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Laboratory Investigation of the Water Damage Resistance of Tuff Asphalt Mixture Modified with Additives

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Abstract: To improve the water damage resistance performance of a tuff asphalt mixture, a tuff mixture with cement and a liquid anti-stripping agent was used as the research object, and limestone and tuff mixtures without additives were selected as contrast samples. Through an improved boiling test and a water stability test before and after aging, the modification effect of the tuff mixture with additives of different types and contents on water damage resistance was evaluated to obtain the appropriate type and content of additives. On this basis, the other road performance measures of the selected mixture were further evaluated by immersion rutting and beam bending tests to verify the modification effect of the additive on the tuff mixture. Results showed that adding the appropriate cement content to the tuff mixture provided excellent resistance to the water damage effect. An optimal content of 2% cement additive in the mixture was obtained, and its high-temperature anti-rutting and low-temperature bending performance were also verified. Adhesion between tuff aggregates and asphalt polymer under water conditions was significantly improved and close to that of limestone aggregates. The modification effect of water stability after mixture aging was better than that of the anti-stripping agent. The residual stability and freeze–thaw splitting strength ratio of 2% cement content mixture were increased by about 21.5% and 16.7%, respectively, compared with those of the tuff mixture control.

Keywords: Tuff asphalt mixture; water damage resistance; cement; anti-stripping agent; adhesion property

Citation: Zhang, X.; Zhang, Y.; Yang, H.; Lin, Q.; Tang, B. Laboratory Investigation of the Water Damage Resistance of Tuff Asphalt Mixture Modified with Additives. *Coatings* **2023**, *13*, 302. https://doi.org/10.3390/coatings13020302

Academic Editors: Valeria Vignali and Claudio Lantieri

Received: 6 December 2022
Revised: 10 January 2023
Accepted: 20 January 2023
Published: 29 January 2023

1. Introduction

Asphalt pavements exhibit many advantages over other pavements, such as low noise, low vibration, comfortable driving, and early opening traffic; it plays an important role in road construction. The aggregates used for asphalt pavements are typically alkaline or neutral high-quality stones, such as limestone and basalt. However, the resources for these building stones are becoming increasing low and will no longer meet long-term needs; consequently, their price is continuously increasing [1,2]. By contrast, acidic aggregates are widely distributed in China and they are easily obtained locally; hence, their cost is relatively low. In particular, a large amount of acidic stones are found in the tunnels of road engineering construction. If these stones can be used effectively, then they will play a role in environmental protection and economic effectiveness. Similar to granite [3], volcanic tuff is a type of acidic stone that is widely distributed in the Zhejiang and Fujian Provinces of China. When used as a building material, tuff exhibits important development value.

Many researchers have conducted research on the feasibility of using volcanic tuff as aggregates in building materials. Kan et al. [4] studied the characteristics of volcanic tuff sand and evaluated its suitability for use in cement mortar. Their results showed that tuff sand improved cement mortar adhesion and durability. Kilic et al. [5] determined how volcanic tuff aggregates affect the unit weight and strength of cement concrete. They found that unit weight and strength decreased as the tuff aggregate content of cement concrete increased. Al-Zboon et al. [6] investigated the effect of Jordanian volcanic tuff on the characteristics of cement mortar. They prepared five mortar specimens by replacing normal aggregates with tuff aggregates in ratios of 0%, 25%, 50%, 75%, and 100%. Then, compressive strength, flexural strength, and unit weight were tested at mortar ages of different days. The results revealed that compressive and flexural strengths were maximal at 50% tuff aggregate ratio, and unit weight decreased as the ratio of tuff increased. Adding volcanic tuff in the appropriate ratio can improve mortar performance.

However, in contrast with the good performance of tuff aggregates in cement concrete, tuff as acidic aggregates used in the mixture of the asphalt pavement layer of high-grade highways is prone to peeling between the aggregates and the asphalt binder after water action, resulting in poor water stability of the asphalt mixture [7–10]. Therefore, tuff is frequently used for the pavement base or cushion layer in road engineering, and only a few studies have been conducted on the performance and application of tuff acidic aggregates in the mixture used for the asphalt pavement layer of high-grade highways [11–13]. For instance, Sun et al. [11] researched the feasibility of the tuff stone widely distributed along the highway in Algeria as the cushion layer material of pavement through the indoor test and field test section, and the results showed that a certain amount of cement was added into the tuff to obtain better road use effect. Goual et al. [12] optimized the composition of a mixture of tuff-limestone sand by compressive strength and saturated drained triaxial tests, and then studied the influence of cement contents on the mechanical characteristics of the optimized mixture. The experimental results indicated the importance of the treatment process with cement, which was necessary in order to mitigate the problems of instability in a wet medium, and showed the possibility of the use of local materials containing tuff and lime sand for the design of pavements in Algeria. Zhang et al. [13] studied the road performances of a tuff asphalt mixture with a liquid anti-stripping agent by laboratory tests, and the results showed that the anti-stripping agent can improve the water stability, high temperature performance, and low temperature performance of the tuff asphalt mixture; however, the adhesion durability of the mixture needs to be further investigated. Yang et al. [7] compared the performance of a tuff asphalt mixture composed of different lithological aggregates and asphalt materials using the water stability test, high and low temperature performance tests. The results indicated that, except for the low-grade asphalt mixture, the performances of the other tuff asphalt mixtures can meet the requirements of the specification, but the adhesion between the tuff and asphalt needs further study.

Furthermore, relative to typical acidic granite, the properties of the asphalt mixture after modified treatment have achieved good results, as reported locally and abroad [14–17]. For example, Birgisson et al. [18] developed a scheme of adding an anti-stripping agent to a granite aggregate asphalt mixture to solve the problem of insufficient water stability. An energy rate index was also proposed to evaluate water damage and the improvement effect of the additive on adhesion for the granite mixture. Kong et al. [19] compared the results of granite and limestone under different warm mixing conditions through an asphalt surface free energy test and a splitting strength test. They found that compared with limestone, the adhesion between granite and warm mixing asphalt was greater, but the splitting strength of the granite asphalt mixture was lower. Liu et al. [20] first determined the optimal content of an anti-stripping agent through an adhesion test and then investigated the road performance of a granite asphalt mixture. Their results showed that the anti-stripping agent can better improve the water stability of the granite mixture. Zou et al. [21] added different cement contents to a granite asphalt mixture. They studied the physical and mechanical properties of the asphalt mixture through water stability, tensile, and indoor compression tests, demonstrating that the increase in cement content can considerably improve the properties of the mixture. Therefore, improving the peel resistance and durability of acidic aggregate asphalt mixtures affected by a water environment is a major concern.

The adhesion problem between acidic aggregates and the asphalt binder under the action of water can easily lead to insufficient water stability and durability of the asphalt mixture. The present study aims to select a typical grade asphalt mixture SUP25 for high-grade highway pavements and compare the effects of different additive contents and types (including cement and anti-stripping agent) on water damage resistance, referring to the above-mentioned modified asphalt mixing methods. It also considers the durability of the tuff asphalt mixture after long-term aging to evaluate the water stability of the tuff asphalt mixture. Finally, this study determines the appropriate additive scheme for the performance improvement of tuff asphalt mixture.

2. Raw Materials

2.1. Asphalt

The asphalt polymer used in this study was 70# base asphalt, which was obtained from the Asphalt Technology Branch of Zhejiang Transportation Resources Investment Co., Ltd. (Hangzhou, China). The test results of various base asphalt indexes are provided in Table 1, indicating that the selected asphalt met the requirements of the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [22].

Table 1. Technical indexes of base asphalt.

<table>
<tr><th colspan="2">Indexes</th><th>Technical Requirements</th><th>Test Results</th><th>Test Methods</th></tr>
<tr><td colspan="2">Penetration (25 °C, 100 g, 5 s), 0.1 mm</td><td>60–80</td><td>68</td><td>T0604</td></tr>
<tr><td colspan="2">Penetration index (PI)</td><td>−1.5 to +1.0</td><td>−0.6</td><td>T0604</td></tr>
<tr><td colspan="2">Ductility (5 cm/min, 10 °C), cm</td><td>≥20</td><td>32</td><td>T0605</td></tr>
<tr><td colspan="2">Softening point (ring-and-ball method), °C</td><td>≥46</td><td>47.5</td><td>T0606</td></tr>
<tr><td colspan="2">Dynamic viscosity (60 °C), Pa.s</td><td>≥160</td><td>180</td><td>T0620</td></tr>
<tr><td colspan="2">Wax content (distillation method), %</td><td>2.2</td><td>2.0</td><td>T0615</td></tr>
<tr><td colspan="2">Density (15 °C), g/cm^3</td><td>-</td><td>1.01</td><td>T0603</td></tr>
<tr><td colspan="2">Solubility (trichloroethylene), %</td><td>≥99.9</td><td>99.9</td><td>T0607</td></tr>
<tr><td rowspan="3">TFOT after 163 °C and 5 h</td><td>Mass loss, %</td><td>≤0.8</td><td>0.6</td><td>T0609</td></tr>
<tr><td>Penetration ratio after heating, %</td><td>≥61</td><td>65</td><td rowspan="2">T0610</td></tr>
<tr><td>Ductility (10 °C), cm</td><td>≥6</td><td>8</td></tr>
</table>

2.2. Additives

Cement was used as an additive of a tuff asphalt mixture, particularly common Portland cement P.O42.5 produced by the Jiangshan South Cement Company Co., Ltd. (Jiangshan, China). Its density was 3.05 g/cm^3. The test indicators were in line with the specifications for the common Portland cement (GB175-2007) [23], as indicated in Table 2.

Table 2. Technical indexes of cement.

Indexes	Results	Technical Requirements
Specific area, m^2/kg	344	≥300
Soundness, mm	1.0	≤5
Flexural strength at 28 days, MPa	8.7	≥6.5
Compressive strength at 28 days, MPa	52.1	≥42.5

In addition, an XT-2 liquid anti-stripping agent was also selected as the additive of the cement contrast scheme. It was manufactured by Changzhou Xintuo Pavement Modification Material Co., Ltd. (Changzhou, China). XT-2 was a non-amine active agent with a dark viscous liquid. Its relative density was 1.0, and its failure temperature was greater than 260 °C.

2.3. Mineral Materials

Tuff and normal limestone were selected as aggregates in the asphalt mixture for the comparative study. The filler used was limestone powder. The coarse and fine aggregates in the tuff asphalt mixture were produced from the tunnel stone of the Zhejiang Wentai Expressway Project. The tuff aggregates are shown in Figure 1. Furthermore, the chemical composition of the selected tuff aggregates obtained using an X-ray diffractometer is provided in Table 3. It indicated that the weight ratio of SiO_2 was more than 65% in the three groups of aggregates. Thus, the tuff aggregates were typical acidic stone. Meanwhile, the basic characteristics of the selected two types of aggregates are listed in Table 4, and they meet the requirements of the regulations [24,25].

Figure 1. Tuff aggregates.

Table 3. Chemical composition of tuff aggregates.

Component		SiO_2	Al_2O_3	K_2O	Fe_2O_3	MgO	CaO	Na_2O
Weight ratio/%	Group 1	75.62	15.33	4.64	2.31	1.19	0.37	0.16
	Group 2	71.58	16.68	5.35	3.27	1.95	0.49	0.28
	Group 3	78.32	12.62	4.11	2.45	1.52	0.36	0.22

Table 4. Basic characteristics of aggregates.

Indexes		Tuff	Limestone	Technical Requirements
Coarse aggregates	Crushed value/%	15.5	23.1	≤28
	Flat particle content/%	8.5	7.0	≤18
	Los Angeles abrasion/%	15.9	14.2	≤30
	Ruggedness/%	2	5	≤12
Fine aggregates	Sand equivalent/%	80	74	≥60
	Angularity/%	51.2	45.6	≥30
	Methylene blue value/$(g \cdot kg^{-1})$	2.0	3.6	≤25
	Silt content (less than 0.075 mm particles)/%	2.6	2.5	≤3

2.4. Mix Design of Asphalt Mixtures

SUP25 gradation used in the lower asphalt course of pavements was adopted in the current study. The respective aggregate curves of tuff and limestone mixtures are shown in Figure 2.

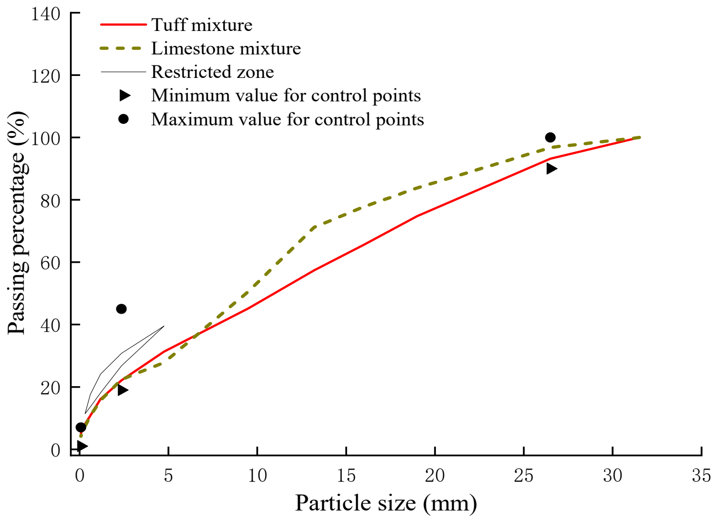


Figure 2. Gradation curves of two SUP25 asphalt mixtures.

After the design gradation was determined, the initial asphalt content P_b of the tuff and limestone mixtures was 4.1% and 3.8%, respectively, in accordance with engineering experience. Four groups of asphalt contents, namely, P_b, P_b-0.5%, P_b + 0.5%, and P_b + 1%, were selected for each asphalt mixture to determine the optimum asphalt content. Meanwhile, five Marshall samples were formed using a gyratory compactor for each asphalt content. The thickness of a sample was 63.5 mm ± 1.3 mm. The forming process was referred to the specifications provided in [22]. The prepared samples were cooled for 24 h at room temperature; the volume parameters were measured and calculated [26], as indicated in Table 5.

Table 5. Volume parameters of SUP25 asphalt mixtures with different asphalt contents.

Asphalt Content/%	Tuff Asphalt Mixture				Limestone Asphalt Mixture			
	3.6%	**4.1%**	**4.6%**	**5.1%**	**3.3%**	**3.8%**	**4.3%**	**4.8%**
Theoretical maximum specific gravity	2.484	2.472	2.450	2.432	2.564	2.545	2.534	2.511
Bulk specific gravity	2.354	2.373	2.379	2.366	2.426	2.443	2.455	2.456
Percent air void/%	5.2	4.0	2.9	2.7	5.4	4.0	3.1	2.2
Percent voids in mineral aggregates/%	12.3	12.0	12.2	12.5	12.7	12.4	12.5	12.9
Saturability/%	57.1	66.7	76.2	78.7	57.2	68.1	75.1	83.3
Filler binder ratio	1.41	1.24	1.10	1.00	1.27	1.11	0.98	0.88

In accordance with the results provided in Table 5, the asphalt content of the tuff and limestone mixtures was 4.1% and 3.8%, respectively, when the designed target percent air void was 4.0%. Meanwhile, the corresponding asphalt–stone ratio was 4.3% and 4.0%, respectively.

After completing the mix design of the asphalt mixtures, the schemes for the additives, including cement and anti-stripping agent, in the tuff asphalt mixture, can be determined. In particular, the proportion of cement was consistent with the amount to be replaced by the filler in asphalt mixtures. That is, the cement content was mixed by 0%, 1%, 2%, and 3% in mineral material weight. An anti-stripping agent was added to the asphalt in accordance with the mass fractions of 3% and 6% in base asphalt weight. In addition, limestone asphalt mixture contained no additives.

3. Test Methods

3.1. Adhesion Test

In this study, an adhesion test was performed to observe the peeling degree of the asphalt film adhering to the aggregate surface under a water environment at a certain temperature, to determine the adhesion grade of aggregates to the asphalt polymer, and to evaluate the asphalt mixture's resistance to water damage. Referring to an existing boiling test [22], a modified boiling test was conducted on the aggregate samples after adding additives to the asphalt mixture. The specific steps of the test were as follows.

(1) In accordance with the mix design of the asphalt mixture, the coarse and fine aggregates were first weighed and then placed in an oven to dry. Meanwhile, the cement and mineral powder were dried by placing them in an oven at 160 °C for 1 h to ensure the mixing temperature.

(2) The coarse and fine aggregates were stirred in a mixing pot. If a liquid anti-stripping agent was used, then it should be mixed thoroughly with the base asphalt. If the cement additive was used, then it should be added with the filler in the mixing pot after the base asphalt was mixed with the aggregates.

(3) The coarse aggregate coated with asphalt polymer was selected from the evenly mixed asphalt mixture. Its particle shape was close to that of a cube, and five group aggregate samples were used in each additive content. Then, the coarse aggregate samples were fastened one by one with a thin wire and placed in a curing oven at 105 °C ± 5 °C for 1 h.

(4) A large beaker filled with water was placed on an asbestos net to bring water to a boil. Then, the coarse aggregate samples were removed from the curing oven, suspended on the test rack, and cooled for 15 min at room temperature.

(5) After the aggregate samples were cooled, they were lifted one by one with a thin line and immersed in the center of a large beaker filled with boiling water. The heating furnace was adjusted such that the water in the beaker remained slightly boiling.

(6) The aggregate samples were removed from the boiling water after soaking for 3 min. Then, they were placed in a container with room temperature water after proper cooling to observe the peeling degree of asphalt film on the surface of the aggregates.

The major advantage of the modified adhesion test is that it can more truly reflect the adhesion state of aggregates coated with asphalt film in an asphalt mixture modified with additives. However, accurately grasping the operation process is still difficult; that is, the adhesion grade evaluation scale is not easy to judge accurately. Therefore, five aggregate samples in parallel testing were selected to determine the stripping rate between the asphalt film and the aggregates. The average value was regarded as the test evaluation result under each additive content. The evaluation standard of the adhesion grade for aggregates is provided in Table 6.

Table 6. Evaluation standard of adhesion grade [22].

Asphalt Stripping Degree	Adhesion Grade
Asphalt film is completely preserved, and stripping area percentage is close to 0.	5
A small amount of asphalt film is stripped, and stripping area percentage is less than 10%.	4
Asphalt film is partially stripped, and stripping area percentage is less than 30%.	3
Asphalt film mostly falls off, and stripping area percentage is more than 30%.	2
Asphalt film is completely removed, the aggregate is basically bare, and asphalt floats on the water surface.	1

3.2. Water Stability and Aging Tests

To evaluate the effect of water stability for a tuff asphalt mixture with different additives, its water damage resistance and durability were examined through water stability tests, including immersion Marshall and freeze–thaw splitting tests before and after aging. The major processes of the tests were referred to the specifications [22]. In addition, four parallel tests were conducted for each sample.

(1) Key indicator of water stability

Through the Marshall test before and after immersion, the residual stability MS_0(%) of the asphalt mixture that reflects the performance indicator for water damage resistance can be calculated as follows:

$$MS_0 = (MS_1/MS) \times 100 \tag{1}$$

where MS_1 is the stability of the Marshall samples after being immersed in water for 48 h, kN; and MS is the stability of the samples before immersion, kN.

Similarly, the freeze–thaw splitting strength ratio TSR (%) can be calculated through the splitting strength test before and after the freeze–thaw cycles as follows:

$$TSR = (\overline{R_1}/\overline{R_2}) \times 100 \tag{2}$$

where $\overline{R_1}$ is the average splitting tensile strength of specimens after the freeze–thaw cycles, MPa; and $\overline{R_2}$ is the average splitting tensile strength without freeze–thaw cycles, MPa.

(2) Aging test

1) After conducting the immersion Marshall test and freeze–thaw splitting test, the aging effect of the asphalt mixture was considered to evaluate the durability of the mixture for water damage resistance. In this study, a long-term aging test was conducted in two steps [27].
2) After tuff mixtures with different additive schemes were mixed, the mixtures were introduced into the tray and tiled. Then, they were placed in an oven at 135 °C for 4 h to implement short-term aging, as shown in Figure 3a.

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

Figure 3. Aging test of asphalt mixtures. (**a**) Short-term aging treatment; (**b**) Long-term aging treatment.

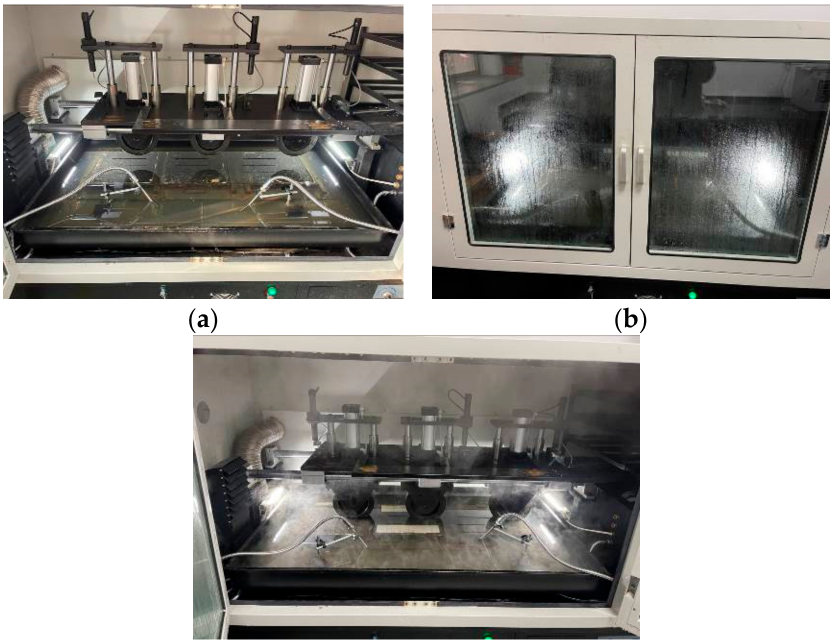
After the short-term aging of the mixture, Marshall samples were formed and cooled. Then, the mold was removed, and the samples were placed in an oven at 85 °C and kept for 5 days under ventilated conditions. Finally, the oven door was opened for natural cooling for 16 h to complete the test simulation process of long-term aging, as shown in Figure 3b.

3.3. High- and Low-Temperature Performance Tests

After the evaluation of water damage resistance, to further verify the suitable additive modification effect of tuff asphalt mixture, this study evaluated the high and low temperature road performance of the tuff mixture with additives by using the immersion rutting and beam bending tests. Three parallel tests were conducted for each sample.

(1) Immersion rutting test

The rutting test is commonly used to evaluate the high-temperature performance of asphalt mixtures; however, only a few related tests are available for considering the water immersion condition. Related tests were conducted to evaluate the road performance of the modified tuff mixture more comprehensively. Referring to the rutting test process of the specification [22], the samples were preheated first and then placed in the rutting loading instrument and soaked in water. Subsequently, the samples were kept in a high-temperature environment at 60 °C for 4 h before loading. The process is illustrated in Figure 4.



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

(**c**)

Figure 4. Loading process of immersion rutting samples at high temperature. (**a**) Soaking; (**b**) Heating and insulation; (**c**) Loading.

Deformation that corresponds to different loading times can be obtained through the rutting test. The dynamic stability (DS) (times/mm) of the asphalt mixture was obtained as follows:

$$DS = 42 \times (t_2 - t_1)/(d_2 - d_1) \tag{3}$$

where t_2 is set as 60 min, d_2 is the deformation of time t_2 (mm), t_1 is 45 min, and d_1 is the deformation of time t_1 (mm).

(2) Beam bending test

The beam bending test is used to evaluate the low-temperature performance of tuff asphalt mixtures with additives; the test primarily refers to the regulations [22]. The size of the bending beam sample was set as 250 mm (length) × 30 mm (width) × 35 mm (height), as shown in Figure 5. After the preloading treatment of the beam samples, three-point bending loading was implemented at a low temperature of −10 °C, as shown in Figure 6, where the distance between the sample supports was 200 mm.

Figure 5. Bending beam samples.

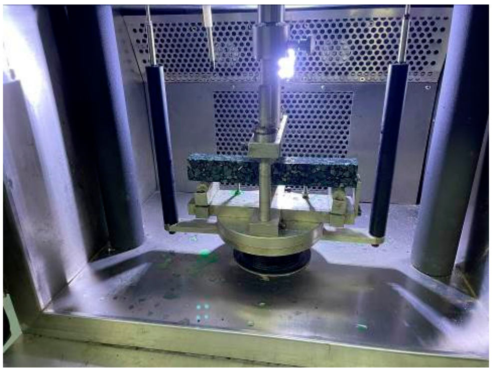


Figure 6. Loading of the beam sample at low temperature.

For the beam bending test, the flexural tensile strength R_B (MPa) of the beam sample at failure, the corresponding maximum flexural strain ε_B at the bottom of the beam, and the flexural stiffness modulus S_B (MPa) can be calculated and obtained. The specific formulas are as follows:

$$R_B = 3 \times L \times P_B/(2 \times b \times h^2) \tag{4}$$

$$\varepsilon_B = 3 \times h \times d/L^2, \tag{5}$$

$$S_B = R_B/\varepsilon_B, \tag{6}$$

where P_B is the maximum load of a sample at failure, N; L is the span of a sample, mm; b is the midspan section width of a sample, mm; h is the midspan section height of a sample, mm; and d is the midspan deflection of a sample at failure, mm.

4. Results and Discussion

4.1. Effect of Different Additives on Adhesion Property

The adhesion property of tuff aggregate samples modified additives with different contents and types were evaluated through the boiling test. The typical results of different aggregate samples are presented in Figure 7, where (a) and (d) are tuff and limestone aggregate samples without additives, (b) and (e) are tuff aggregates with 1% and 2% cement contents, and (c) and (f) are tuff aggregates with 0.3% and 0.6% anti-stripping agent contents, respectively.

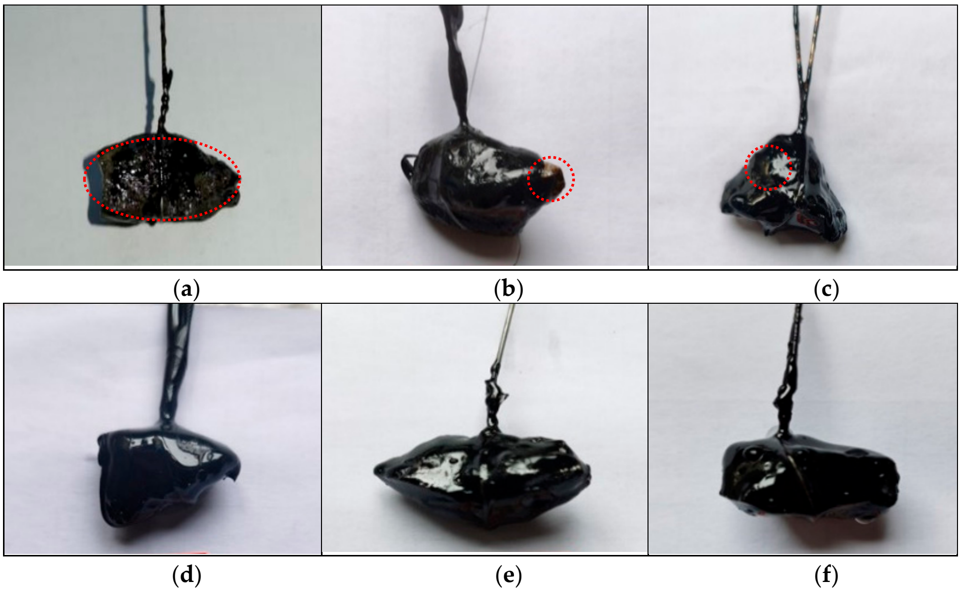


Figure 7. Typical results of the boiling test. (**a**,**d**) are tuff and limestone aggregate samples without additives, (**b**,**e**) are tuff aggregates with 1% and 2% cement contents, and (**c**,**f**) are tuff aggregates with 0.3% and 0.6% anti-stripping agent contents, respectively. The red dashed circle represented the presence of flaking asphalt in the coarse aggregate.

In accordance with the boiling test results, Figure 7 shows that compared with the integrity of the asphalt film in the limestone aggregate sample, the tuff aggregate sample without additives exhibited an evident phenomenon of asphalt film peeling after water boiling, and thus, the adhesion property of tuff aggregates was poor. The results also indicated that the asphalt film peeling area of the tuff aggregates was reduced after combining additives, but additive content exerted an important influence on the improvement effect. To clearly show the adhesion of tuff aggregate samples under different additive schemes, the mean values of adhesion grade are provided in Table 7, where limestone and tuff represent the corresponding aggregate samples without additives.

Table 7. Adhesion grade of aggregate samples with different additives.

Types	Limestone	Tuff	Tuff with Different Cement Contents			Tuff with Different Anti-Stripping Agent Contents		
			1%	2%	3%	0.3%	0.6%	0.9%
Grade	5	2	3	5	5	3	5	5

As indicated in Table 7, the adhesion grades between tuff aggregate and limestone aggregate samples without additives presented an evident gap. Meanwhile, the modification effect of additives on the tuff aggregate samples was different. For example, the adhesion grades of adding 1% cement and 0.3% anti-stripping agent samples were both 3, indicating that the improvement effect was insignificant. Meanwhile, the results of other higher additive contents were close to that of the limestone aggregate sample, and the improvement effect of the adhesion property was good. Therefore, tuff samples with additives, including 2% and 3% cement contents and 0.6% and 0.9% anti-stripping agent contents, were selected to evaluate the performance of water damage resistance further.

4.2. Effect of Different Additives on Water Stability

To better evaluate the water damage resistance performance of tuff asphalt mixtures modified with different additives, water stability tests of asphalt mixtures, including the immersing Marshall test and the freeze–thaw splitting test, were conducted. For the selection of asphalt mixture types, tuff mixtures modified with additives for adhesion grade 5 were adopted, including 2% and 3% cement contents and 0.6% and 0.9% liquid anti-stripping agent contents. Tuff and limestone mixtures modified without additives were considered to be the control.

The results of the water stability tests are presented in Figures 8 and 9, where L and T represent limestone and tuff mixture control, and 2%C and 3%C denote tuff mixtures with an additive of 2% and 3% cement contents, while 0.6%A and 0.9%A signify tuff mixtures with an additive of 0.6% and 0.9% anti-stripping agent contents. The error of the test results was controlled within 10%.

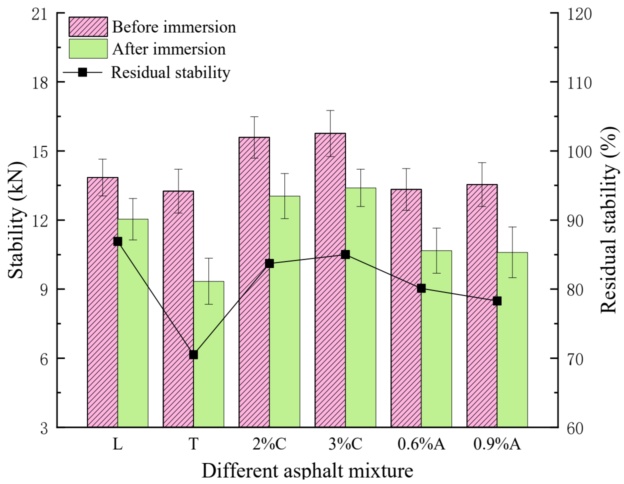


Figure 8. Results of the immersion Marshall test.

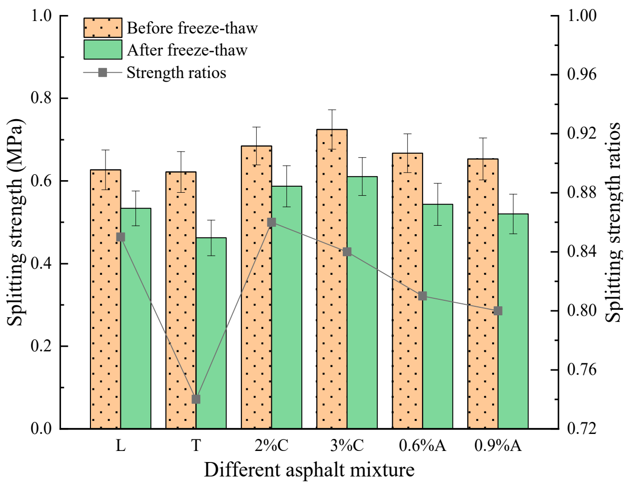


Figure 9. Results of the freeze–thaw splitting tests.

On the basis of the results obtained by the immersion Marshall test, Figure 8 shows that the stability indexes of tuff mixtures modified with cement before immersion were higher than those of the limestone mixture. Moreover, the indexes of the other mixtures were not considerably different, but they were all slightly smaller than that of the limestone mixture. Meanwhile, after being submerged for 48 h, the stability of all the mixture samples was decreased, but the reduction degrees presented significant differences. The tuff control sample was the greatest, and the corresponding residual stability was 70.5%. The tuff mixture with an anti-stripping agent was the second, and the corresponding residual stability was 80.1% and 78.3% after adding 0.6% and 0.9% additives, which were nearly 13.6% and 11.1% higher than that of the tuff control sample, respectively. The result of the limestone mixture sample decreased the least, and its residual stability was

86.9%. In addition, the residual stability of the tuff mixture with 2% and 3% cement contents were not significantly different, i.e., 83.7% and 85%, respectively. Thus, they were similar to the results of the limestone mixture. Compared with the tuff control sample, the improvement of the residual stability for the tuff mixtures with 2% and 3% cement contents was about 18.7% and 20.6%, respectively. This result indicated that the modification effect of the cement additive for water stability was more significant than that of the liquid anti-stripping agent.

Meanwhile, the result of the freeze–thaw splitting test presented in Figure 9 indicated that compared with the limestone mixture, the splitting strength of the tuff mixture modified with additives was increased, but its strength decreased after the freeze–thaw cycles. In particular, the splitting strength of the tuff control sample exhibited the greatest reduction, and the corresponding strength ratio was 0.74. The result was followed by adding the anti-stripping agent, and the corresponding strength ratios with the 0.6% and 0.9% additives were 0.81 and 0.80, which increased by nearly 9.5% and 8.1% compared with the control sample, respectively. In addition, the strength ratios with 2% and 3% cement additive were 0.86 and 0.84, respectively, which were similar to the results of the limestone mixture (0.85) and increased by about 16.2% and 13.5% compared with the control sample, indicating

4.3. Effect of Aging on Water Stability

To verify the adhesion and durability of tuff mixture modified additives under long-term use, the influence of aging on the asphalt mixture was further considered on the basis of the aforementioned two types of water stability tests. The results of the immersion Marshall test and freeze–thaw splitting test after aging are presented in Figures 10 and 11, respectively, where the error of the test results was controlled within 10%.

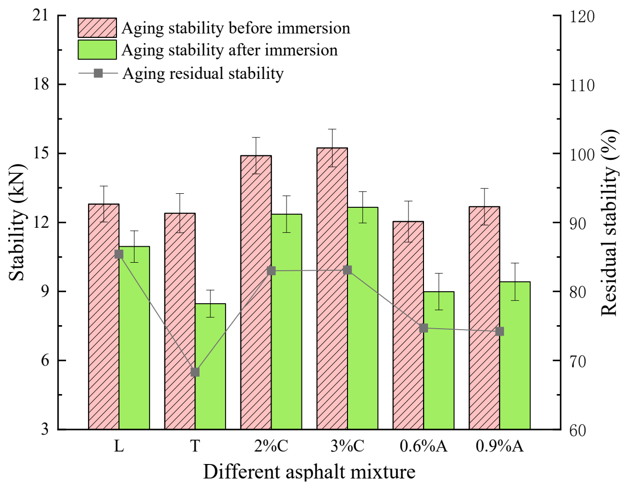


Figure 10. Results of the immersion Marshall tests that considered aging.

In accordance with the results presented in Figures 10 and 11, the law of stability and splitting strength indexes for various mixtures after aging was similar to that before aging. For example, regardless of whether for stability or splitting strength, the decrease rate of the tuff control sample was the most evident after aging and water action, and the corresponding residual stability and freeze–thaw splitting strength ratio was only 68.3% and 0.72. For the results of the tuff mixtures added with 2% and 3% cement contents, the corresponding residual stability was 83% and 83.1%, and the freeze–thaw splitting strength ratio was 0.84 and 0.83, which were close to those of the limestone mixture (85.4% and 0.84). Compared with those of the tuff control sample, the former increased by nearly 21.5% and 21.7%, while the latter increased by about 16.7% and 15.3%, respectively. For the indexes of tuff mixtures added with 0.6% and 0.9% anti-stripping agent contents, the corresponding residual stability was 74.7% and 74.2%, and the splitting strength ratio was 0.74 and 0.75. Compared with that of the tuff control sample, the former was only improved by 9.4%

and 8.6%, while the latter was only improved by 2.8% and 4.2%, respectively. Therefore, the improvement effect of the liquid anti-stripping agent on the water stability of the tuff mixture after aging was not as significant as that of the cement additive.

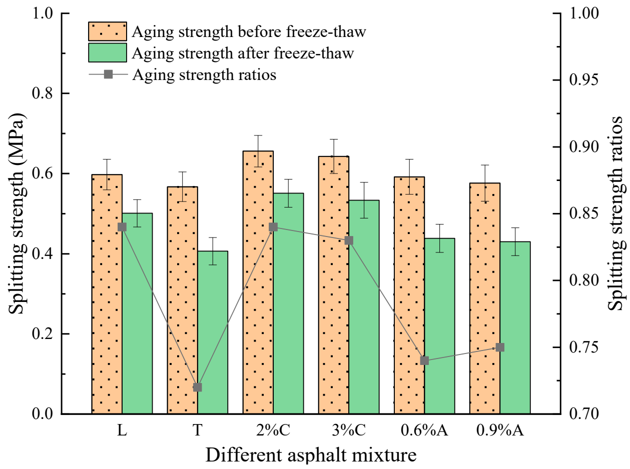


Figure 11. Results of the freeze–thaw splitting tests that considered aging.

To more visually illustrate adhesion durability, the respective average values of residual stability and the freeze–thaw splitting ratio indexes before and after aging were compared, as shown in Figures 12 and 13.

In accordance with the results in Figures 12 and 13, the residual stability and freeze–thaw splitting ratio of the mixture in each type decreased after aging. For the decrease rate of residual stability and the freeze–thaw splitting ratio after aging compared with the respective results before aging, the results of adding an anti-stripping agent were the most evident; such as for the former index, which decreased by 6.7% and 5.2% with the 0.6% and 0.9% additives, and the latter index, which decreased by 8.6% and 6.3%, respectively. In addition, the decrease rates of adding a cement additive were close to results of the limestone and tuff control samples, such as for the former index, which only decreased by 0.8% and 2.2% with 2% and 3% additives, and the latter index, which decreased by 2.3% and 1.2%, respectively. Thus, the above results indicated that the mixture with the liquid anti-stripping agent was more susceptible to aging, and the modification effect of adding cement additive was significantly more stable than that of the liquid anti-stripping agent additive. The modification effects of 2% and 3% cement contents were similar.

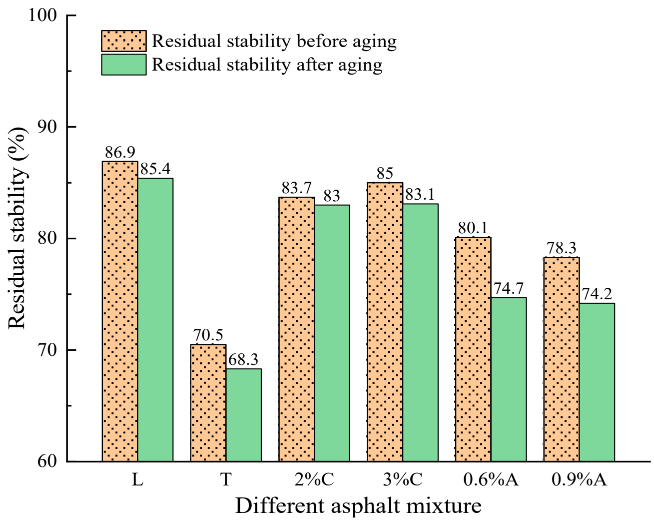


Figure 12. Comparison of residual stability before and after aging.

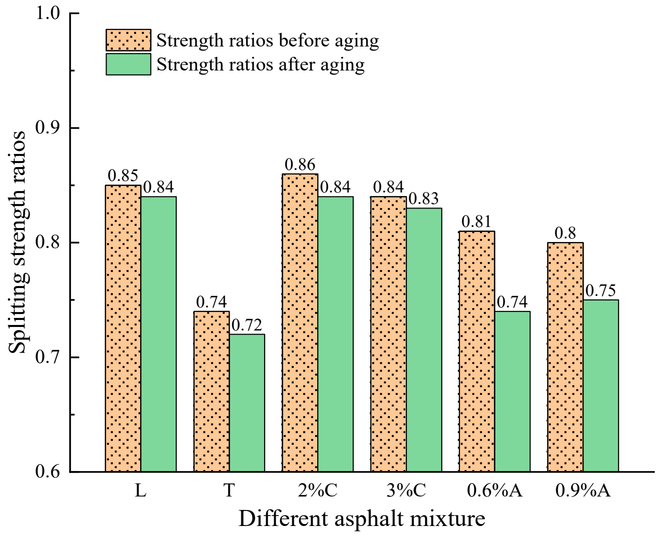


Figure 13. Comparison of freeze–thaw splitting strength ratio before and after aging.

4.4. High- and Low-Temperature Performance

(1) High-temperature performance

The results of the tuff mixture with cement additive schemes were further obtained through the rutting test of the mixtures before and after immersion. The error of the test results was controlled within 10%, as shown in Figure 14.

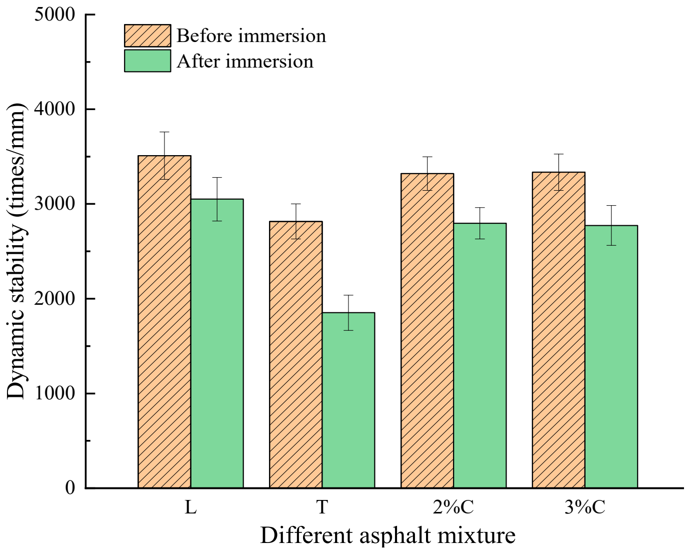


Figure 14. Results of the rutting test for dynamic stability.

As shown by the results in Figure 14, regardless of whether the mixture samples were immersed or not, the tuff control sample in all the mixture types exhibited the smallest dynamic stability value, and its decrease rate compared with that of the limestone mixture with the maximum dynamic stability index was also the largest. The results of the tuff control samples before and after immersion reached nearly 80.2% and 60.7% of the limestone mixture, respectively. However, the dynamic stability indexes of the tuff mixture were improved and close to those of the limestone mixtures after adding 2% and 3% cement additives, reaching 94.6% and 95.0% of the limestone mixture before immersion, and 91.7% and 90.9% after immersion, respectively. Moreover, the high-temperature rutting resistance of the tuff mixture was similar after adding 2% or 3% cement, and the modification effect of cement additive was verified.

(2) Low-temperature performance

Through the beam bending test, the relevant low-temperature performance indexes of the asphalt mixture can be obtained, and the mean values of the results are provided in Table 8. The error of the test results was controlled within 10%.

Table 8. Results of the beam bending index of the asphalt mixtures.

Mixture Types	Flexural Tensile Strength (MPa)	Maximum Flexural Strain (με)	Flexural Stiffness Modulus (MPa)
L	5.32	2915	1824
T	6.10	2405	2535
2%C	5.90	2676	2205
3%C	5.95	2575	2311

As shown in Table 8, the maximum flexural strain of the tuff sample after adding 2% and 3% cement reached 2676 με and 2575 με, respectively, which satisfied the specification requirements [18]. Compared with the tuff control sample, the beam bending performance indexes of the tuff mixture samples with 2% and 3% cement were modified. The maximum flexural strain of the tuff sample increased by 11.27% and 7.07%, while its flexural stiffness modulus decreased by 13.02% and 8.84%, respectively. The low temperature crack resistance of the tuff asphalt mixture can be improved after adding 2% or 3% cement, but the test results after adding 2% cement were close to that of the limestone mixture. Therefore, the tuff mixture modified with 2% cement content was better than the one modified with 3% cement content.

5. Conclusions

Through a series of laboratory tests, the water damage resistance of a tuff asphalt mixture modified with different additives was investigated, and the major conclusions drawn were as follows.

(1) The adhesion property of tuff aggregates under water conditions was poor, and the improvement effect after implementing different additive schemes exhibited differences. The modification effect for adding 1% cement or 0.3% liquid anti-stripping agent was inevident, but the effect of adding higher contents was better. That is, the adhesion grade can reach 4 or 5, and it was close to that of limestone aggregate.

(2) The water stability indexes of the tuff mixture control sample were the smallest among all the mixture samples, but the residual stability and freeze–thaw splitting ratio of the tuff mixture with different additives were improved. The modification effect of the cement scheme was better than that of the anti-stripping agent scheme, and its results were close to those of the limestone mixture.

(3) Compared with the water stability indexes of the tuff mixture control sample after aging, residual stability was improved after adding a liquid anti-stripping agent, but the improvement effect was not as significant as that of adding cement. The freeze–thaw splitting strength ratio of the tuff mixture with liquid anti-spalling agent was not good, while the index of the tuff mixture with cement was more significant and closer to the result of the limestone mixture.

(4) The high-temperature performance of the tuff mixture after adding cement was improved and close to that of the limestone mixture. The dynamic stability index of the tuff mixture was similar after adding 2% or 3% cement content. Meanwhile, the low-temperature performance of the tuff mixture was also improved after adding cement. However, the results of adding 2% cement content were closer to that of the limestone mixture, and thus, the modification effect with 2% cement content was better than that with 3% cement content.

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

Funding: This research was supported by the Science and Technology Project of Transportation Department in Zhejiang Province (grant number 2020013), the Fundamental Research Funds of Zhejiang Sci-Tech University (grant number 2021Q037).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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