and mainly use basalt aggregate. Aggregate characteristics are an important factor in the performance of asphalt pavement, and it is expected that the characteristics of basalt aggregate from Jeju Island will be different from those of Hawaii. Jeju Island's volcanic rocks exhibit a porous structure with many pores of various sizes and distributions due to various environmental factors, and their geological and mechanical characteristics also differ from region to region. According to the results of studying the engineering characteristics of Jeju Island basalt according to geological rock type and regional classification, Pyoseon-ri basalt had engineering characteristics similar to porous basalt and was weaker than the basalt in the Cheolwon area. Unlike the Pyoseon-ri basalt, the trachytic basalt showed characteristics similar to general basalt. In addition, compared to other basalts, its strength was very high and comparable to that of domestic granite in terms of compression and tensile strength [21,22]. Jang and Choi conducted quality tests such as aggregate stability, aggregate abrasion resistance, and aggregate crushability tests, as well as component analysis and strength evaluation to use Jeju Island basalt as a coarse aggregate for concrete. The compressive and tensile strengths of basalt from Jeju Island were higher than those of rocks from other regions, but basalt aggregates from some regions were found to not satisfy Korean standards [23]. Kim and Lee conducted a study to mix Jeju Island basalt stone sludge with cement and used it as a filler for modified and recycled asphalt mixtures and general asphalt mixtures. They concluded that it could be used as a filler for asphalt mixtures and derived the applicability and scope of use of Jeju Island basalt stone dust sludge [24].

As with previous research results, it can be seen that basalt from Jeju Island has various engineering properties. Therefore, systematic research is needed on the characteristics of basalt aggregate from Jeju Island and the asphalt mixtures using them as aggregate. Accordingly, this study aims to evaluate the suitability of Jeju Island basalt as an aggregate for asphalt road pavement by evaluating the mechanical properties of Jeju Island basalt aggregate and evaluating the basic properties and performance of asphalt mixtures using basalt aggregate.

1.2. Scope and Content

Basalt aggregate from Jeju Island may have different properties from general granite aggregate, so it is necessary to evaluate the basic aggregate properties for application in an asphalt mixture. In this study, the chemical composition and surface shape of basalt and granite aggregates were analyzed, and the engineering properties of basalt aggregate and filler were evaluated. The mix design was performed using Jeju Island basalt as the aggregate, and the basic properties of the mixture for the surface layer, the intermediate layer, and the base layer were evaluated. Additionally, this study evaluated the permanent deformation resistance through a wheel tracking test and moisture susceptibility evaluation through a dynamic immersion test (DIT) and a tensile strength ratio (TSR) test. Figure 1 shows the flowchart of the experimental overview for this study.

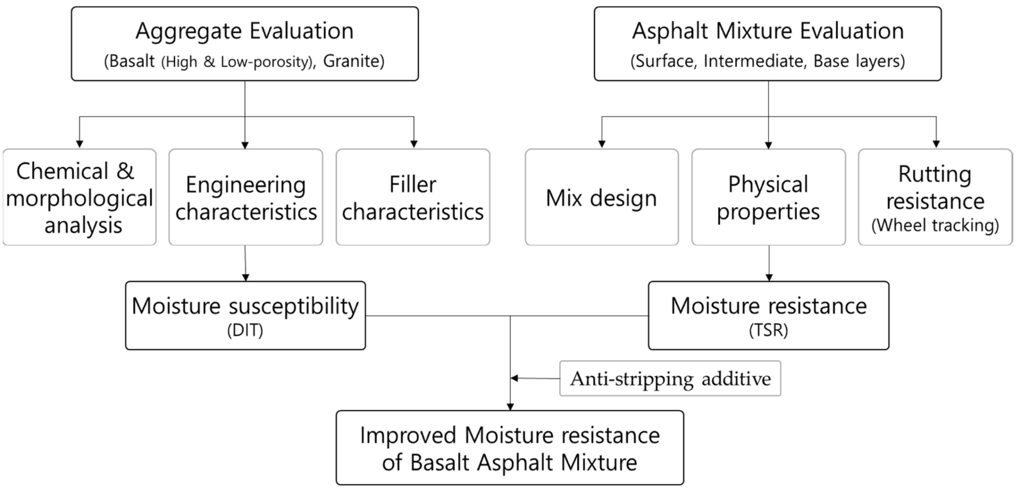


Figure 1. Flowchart of experimental overview.

2. Evaluation of Basalt Aggregates and Filler Characteristics

2.1. Chemical Composition and Surface Morphology Analysis of Basalt Aggregates

X-ray fluorescence (XRF) was used to compare the chemical composition of basalt and granite aggregates, and the relative content of the major crystalline elements was analyzed based on the intensity of the Ka rays of the metallic elements in each crystal. The samples for analysis were low-porosity basalt, high-porosity basalt, and granite, as shown in Figure 2. The comparison of the major components is presented in Table 1.


(a) (b) (c)

Figure 2. Types of aggregate: (**a**) low-porosity basalt; (**b**) high-porosity basalt; (**c**) granite.

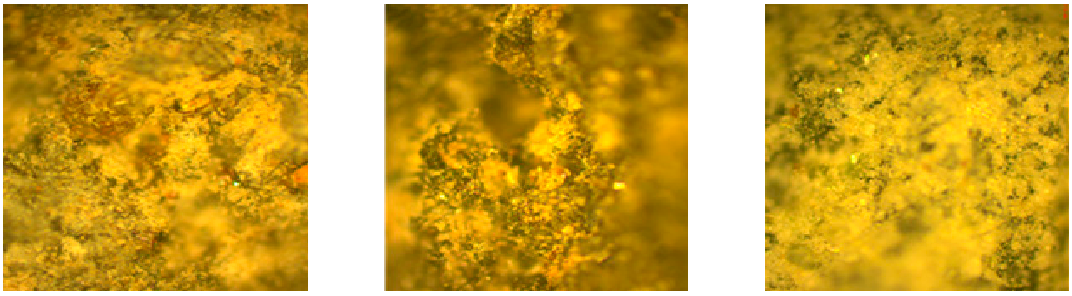
Table 1. Comparison of major components of aggregates.

Composition \ Aggregate Type	Low-Porosity Basalt (%)	High-Porosity Basalt (%)	Granite (%)
SiO_2	42.790	44.809	66.888
Fe_2O_3	18.547	19.707	3.706
Al_2O_3	15.649	16.431	15.705
CaO	12.357	11.839	3.990
TiO_2	3.279	3.198	0.522
MgO	2.842	1.964	0.690
BaO	-	-	0.565
K_2O	1.887	1.038	7.587
Na_2O	1.215	-	-
P_2O_5	0.832	0.593	-
MnO	0.275	0.275	0.056
SrO	0.213	0.146	0.156
ZrO_2	0.120	-	0.090
Rb_2O	-	-	0.045

The overall chemical compositions of low-porosity and high-porosity basalt aggregates were found to be very similar. The total alkali oxide content was measured to be about three times higher in the high-porosity basalt, with K_2O being about 1%, and for the low-porosity basalt, the sum of K_2O and Na_2O was about 3%. For the granite aggregate, the three major crystalline components were found to be approximately 67% SiO_2, 16% Al_2O_3, and 8% K_2O. On the other hand, the three major crystalline components were significantly different for the basalt aggregate, with approximately 45% SiO_2, 19% Fe_2O_3, and 16% Al_2O_3. In general, rocks with lower SiO_2 ratios and higher Fe content tend to have higher density. Thus, basalt aggregates may have a slightly higher density than granite aggregates. The main components of granite aggregates and basalt aggregates are clearly different, but the surface charges are not expected to be different due to this. However, there is a possibility of a difference in the magnitude of the surface charge.

To verify the difference in surface morphology, the real-size photo and 500× microscope photos were measured and analyzed. Figure 3 is three 500× microscope photos of high-porosity basalt, low-porosity basalt, and granite. As observed in the figure, when comparing granite and basalt, granite has a more uniform and dense crystalline structure, while basalt has a lower density crystalline structure with large and fine crystals mixed. High-porosity basalt has a much higher distribution of larger and smaller pores than low-porosity basalt.

Based on the comparison results of the chemical composition and the surface morphology of basalt and granite aggregates as aggregates for asphalt road pavement, the difference between granite and basalt is expected to be mainly in the resistance to gravity load due to the density of the crystalline material. In terms of adhesion to the asphalt binder, it is believed that the difference in contact area per unit volume due to hardness between crystals and pore distribution is more likely to be a variable than the difference in chemical composition.



(**a**) (**b**) (**c**)

Figure 3. Surface photos of basalt and granite (500×): (**a**) low-porosity basalt, (**b**) high-porosity basalt, and (**c**) granite.

2.2. Analysis of Engineering Characteristics of Basalt Aggregate

To analyze the engineering characteristics of low-porosity and high-porosity basalt aggregates, an analysis of the size of the aggregates obtained from the cold bin of an asphalt-mixture-producing plant on Jeju Island was performed, and the particle size analysis results by cold bin aggregate type are presented in Table 2. For the low-porosity basalt aggregate, both the 20 mm and 13 mm coarse aggregates exceeded the standard range. On the other hand, the 20 mm aggregate was found to be outside the standard range for the high-porosity basalt aggregate. The standard values presented in this study were applied as specified in the Asphalt Concrete Pavement Construction Guidelines of the Ministry of Land, Infrastructure, and Transport of South Korea [25].

Table 2. Particle size analysis of basalt aggregates.

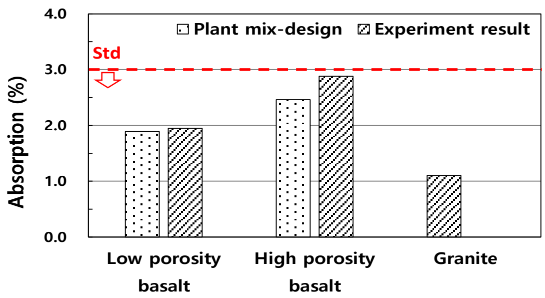
Cold Bin		Seive (mm)	Pass Rate (%)		
			Low-Porosity Basalt	High-Porosity Basalt	Standard
Coarse aggregates	40 mm	50	100	100	100
		40	93	98	90–100
		25	53	49	20–55
		20	2	2	0–15
		10	0	0	0–5
	20 mm	25	100	100	100
		20	100	100	90–100
		13	58	17	20–55
		10	28	2	0–15
		5	3	0	0–5
	13 mm	20	100	100	100
		13	100	97	90–100
		10	84	58	40–70
		5	23	1	0–15
		2.5	11	0	0–5
Fine aggregates		10	100	100	100
		5	90	96	80–100
		2.5	73	78	65–100
		1.2	56	63	40–80
		0.6	24	35	20–65
		0.3	15	25	7–40
		0.15	10	18	2–20
		0.08	0	5	0–10

The density and water absorption test results of low-porosity and high-porosity basalt aggregates are presented in Table 3, and both types of aggregate satisfied the standards. The density was relatively high due to the characteristics of basalt aggregates, and the absorption rate of high-porosity basalt aggregate was higher than that of low-porosity basalt aggregate in the case of coarse aggregate, and the absorption rate of low-porosity basalt aggregate was higher in the case of fine aggregate.

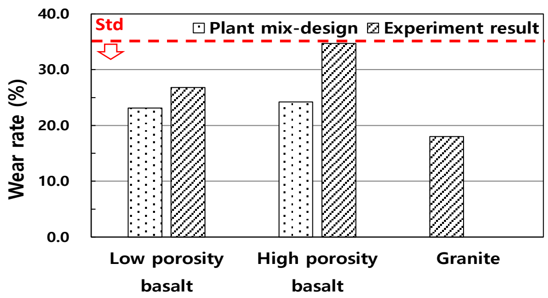
Table 3. Density and absorption test results of basalt aggregates.

Properties	Cold Bin	Low-Porosity Basalt	High-Porosity Basalt	Standard
Density in absolute dry state (g/cm^3)	40 mm	2.60	2.51	2.5 or higher
	20 mm	2.67	2.54	
	13 mm	2.67	2.58	
	Fine	2.69	2.72	
Absorption (%)	40 mm	2.03	2.37	3.0 or less
	20 mm	2.10	2.94	
	13 mm	1.95	2.88	
	Fine	2.90	1.98	

The aggregate abrasion test, flat and elongated aggregate ratio test, and aggregate stability test were conducted for both types of basalt aggregate, and both were found to meet the quality standards, as presented in Table 4. These experimental results were compared with the values presented in the mix design by the Jeju asphalt plant and were further compared with the values of general granite aggregates and are shown in Figure 4. Density and stability were found to be similar for basalt aggregate and granite aggregate, and the absorption rate and abrasion rate were found to be higher for basalt aggregate. In the case of basalt aggregate, there was a slight difference between the properties obtained through experiments and the properties provided by the Jeju asphalt plant due to the variability caused by irregular pores in the aggregate itself, and the difference was larger in high-porosity basalt than in low-quality basalt.



(**a**)



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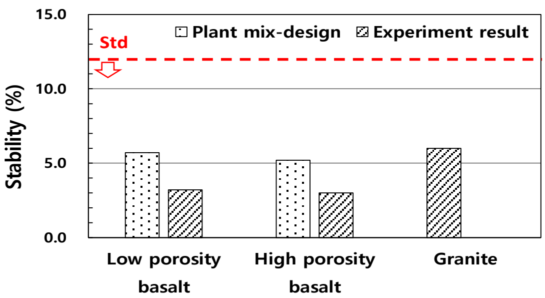
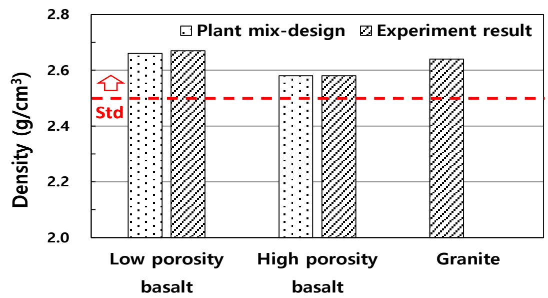


(**c**)



(**d**)

Figure 4. Comparison of engineering properties of basalt and granite aggregate (13 mm): (**a**) absorption, (**b**) abrasion rate, (**c**) stability, and (**d**) density.

Table 4. Aggregate test of basalt.

Properties	Cold Bin	Low-Porosity Basalt (%)	High-Porosity Basalt (%)	Standard
Abrasion rate	40 mm	30.2	39.4	40 or less
	20 mm	28.8	38.3	
	13 mm	26.8	34.7	35 or less
	Fine	-	-	
Flat and elongated aggregate ratio	40 mm	15.1	18.2	20 or less
	20 mm	9.4	11.2	
	13 mm	8.1	9.3	
	Fine	-	-	
Stability	40 mm	2.9	2.8	12 or less
	20 mm	3.1	3.7	
	13 mm	3.2	3.0	
	Fine	3.6	3.3	15 or less

2.3. Evaluation of Filler Characteristics

Fillers used for the asphalt mixture in Korea are typically limestone and baghouse fines generated during the production process of the asphalt concrete plant. Additionally, in areas with heavy rainfall, more than 50% of the weight of the filler can be replaced with hydrated lime or cement. On Jeju Island, filler mixed with baghouse fines based on basalt aggregate and cement is used. Therefore, filler tests were conducted on cement and baghouse fines from low-porosity basalt, as well as from high-porosity basalt. The baghouse fines were sampled from the asphalt plant that supplied basalt aggregates for this study. The mixing ratio of cement to baghouse dust was 6:4. The test results exhibited that all three types of fillers met the criteria defined in Korean standards for asphalt concrete mixtures [25], as presented in Table 5.

Table 5. Filler test result.

Properties	Cement + Baghouse Fines of Low-Porosity Basalt	Cement + Baghouse Fines of High-Porosity Basalt	Korean Standard
Moisture content (%)	0.338	0.375	1 or less
Specific gravity	2.909	2.923	-
PRV (percent of rigden voids)	42.57	42.16	-
Swelling test (%)	1.86	1.88	3 or less
Flow (%)	41.0	39.3	50 or less

3. Mix Design and Performance Evaluation of Basalt Asphalt Mixture

3.1. Mix Design of Basalt Asphalt

Aggregates were supplied for each cold bin from the asphalt plant on Jeju Island, and an asphalt mixture was produced in the laboratory according to the plant's mix design table to evaluate the physical properties. However, the combined gradation of the aggregate and the basic properties of the mixture were found to be highly variable, exceeding the standard values. Therefore, in this study, all aggregates for each cold bin were sieved and classified by particle size, and mix design was performed. Through this process, it was possible to minimize the error in the combined gradation of the aggregate and reduce the variability of the test results.

The asphalt mixture types for this study were selected as WC-2 for surface layer, MC-1 for intermediate layer, and BB-2 for base layer. The gradation of each mixture was selected as the central gradation of the standard range, and the final determined gradations are shown in Figure 5. The filler was used by mixing cement and baghouse fines in a ratio of

6:4. The PG 64-22 grade asphalt binder (AP-5 in penetration grade) supplied by domestic company G was applied to all mixtures.

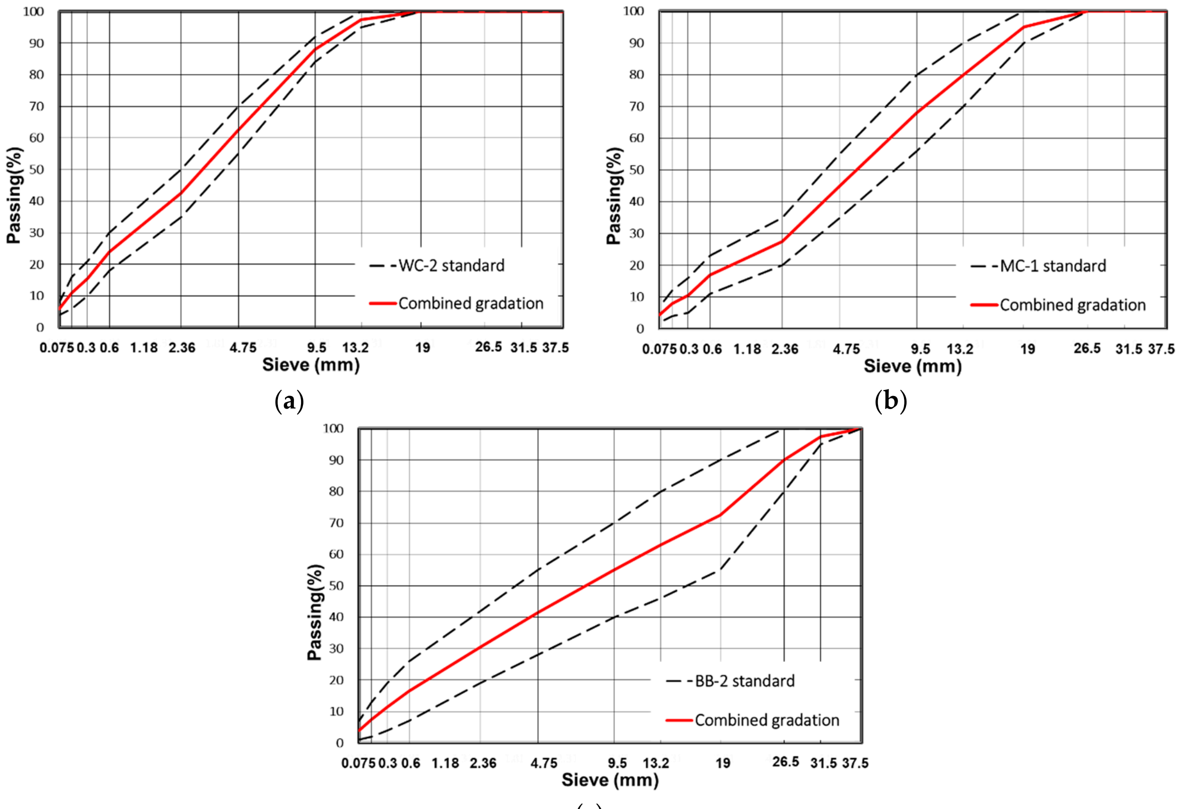


Figure 5. Combined gradations for (**a**) WC-2, (**b**) MC-1, and (**c**) BB-2.

When producing asphalt mixture specimens, the mixing temperature was set to 160 °C, and the compaction temperature was set to 150 °C. The number of compactions was 50 times on both sides of the specimen based on the standard procedure of the Marshall compaction equipment.

The optimal asphalt content was determined based on a target air void of 4.0% for the surface and intermediate layers and 5.0% for the base layer, within a range of 3.5% to 6.0% depending on the mixture type. Table 6 summarizes the mix design results. The optimum asphalt contents for the asphalt mixture using low-porosity and high-porosity basalt aggregates are as follows: for the surface layer, 5.7% and 5.9%, respectively; for the intermediate layer, 5.3% and 5.4%, respectively; and for the base layer, 4.7% and 5.1%, respectively. The optimum asphalt content for the asphalt mixture using high-porosity basalt aggregate was higher than that of low-porosity basalt aggregate. This is due to the high-porosity basalt aggregate having large and numerous pores, so the absorption rate of the aggregate is high.

3.2. Evaluation of Basic Properties

Using the previously determined mix proportions, the basic physical properties of WC-2 asphalt mixture for the surface layer, MC-1 asphalt mixture for the intermediate layer, and BB-2 asphalt mixture for the base layer were evaluated. The test methods and standards were based on the Ministry of Land, Infrastructure, and Transport's Guidelines for Asphalt Concrete Pavement Construction [25]. The Marshall stability and flow value were tested according to KS F 2337 [26], and the indirect tensile strength and toughness were tested according to KS F 2382 [27]. The physical properties of the mixtures for the surface, the intermediate, and the base layers using Jeju Island basalt aggregate were found to be satisfactory in all tests, as exhibited in Tables 7–9 and Figure 6. Note that three specimens were produced for each type of mixture and tested, and the average value is shown. The Marshall stability of the asphalt mixture using high-porosity basalt was higher than the mixture using low-porosity basalt in the Marshall stability test of the mixture for the surface and intermediate layers. This is because, although the aggregate tests showed that low-porosity basalt aggregates were generally superior to high-porosity basalt aggregate, it is difficult to conclude that asphalt mixtures with low-porosity basalt aggregates are superior to high-porosity basalt aggregates due to the addition of cement and differences in mix proportions, among other factors.

Table 6. Mix design test result using basalt aggregates.

Mixture Type	Properties	Low-Porosity Basalt	High-Porosity Basalt
Surface layer (WC-2)	Nominal maximum aggregate size (mm)	13	
	Theoretical maximum density (g/cm^3)	2.544	2.558
	Apparent density (g/cm^3)	2.437	2.452
	Air void (%)	4.2	4.1
	Asphalt content (%)	5.7	5.9
Intermediate layer (MC-1)	Nominal maximum aggregate size (mm)	20	
	Theoretical maximum density (g/cm^3)	2.547	2.520
	Apparent density (g/cm^3)	2.438	2.412
	Air void (%)	4.3	4.3
	Asphalt content (%)	5.3	5.4
Base layer (BB-2)	Nominal maximum aggregate size (mm)	30	
	Theoretical maximum density (g/cm^3)	2.567	2.501
	Apparent density (g/cm^3)	2.439	2.366
	Air void (%)	5.0	5.4
	Asphalt content (%)	4.7	5.1

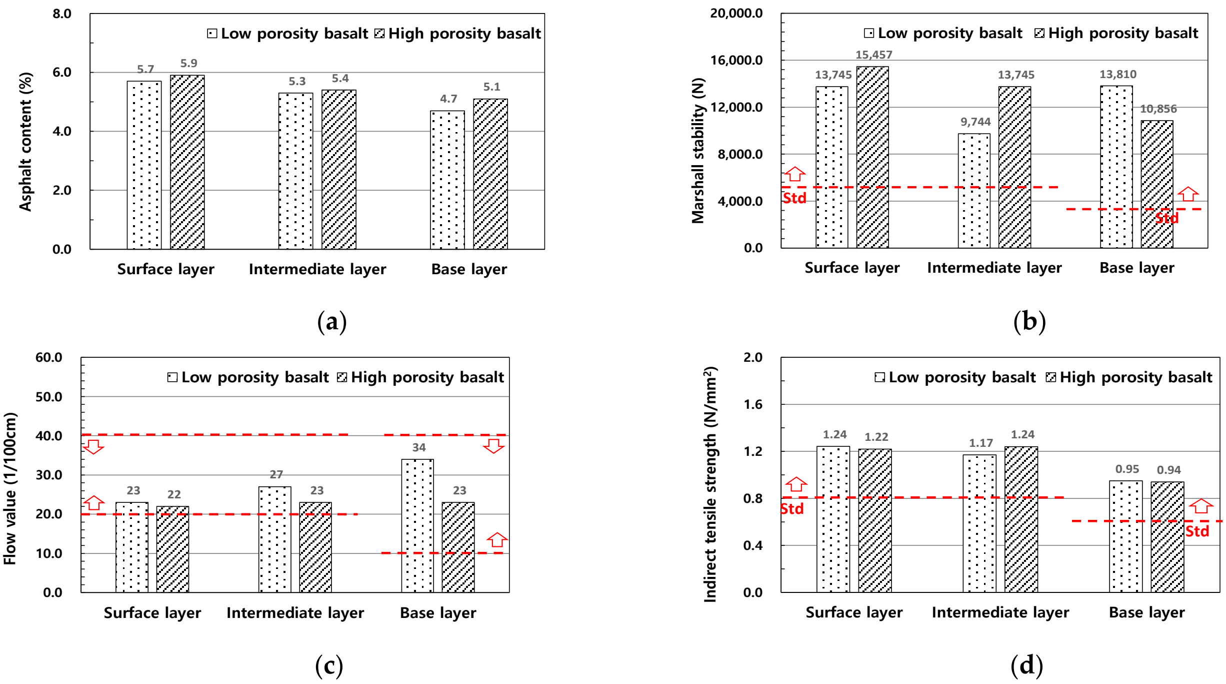


Figure 6. Comparisons of physical properties for basalt asphalt mixtures: (**a**) asphalt content, (**b**) Marshall stability, (**c**) flow value, and (**d**) indirect tensile strength.

Table 7. Physical properties of basalt asphalt mixture for surface layer (WC-2).

Properties	Low-Porosity Basalt	High-Porosity Basalt	Standard
Void filled with asphalt cement (%)	76	77	65~80
Void in mineral aggregate (%)	17.6	18.0	14 or higher
Marshall stability (N)	13,745	15,457	5000 or higher
Flow value (1/100 cm)	23	22	20~40
Indirect tensile strength (N/mm^2)	1.24	1.22	0.80 or higher
Toughness (N·mm)	14,626	12,456	8000 or higher

Table 8. Physical properties of basalt asphalt mixture for intermediate layer (MC-1).

Properties	Low-Porosity Basalt	High-Porosity Basalt	Standard
Void filled with asphalt cement (%)	74	75	65~80
Void in mineral aggregate (%)	16.8	17.1	14 or higher
Marshall stability (N)	9744	13,745	5000 or higher
Flow value (1/100 cm)	27	23	20~40
Indirect tensile strength (N/mm^2)	1.17	1.24	0.80 or higher
Toughness (N·mm)	13,596	14,626	8000 or higher

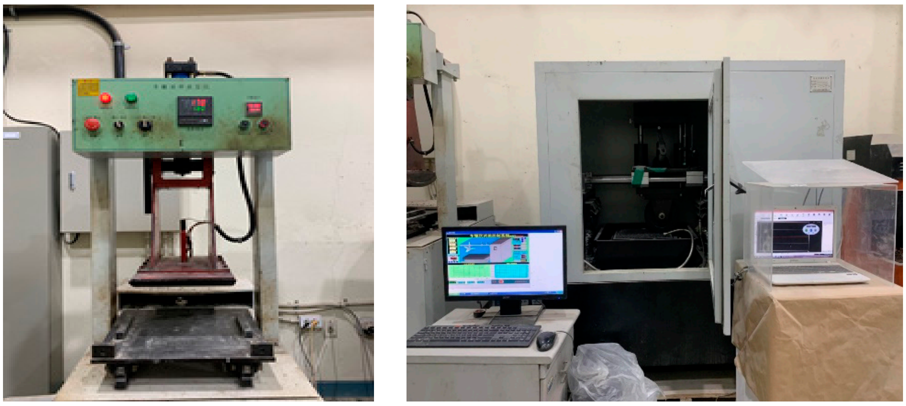
Table 9. Physical properties of basalt asphalt mixture for base layer (BB-2).

Properties	Low-Porosity Basalt	High-Porosity Basalt	Standard
Void filled with asphalt cement (%)	69	69	60~75
Void in mineral aggregate (%)	16.1	17.0	12.5 or higher
Marshall stability (N)	13,810	10,856	3500 or higher
Flow value (1/100 cm)	34	23	10~40
Indirect tensile strength (N/mm^2)	0.95	0.94	0.60 or higher
Toughness (N·mm)	12,973	10,513	6000 or higher

3.3. Evaluation of Permanent Deformation Resistance

A wheel tracking test was conducted to evaluate the resistance to permanent deformation of the Jeju Island basalt asphalt mixtures. This test was conducted on the basalt asphalt mixtures for the surface layer and intermediate layer for which the mix design was previously performed and was produced using low-porosity and high-porosity basalt aggregate, respectively.

The resistance to permanent deformation of the asphalt mixtures is evaluated using either the deformation strength criterion or the Marshall stability and flow value criteria. The previous experiment in Section 3.2 verified that the asphalt mixture meets the Marshall stability and flow value criteria. The wheel tracking test can more directly evaluate the resistance to permanent deformation of the asphalt mixture. The test was conducted according to KS F 2374 [28], a wheel tracking test method for asphalt mixtures, and the test specimens were prepared using the compaction equipment shown in Figure 7a. The test was conducted using the equipment shown in Figure 7b, and the total load was fixed at 686 N at a temperature of 60 ± 0.5 °C, and the contact pressure was maintained at 628 ± 15 kPa. Four mixtures were tested, and the test results are presented in Table 10. Note that two specimens were produced for each type of mixture and tested, and the average value is shown. The dynamic stability of asphalt mixtures using basalt aggregates is generally low. The asphalt mixture for the intermediate layer using low-porosity basalt aggregates is slightly below the Korean standard (750 cycles/mm). The low permanent deformation resistance of asphalt mixtures using basalt aggregate is believed to be due to the high asphalt content due to the high absorption rate of the aggregate and the high abrasion rate of the aggregate. Therefore, when using basalt aggregate, it is desirable to increase resistance to permanent deformation by applying a coarser combined gradation for the mixture.



(**a**) (**b**)

Figure 7. Wheel tracking test. (**a**) Specimen compaction equipment for wheel tracking, and (**b**) wheel tracking test equipment.

Table 10. Wheel tracking test results.

Mixture Type	Low-Porosity Basalt		High-Porosity Basalt		Standard
	Dynamic Stability (cycle/mm)	Rut Depth (mm)	Dynamic Stability (cycle/mm)	Rut Depth (mm)	
Surface layer	871	6.71	890	6.91	750 cycle/mm or more
Intermediate layer	679	5.36	1346	7.17	

4. Evaluation of Moisture Resistance of Basalt Asphalt Mixtures

4.1. Evaluation of Moisture Resistance

As Jeju Island has the characteristic of high precipitation, the road pavement on Jeju Island is expected to be more likely to experience moisture-induced damage; therefore, it is important to secure the moisture resistance performance of the pavement. To this end, a dynamic immersion test (DIT) was performed to evaluate the stripping resistance of basalt aggregate, and a tensile strength ratio (TSR) test was performed to evaluate the moisture resistance performance of the mixture using basalt aggregate.

The DIT was conducted to evaluate the stripping resistance of low-porosity and high-porosity basalt aggregates. DIT measures the rate at which the asphalt binder covering the aggregates peels off in water. According to the Korean standard, if the test result is below 50%, the aggregates are vulnerable to moisture damage; thus, an anti-stripping additive must be applied. Figure 8 shows the test equipment of DIT.

The condition of basalt aggregate after the DIT is shown in Figure 9. Figure 10 shows the test results comparing the results from the general granite aggregate. The test results show that the coverage rate after dynamic immersion of low-porosity basalt aggregate was 20%, and that of high-porosity basalt aggregate was 10%, which fall significantly below the quality standard of 50%. This is because the specific surface area of basalt aggregate is large due to the many pores, so the film thickness is thinner than that of granite aggregate in the DIT test using the same amount of asphalt binder. Therefore, the adhesion between the basalt aggregate and the asphalt binder was lowered, so the coverage rate was lower after DIT than that of granite aggregate. Based on the test results, when basalt aggregate is used in asphalt pavement, it is strongly recommended to use an anti-stripping additive.

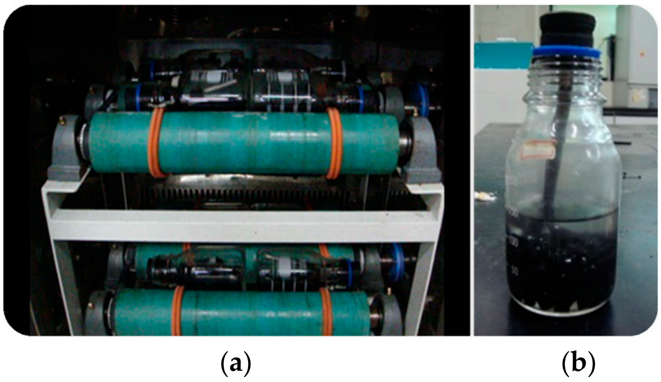


Figure 8. Dynamic immersion test (DIT): (**a**) test equipment; (**b**) sample in glass bottle with water.

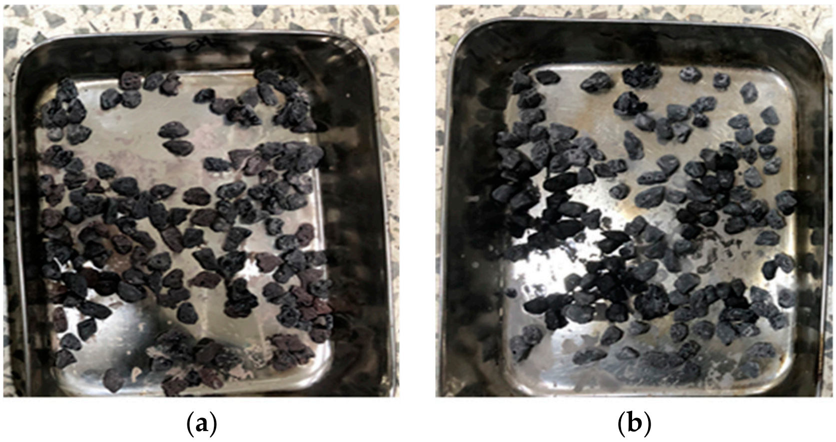


Figure 9. Condition of basalt aggregate after DIT test: (**a**) low-porosity basalt and (**b**) high-porosity basalt.

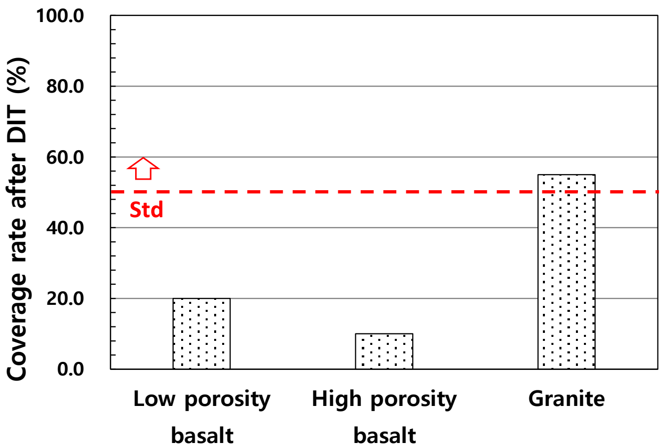


Figure 10. Results of DIT.

Based on the DIT result, it was necessary to evaluate the moisture resistance of the asphalt mixture using Jeju basalt aggregate. The moisture sensitivity of the basalt asphalt mixture was evaluated through the tensile strength ratio (TSR) test. As shown in Figure 11, the test method of KS F 2398 (test method for moisture resistance of asphalt mixture) was applied [29]. The same four types of asphalt mixtures as in the permanent deformation resistance evaluation were evaluated; the same mixing ratio was applied, and specimens with a porosity of 7 ± 0.5% were produced. The TSR test results of four types of basalt asphalt mixtures are shown in Table 11. Note that six specimens were produced for each mixture type. Three specimens were tested without moisture treatment, and the remaining three specimens were tested after moisture treatment, and the average values are presented. The asphalt mixture for the surface layer satisfied the quality standards, but the asphalt mixture for the intermediate layer did not meet the quality standards for both high-porosity and low-porosity aggregates. In particular, the tensile strength ratio of the asphalt mixture for the intermediate layer using porous aggregate was found to be 0.4, showing very low resistance to moisture.

(**a**) (**b**)

Figure 11. Tensile strength ratio test: (**a**) preparation of test specimens and (**b**) test equipment.

Table 11. Result of TSR test.

Mixture Type	Low-Porosity Basalt	High-Porosity Basalt	Standard
Surface layer	0.85	0.95	0.80 or higher
Intermediate layer	0.69	0.40	

This is the same trend as for the results of the coverage rate after the dynamic immersion test of the basalt aggregate. In the case of the mixture for the intermediate layer, the combined gradation of the aggregate is coarser, and the asphalt binder and filler contents are lower than those of the mixture for the surface layer, so it is believed that the characteristics of basalt aggregate, which has a low adhesion between the aggregate and the binder, are shown to be greater. Therefore, it is judged that the occurrence of potholes in Jeju Island's asphalt pavement is serious due to the insufficient moisture resistance performance of basalt aggregate and the high rainfall on Jeju Island.

4.2. Application of Anti-Stripping Additive to Basalt Asphalt Mixture

Delamination of the asphalt mixture occurs due to the weakening of the bond between the aggregate and the asphalt binder, deteriorating the performance of the asphalt pavement. In order to improve the service life of asphalt pavement, resistance to stripping of the asphalt mixture must be secured. In general, the materials used to achieve the anti-stripping effect of aggregates and asphalt binders include hydrated lime and liquid anti-stripping agents. Hydrated lime is used not only as a filler but also as an anti-stripping material for asphalt mixtures and has various effects such as reducing stripping, reducing aging, reducing permanent deformation, and increasing crack resistance [30–33]. In the United States, hydrated lime is mainly applied to prevent the stripping of asphalt mixtures, and the use ratio of hydrated lime in the United States is found to be a minimum of 0.7% and a maximum of 2.5% of the weight of total aggregate [34,35]. A liquid anti-stripping agent is a surfactant that acts to improve the bond between aggregate and asphalt binder. Since there are various types of liquid anti-stripping agents and their performance effects differ depending on the type of aggregate, the suitability of the anti-stripping material must be determined by performing a dynamic immersion test for the aggregate used. The dosage rate of the liquid anti-stripping agent is determined using the rate provided by the supplier and the DIR test results, and generally, 0.5% of asphalt binder is used [36,37].

Three types of aggregates (low-porosity basalt, high-porosity basalt, and granite) and five types of anti-stripping materials (hydrated lime, cement, and liquid anti-stripping agent S, N, and O products) were used in the DIT experiment. The usage ratios of the anti-stripping materials are as follows: liquid anti-stripping agents S and N are 0.5% of the asphalt content, and liquid anti-stripping agent O is 0.35% of the asphalt content. Additionally, cement and hydrated lime are each used at a rate of 1.5% of the aggregate weight. The test results are shown in Figure 12. The effects varied depending on the types of aggregate and anti-stripping material used. When liquid anti-stripping agent O was added, the coverage rate after DIT for low-porosity basalt increased from 20% to 60%. For high-porosity basalt, it increased from 10% to 50%, and for granite, it increased from 55% to 80%. It was observed that liquid anti-stripping agent O showed the most significant improvement, making it the most effective choice.

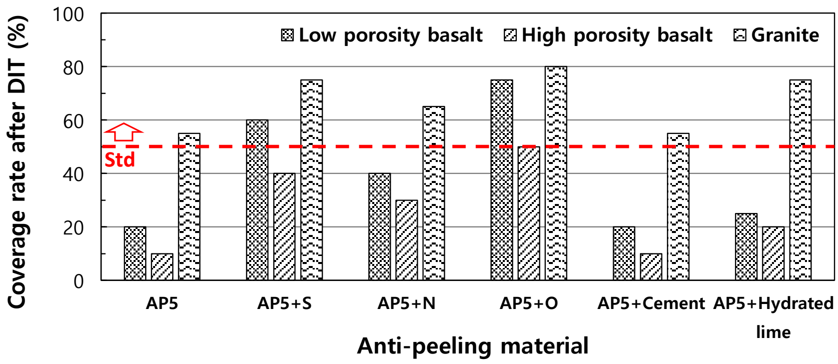


Figure 12. DIT results for each anti-stripping material.

A TSR test was conducted to verify the improvement of asphalt mixtures in moisture resistance performance. The test was conducted on the same four types of mixtures as the previous TSR test, and liquid anti-stripping agent O was used because its effect was superior in the DIT and satisfied the quality standard. As shown in Figures 13 and 14, the TSRs of all mixtures increased compared to those before the application of anti-stripping materials (Table 11). In particular, the basalt asphalt mixture for the intermediate layer showed a significant increase to a level that meets the quality standard.

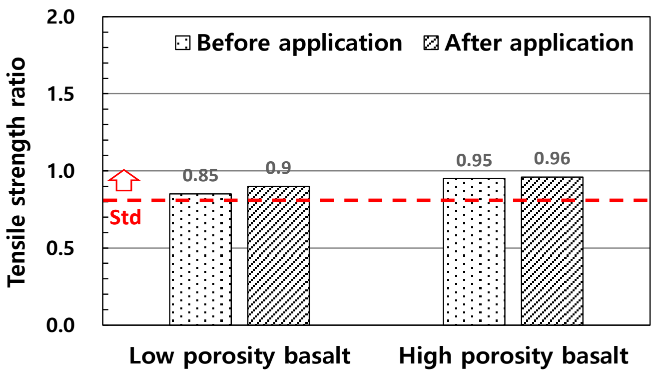


Figure 13. Tensile strength ratio according to application of anti-stripping agent (mixture for surface layer).

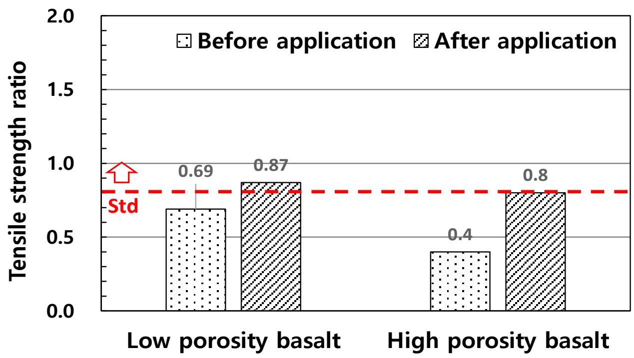


Figure 14. Tensile strength ratio according to application of anti-stripping agent (mixture for intermediate layer).

5. Conclusions

This study evaluated the suitability of basalt on Jeju Island as an asphalt road pavement aggregate by evaluating the engineering properties of basalt aggregate and the basic properties and performance of asphalt mixtures using basalt aggregate. The conclusions derived through this study are as follows.

1. A comparison was made between Jeju Island's basalt and the granite. As aggregates for asphalt road paving, they exhibited a large difference in the hardness of the crystalline structures and the contact area per unit volume due to pore distribution. Regarding quality, the abrasion rate, stability, and absorption rate of basalt were slightly lower than those of the granite, but basalt met the Korean quality standards.
2. The mix design of asphalt mixtures for the surface, intermediate, and base layers was performed using Jeju Island basalt aggregate. The optimum asphalt contents of the asphalt mixture using low-porosity basalt aggregate and high-porosity basalt aggregate were 5.7% and 5.9% for the surface layer, 5.3% and 5.4% for the intermediate layer, and 4.7% and 5.1% for the base layer, respectively, which were slightly higher than those of the typical asphalt mixture using granite aggregate.
3. The basic properties of the asphalt mixtures using basalt aggregate for the surface, the intermediate, and the base layers satisfied the quality standards. To evaluate the resistance to permanent deformation, a wheel tracking test was performed on asphalt mixtures for the surface layer and intermediate layer using low-porosity and high-porosity basalt aggregates. The test results indicated that the dynamic stability of the asphalt mixture using Jeju Island's basalt as the aggregate was lower than the typical granite asphalt mixture.
4. As a result of evaluating the stripping resistance of basalt aggregate through a coverage test after dynamic water immersion, it was found that the coverage rates of low-porosity basalt aggregate and high-porosity basalt aggregate were 20% and 10%, respectively, which fell far short of the quality standard of 50%. A tensile strength ratio test was performed to evaluate the moisture resistance performance of the mixture using basalt aggregate, and the tensile strength ratio of the asphalt mixture for the intermediate layer was found to be significantly below the quality standards. Therefore, the asphalt mixture using Jeju Island basalt aggregate appears to have low resistance to moisture damage and needs improvement.
5. To improve the lack of moisture resistance of Jeju Island basalt aggregate, an anti-stripping material was applied and evaluated. To select an appropriate anti-stripping material, DIT was performed using three types of aggregates (low-porosity basalt, high-porosity basalt, and granite) and five types of anti-stripping materials (hydrated lime, cement, and liquid anti-stripping agents S, N, and O products). As a result of the test, it was found that when liquid anti-stripping agent O was added, it showed the best effect and satisfied the quality standards. Additionally, a tensile strength ratio test was performed to determine whether the moisture resistance performance of the

asphalt mixture was improved. A test was conducted on two types of aggregates (low-porous basalt and high-porosity basalt) and two types of mixes (for surface layer and intermediate layer) with the addition of liquid anti-stripping agent O. As a result of the test, the tensile strength ratio of all mixtures increased, and in particular, the tensile strength ratio of basalt asphalt for intermediate layers, which did not meet the quality standards before adding anti-stripping agent, increased significantly to a level that satisfied the quality standards. Therefore, it is concluded that in order to apply Jeju Island basalt to asphalt pavement, an appropriate anti-stripping material must be applied.

Author Contributions: Conceptualization, C.B.; methodology, S.H and C.B.; validation, S.H and C.B.; formal analysis, S.H and C.B.; investigation, S.H and C.B.; resources, S.H and C.B.; data curation, S.H and C.B.; writing—original draft preparation, S.H.; writing—review and editing, C.B.; visualization, S.H.; supervision, C.B.; project administration, C.B.; funding acquisition, C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant No. 22POQW-B152342-01).

Data Availability Statement: The data presented in this study are available in article.

Conflicts of Interest: The authors declare no conflict of interest.

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