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# Durability Evaluation Study for Crumb Rubber–Asphalt Pavement

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**Abstract:** In this study, the failure mechanism of crumb rubber–asphalt pavement was analyzed under the combined effects of low temperature, water, and traffic load. The investigation was carried out based on the mechanical and deformational properties of crumb rubber–asphalt mixture and the typical environmental and load conditions such pavement is typically exposed to. A method was proposed for objective evaluation of the interfacial adhesion between rubber crumbs and asphalt through consideration of the effects of the characteristics of the materials and the working environment. The main evaluation method used herein included the indirect tensile strength test under freeze–thaw–boiling cycle, and the Cántabro abrasion test under water-immersion was adopted as an auxiliary method. The evaluation system has the advantages of simple implementation, realistic simulation of the actual working state of the mixture, and reliable results. Moreover, it is a durability evaluation method that can be specifically applied to asphalt mixtures with some special aggregates or stone mastic asphalt (SMA) mixtures.

**Keywords:** durability; evaluation method; adhesion; asphalt pavement; rubber crumbs

## 1. Introduction

Crumb rubber–asphalt mixture is a new type of deicing pavement material prepared by replacing some of the aggregates in asphalt mixture with mechanically sheared particles of waste rubber tires and mixing them uniformly with high-performance modified asphalt [1–6]. The addition of rubber crumbs changes the original structure of the mixture and the contact state between the materials so that the pavement is more easily loosened than an ordinary asphalt pavement [7]. An investigation has generally shown early damage to the domestic crumb rubber–asphalt pavement test roads for snow-melting [8]. This is mainly ascribed to the insufficient adhesive force between rubber crumbs and bitumen; therefore, the rubber crumbs detach easily from the road surface under load [9]. Water then invades the road surface, and the dynamic water pressure causes the mixture to become loose [10]. Therefore, the durability problem of the crumb rubber–asphalt mixture can be attributed to the lack of adhesion between the asphalt and various aggregates, especially crumb rubber, and the water instability [11]. Thus, related research into crumb rubber–asphalt pavement mainly aims at improving the performance and optimization of material composition [12–15]. The lack of convenient and effective durability evaluation methods seriously hinders the performance research and engineering application progress of crumb rubber–asphalt pavement [16,17]

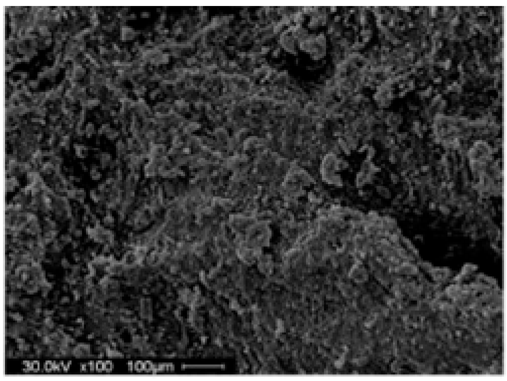
In terms of material composition and mechanical properties, crumb rubber–asphalt pavement is different from ordinary asphalt pavement [18]. Therefore, the durability evaluation method for conventional asphalt concrete pavement is no longer applicable to crumb rubber–asphalt pavement [19]. However, research on the effective durability evaluation method for such special bituminous mixture has rarely been carried out. Moreover, recent research tends to use more advanced scientific experimental methods, such as nuclear magnetic resonance (NMR) spectroscopy and microscopy [20–24]. These methods require precise and complex test instruments and are suitable for the analysis of asphalt mixtures from a microscopic perspective. These complex test methods are time-consuming and no longer convenient when evaluating the performance of crumb rubber–asphalt mixtures in engineering laboratories. More importantly, these evaluation test methods are not based on the damage mechanism and mode, which makes them unsuitable for evaluating the durability of crumb rubber–asphalt pavement.

Rubber crumbs are materials with a certain linear elasticity [25,26], thus their addition leads to inevitable changes in the mechanical properties of the crumb rubber–asphalt pavement [27–29], which in turn leads to a difference in the failure mechanism from that of ordinary asphalt mixture-based pavement. In order to study the durability evaluation method of crumb rubber–asphalt mixture more scientifically, it is necessary to understand the interface adhesion and failure mechanism.

### *1.1. Effects of the Surface Characteristics of Rubber Crumbs*

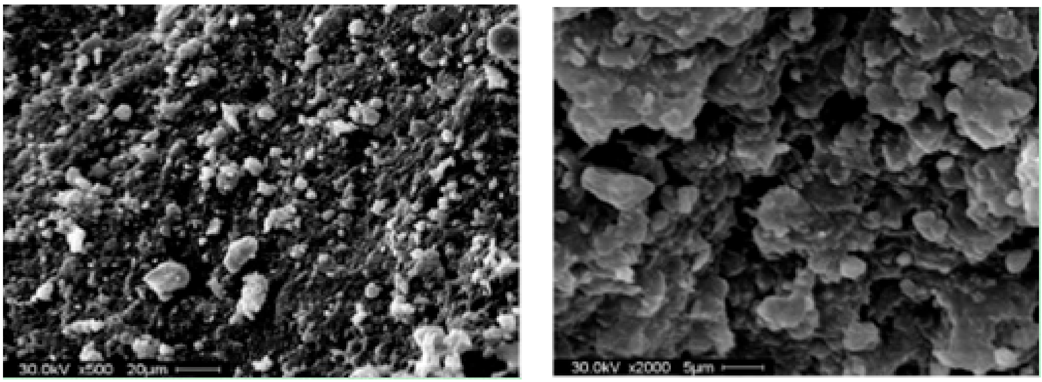
Rubber powder is used to modify asphalt based on the fact that under the action of high temperature and shear, rubber powder absorbs lighter constituents from asphalt, which leads to an increased softening point and decreased ductility of asphalt. Moreover, the "swelling effect" occurs and deformations are induced in rubber particles due to swelling. The surface of the rubber powder is gradually softened. A three-dimensional continuous phase is formed into the asphalt matrix and the mechanical properties of binders are influenced significantly. The successful application of rubber powder-modified asphalt is attributed to the reaction of the above-mentioned mechanism [30–32]. However, in crumb rubber–asphalt pavement, rubber crumbs are incorporated as aggregates [33]. Since rubber crumbs are incorporated as aggregates, when the temperature of the rubber crumbs is low the contact time with the asphalt is short, and the swelling effect is not obvious; in addition, in this case, the adhesion of the asphalt to the rubber crumbs can also be compromised. Notably, many studies have also evaluated the adhesion of the asphalt to aggregate by analyzing the cohesion of bituminous binders [34]. For rubber powder modified asphalt, this research idea is correct and applicable. However, when the rubber crumbs are incorporated as aggregates into the asphalt mixture, the cohesion angle is no longer suitable for evaluating the adhesion of the asphalt to the rubber crumbs.

Electron microscopy images of rubber crumbs at different magnifications (100×, 500×, 2000×) (Figure 1) show their surface to be uneven with granular protrusions. The rubber crumbs have no sharp edges and are approximately circular and smooth. Therefore, the interface characteristics of rubber crumbs are less conducive to coating with an asphalt film than those of ordinary stone aggregates, and mechanical adhesion between the components will thus be inferior [35].




(**a**)

**Figure 1.** *Cont.*




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

**Figure 1.** Electron micrographs of surfaces of rubber crumbs: (**a**) magnification level at 100×; (**b**) magnification level at 500×; and (**c**) magnification level at 2000×.

The interface between asphalt film and rubber crumb becomes the weakest interface for component adhesion in the mixture, and complex environmental and loading effects can easily damage this interface [34], resulting in peeling off of the road surface and damage in the internal structure. Furthermore, the high elasticity of the rubber crumbs makes it easy for them to deform and recover under load, which damages their bitumen coating. Under the action of hydrodynamic pressure, the bitumen film rapidly peels off and loses its adhesion effect, resulting in rapid devastation such as loose spalling.

### *1.2. Combined Effects of Low Temperature, Water, and Traffic Load*

Rubber crumbs are mainly used as an additive for roads that are exposed to winter ice and snow under a seasonally frozen working environment [36]; therefore, the crumb rubber–asphalt pavement inevitably encounters low temperature, ice-water, and traffic load conditions in combination. Under low-temperature conditions, the crumb rubber–asphalt mixture is in the elastic-plastic state, and a drop in temperature probably leads to its cracking; such conditions are generally accompanied by snow and icy weather. When the road structure is frozen, the asphalt still deforms under the action of the traffic load due to the high elasticity of the rubber crumbs in the mixture, and the melted ice water enters the pavement, where it reduces the degree of bonding between the aggregate and asphalt. These combined problems of moisture entering the mixture due to the decrease in the viscosity of asphalt at low temperatures and the water-induced reduction of adhesion of the asphalt with the aggregate are then exacerbated by flow-scouring inside the mixture due to the hydrodynamic pressure generated by traffic load.

In summary, the combined effects of (a) low temperature, (b) meltwater and (c) traffic load have a major impact on the road performance of crumb rubber–asphalt pavement. Therefore, it is of great importance to study the durability of crumb rubber–asphalt mixture under the coupling of these three factors. In this study, the durability of crumb rubber–asphalt pavement was evaluated in detail based on the actual working environment, and a corresponding comprehensive evaluation method was proposed.

## 2. Materials and Methods

### *2.1. Materials*

The materials used in this study included SK-70 matrix asphalt (SK Group, Seoul, Korea), SBS modified asphalt, TPS modified (12%, 13.5% and 15% dosage) asphalt, basalt mineral aggregates, 0–3 mm machine-made sand, mineral powder, and rubber-particles produced by the normal temperature mechanical shearing method [37,38]. Thermoplastic styrene (TPS) refers to SEBS and SBS blend modified material, and is a common high viscosity asphalt modifier. TPS-modified bitumen is frequently used in porous bitumen concrete (PAC) and open-graded friction course (OGFC) with characteristics of high viscosity and high elasticity [39,40]. Machine-made sand is a material that is crushed using alkaline rock materials such as limestone and is widely used as a fine aggregate in China. Rubber particles have a 0.6–2.36 mm size range with a 1.18-mm particle size passing ratio of 25%. The densities of the raw materials are listed in Table 1. The properties of different asphalts are shown in Table 2.

**Table 1.** The density of raw materials.

| Material Type | Coarse Aggregate | Machine-Made Sand | Mineral Powder | Rubber Particles |
|---|---|---|---|---|
| (Apparent) Density (g/cm$^3$) | 3.085 | 2.960 | 2.646 | 1.15 |

**Table 2.** The properties of different asphalts. SBS: Styrene-Butadiene-Styrene; TPS: Thermo Plastic Styrene.

| Asphalt | Penetration at 25 °C (0.1 mm) | Ductility at 10 °C (cm) | Softening Point (°C) | Viscosity at 60 °C (Pa. s) |
|---|---|---|---|---|
| SK-70 | 70.9 | 158.9 | 48.4 | 249 |
| SBS | 53 | 115 | 87 | 1213 |
| 12% TPS | 49 | 69 | 81.5 | 58,175 |
| 13.5% TPS | 43.9 | 72 | 88.5 | 78,460 |
| 15% TPS | 37.5 | 82 | 95 | 194,600 |

Stone mastic asphalt (SMA-16) mixture with rubber crumbs was selected as the durability evaluation object [41]. In this study, the mix ratio of crumb rubber-asphalt mixture was designed by the course aggregate void filling method [42], taking 4% as the target void ratio, formulating 10% of mineral powder, 3% of rubber particles and 6.5% of asphalt–aggregate ratio. The calculated amount of coarse aggregate was 80%, and the amount of fine aggregate was 7%. The amount of TOR (rubber Vita-linker) was 4% of the rubber crumbs, that is, 0.12% of the asphalt mixture [43]. The mixing temperature of the mixture is different from asphalt type, and the design grade is presented in Table 3.

**Table 3.** Design Synthesis Grading of SMA-16.

| Sieve (mm) | 19 | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Passing rate (%) | 100 | 93.4 | 79.9 | 54.8 | 23.9 | 22.8 | 18.2 | 13.7 | 11.7 | 10.7 | 8.9 |

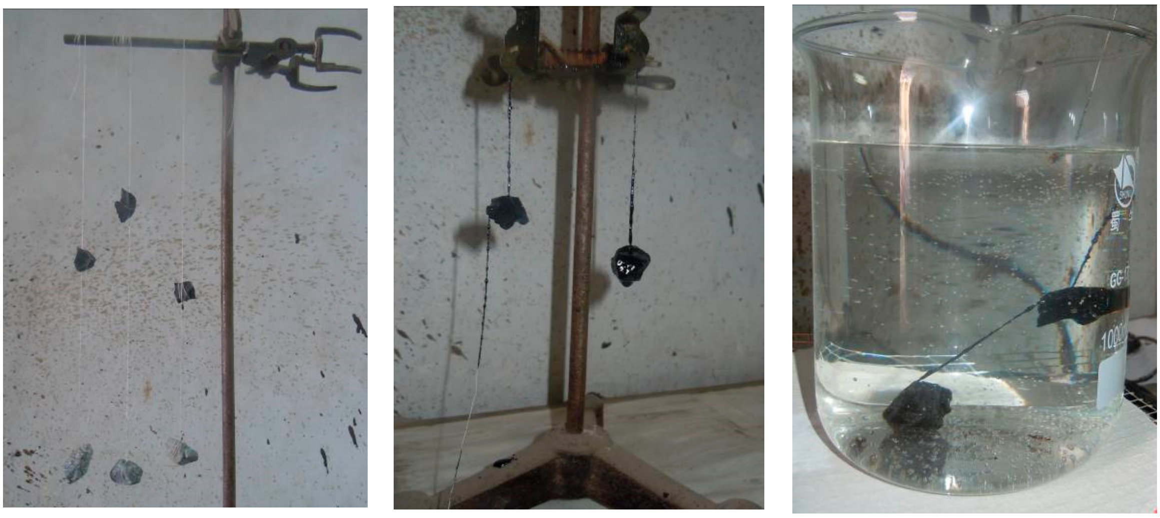
### *2.2. Experimental Methods Setup*

#### 2.2.1. Adhesion Evaluation for Asphalt and Crumb Rubber Coarse Aggregate

The net adsorption test developed by the Strategic Highway Research Program in the USA is based on the bitumen–water–mineral system [44]. This test was developed to evaluate the affinity of bitumen for aggregate and to determine the water sensitivity of a given bitumen–aggregate pair. Briefly, the aggregate is placed in a flowing bitumen–toluene solution, and the absorbance of the solution is measured using a photometer to calculate the amount of bitumen being stripped off. The static immersion test (AASHTO T 182) uses water osmosis to simulate the water-related damage after an actual road surface comes in contact with water [45]. Nonetheless, the above-mentioned mainstream foreign methods include subjective analyses and have long test durations and insufficient reliability. China's "Testing Procedures for the Mixing of Asphalt and Asphalt Mixtures for Highway Engineering" (JTG E 20-2011) adopts a water-boiling method in which the adhesion grade is determined according to the degree of peeling of bitumen membrane from the surface of a coarse aggregate particle in boiling water (grades range from 1 to 5) [46]. After a comprehensive analysis, this study proposed an improved evaluation method based on the existing standard boiling method.

The improved method is based on the method of "Adhesion test of asphalt and coarse aggregate (T 0616)" [46] and "Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water" (ASTM D 3625) [47]. It can be used for both crumb rubber–aggregate and rock aggregate by making the following specific modifications:

(a) The rubber crumbs have low density. To prevent the bitumen-covered crumbs from failing to be immersed in water, which would otherwise affect the test results, stone and rubber crumb are tied together with a cotton thread before testing so that the rubber crumbs will be weighed down by the mineral materials. However, in the boiling water, they are separated by 5 cm, with the mineral material beneath the rubber crumb (Figure 2a), and both become completely immersed in boiling water.



(a) (b) (c)

**Figure 2.** The test procedure for the boiling of minerals and rubber crumbs: (**a**) test preparation; (**b**) suspension cooling; and (**c**) boiling process.

(b) In the actual production of the crumb rubber–asphalt mixture, the rubber crumbs are directly dispersed in the mixing tank without heating. Therefore, the rubber crumbs are required to be immersed in hot asphalt at a normal temperature, and the mineral aggregate is required to be immersed in hot asphalt at a higher temperature (175 °C).

(c) In the suspension cooling process, it is preferable to suspend the mineral material parallel to the rubber crumbs to prevent the asphalt on the surface of the asphalt-coated rubber crumbs from dripping onto the surface of the mineral material (Figure 2c).

(d) Considering that the crumb rubber–asphalt mixture is more deformable than an ordinary mixture, the working environment places higher adhesion requirements upon it, thus the boiling time of 3 min (or 10 min by ASTM D 3625) in the original specification is adjusted to 20 min, while the evaluation standard remains unchanged.

The coarse aggregate in the crumb rubber–asphalt mixture is divided into stone material and rubber crumbs. Their sizes are different; therefore, to avoid incomparability in test results caused by different aggregate specifications, a consistent aggregate size of 9.5–13.2 mm was used in this study. The method easily detected the differences in the adhesion of bitumen to stone minerals and rubber crumbs under the same test conditions.

#### 2.2.2. Adhesion Evaluation Method for Bitumen and Crumb Rubber Fine Aggregate

At present, the test methods for evaluation of adhesion pertain to coarse aggregates. In contrast, fewer adhesion test methods have been developed for fine aggregates [34]. However, damage to the mixture and peeling off are more likely to arise from finer aggregates than from coarser aggregates because their adhesion with bitumen is poorer. Therefore, the influence of the adhesion of fine rubber-particle aggregate with bitumen on the moisture stability of the mixture should not be ignored, and it is necessary to propose an evaluation method for the adhesion of bitumen to fine aggregate. This study proposed that the adhesion of asphalt and fine aggregate can be evaluated by a combined boiling–sieving method, as follows:

(1). Three 500-g samples of crumb rubber–asphalt mixture were prepared according to the design grade and the corresponding asphalt–aggregate ratio and were each placed on a flat bottom plate. The three samples were subjected to the following tests, and the average value was considered as the test result.

(2). The hot asphalt mixture on the flat bottom plate was cooled to room temperature. While cooling, the crumb rubber asphalt mixture was gently turned with a shovel so as not to damage the agglomerate; it should not be separated by hand or broken with a hammer.

(3). The mixture was collected, weighed to determine the mass $m_1$, and then passed through a sieve with 4.75-mm-wide holes (as shown in Figure 3). A small shovel was used to guide the mixture gently so that it passed through the sieve holes freely without damaging its bonding state. The use of a shaker was strictly forbidden. The mixture on the 4.75 mm-square mesh was collected and weighed to determine the mass $m_2$.

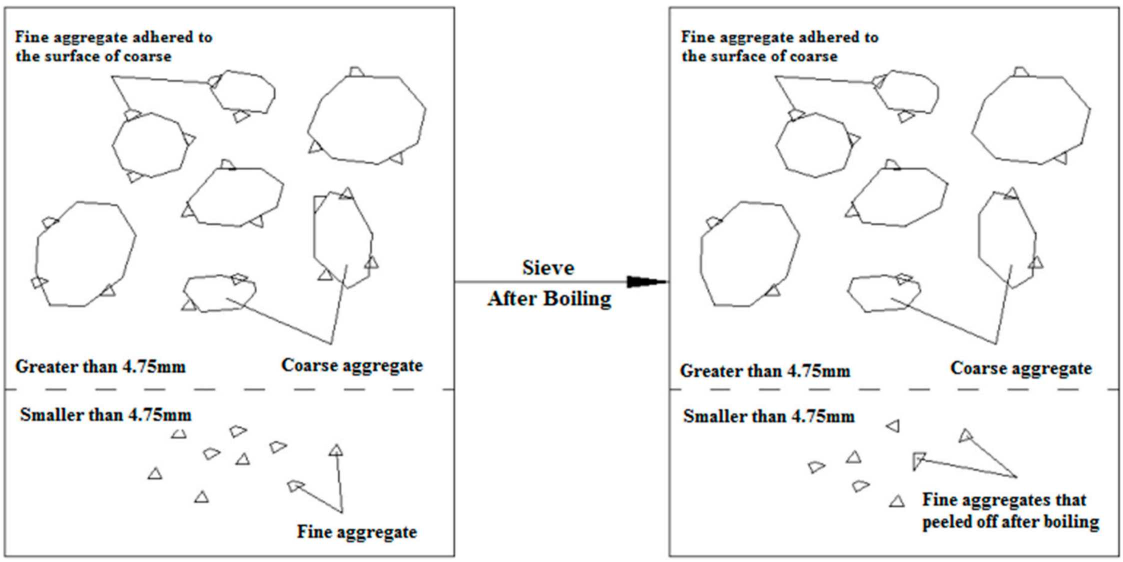



**Figure 3.** Schematic illustration of the boiling–sieving method.

(4). The collected mixture was immersed in a large beaker containing boiling water, and the degree of heating was adjusted to keep the water in a boiling state. The mixture was gently stirred with a glass rod during the boiling process, and a piece of paper was used to remove asphalt floating on the water surface.

(5). After boiling for 20 min, the mixture was taken out, placed in a flat pan, and cooled to room temperature. While cooling, the mixture was gently tumbled with a shovel, as in step 2.

(6). After the cooling of the mixture and the occurrence of complete evaporation of water, the mixture was again passed through the 4.75-mm-square mesh, using a shovel to help any free mixture to pass through the sieve, with the same requirements as in step 3. The part of the mixture that did not pass through the 4.75-mm sieve holes was weighed and its mass was recorded as $m_3$.

The design concepts and calculation methods of the boiling–sieving method are as follows:

1. The mixture was in a freely bonded state after mixing and cooling. The crumb rubber asphalt mixture generally adopted intermittent gradation (2.36–4.75 mm). For convenience, this study used 4.75 mm as the boundary point between coarse and fine aggregates.
2. It was assumed that the mass of asphalt mastic (bitumen and mineral powder) coating the surface of the aggregate was directly proportional to the mass of the coarse and fine aggregate. In the mixture design, the mass ratio of the coarse aggregate was recorded as $a_1$, and the mass ratio of fine aggregate was recorded as $a_2$.

$$m_C = m_1 \times \frac{a_1}{a_1 + a_2} \tag{1}$$

$$m_F = m_1 \times \frac{a_2}{a_1 + a_2} \tag{2}$$

In Equations (1) and (2): $m_C$—The mass of coarse aggregate covered with asphalt and mineral powder (g); $m_F$—The mass of fine aggregates coated with asphalt and mineral powder (g); $m_1$—Total mass of the mixture (g); $a_1$—The mass ratio of coarse aggregate in the mix design (%); $a_2$—The mass ratio of fine aggregate in the mix design (%);
3. Boiling led to peeling off of some fine aggregates from the surface of the coarse aggregates, and the peeling rate of the fine aggregate was the ratio of the mass of the exfoliated fine aggregate to the mass of the fine aggregate on the surface of the coarse aggregate before boiling:

$$\triangle L = \frac{m_2 - m_3}{m_2 - m_C} \tag{3}$$

In Equation (3): $\triangle L$—Fine aggregate peeling off rate after boiling (%); $m_2$—The mass of the mixture with particles above 4.75 mm in diameter after mixing and cooling, including coarse aggregates coated with asphalt, adhering fine aggregates, and fine aggregates coated with asphalt forming agglomerates (g); $m_3$—The mass of the mixture with particles above 4.75 mm in diameter after boiling and secondary screening (g);

The boiling–sieving method has some deficiencies for evaluating the adhesion of asphalt to fine aggregates. This method can only be used to evaluate the overall adhesion of asphalt to all fine aggregates, including stone aggregates and rubber particles. This is the first method developed that can be used to evaluate the adhesion properties of fine aggregates in the asphalt mixture.

### 2.2.3. Moisture Stability Evaluation Method of Crumb Rubber–asphalt Mixture

Owing to the mechanical and deformational properties of the crumb rubber–asphalt mixture, the harsh environmental conditions, and repeated traffic load to which it is exposed, the study of the moisture stability of the crumb rubber–asphalt pavement is significantly important [48]. Conventional evaluation methods for asphalt mixture moisture stability, such as the Marshall water immersion test and the indirect tensile strength test under freeze–thaw cycle, are not sufficient to evaluate the long-term moisture stability of crumb rubber–asphalt pavement under special environmental conditions and repeated traffic load [49,50]. Based on the characteristics of rubber crumbs, the actual environmental conditions of the pavement and load effects to which it was exposed [38], this study proposed the indirect tensile strength test under a freeze–thaw–boil cycle as the main evaluation method for the moisture stability of the crumb rubber–asphalt mixture. Furthermore, considering the deformation performance of the crumb rubber–asphalt mixture, the Cántabro abrasion test [46] under water immersion was used as an auxiliary evaluation method. This test method can be used to comprehensively evaluate the long-term water stability of the crumb rubber–asphalt mixture.

(1) Indirect Tensile Strength Test under Freeze–Thaw–Boil cycle

The proposed indirect tensile strength test differs from the conventional indirect tensile strength test under freeze–thaw (as ASTM D 4867) [51] in that a set of test specimens are subjected to freeze–thaw and boiling treatment, and the water stability performance of these specimens is analyzed compared to untreated test specimens and test specimens under special treatment. The test method is based on the following principles: the water that enters the interior of the mixture in the ice and snow season is simulated by exposing a vacuum-saturated test specimen to a freeze–thaw cycle; and, the repeated scouring action of the dynamic water pressure generated by dynamic wheel load is simulated by continuous boiling in water at 100 °C. By incorporating these two aspects, the improved method test can better evaluate the water stability of crumb rubber–asphalt mixture than the conventional freeze–thaw split test. Further, as described above, in order to more objectively evaluate the long-term water stability performance of the crumb rubber–asphalt mixture, a test specimen that has been aged for a long term (refer to "Practice for Shortened Long Term Aging of Hot Mix Asphalt " T 0734) [46] is also subjected to the indirect tensile strength test under a freeze–thaw–boil cycle, and the durability of this mixture specimen against water damage is obtained by comparative analysis. The test implementation process is shown in Figure 4.

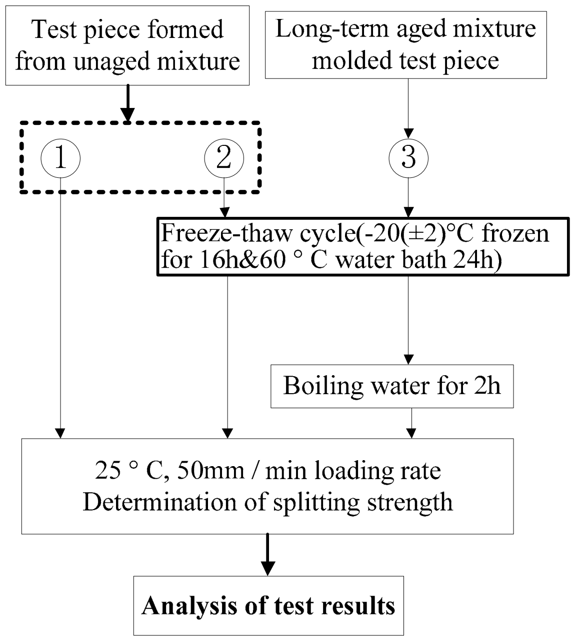



**Figure 4.** Schematic illustration of the test process.

The specific steps in the indirect tensile strength test under a freeze–thaw–boil operation are as follows:

(a) The test specimens, which correspond to the samples of the mixture that have been subjected to standard Marshall compaction molding, are randomly divided into three groups, each group comprising no less than four specimens.

(b) The average value of the splitting strength of the first group of specimens at 25 °C, recorded as $\overline{R_{T1}}$, is obtained directly. The second and third sets of specimens are vacuum-saturated for 15 min at 97.3–98.7 kPa and then returned to normal pressure for 0.5 h in water. The test specimens are taken out of the water and placed at a temperature of −18 °C for 16 h.

(c) The second set of test specimens are thawed to 25 °C, and the average value of the splitting strength of the set is determined and recorded as $\overline{R_{T2}}$. After the freeze–thaw cycle, the third set of test specimens are immediately placed in boiling water for 2 h and then cooled to 25 °C before measuring the splitting strength, which is recorded as $\overline{R_{T3}}$.

(d) The tensile strength ratios $(TSR)$ of the crumb rubber–asphalt mixture, $TSR_1$, and $TSR_2$ are respectively calculated according to Equations (4) and (5) as follows:

$$TSR_1 = \frac{\overline{R}_{T2}}{\overline{R}_{T1}} \times 100 \quad (4)$$

$$TSR_2 = \frac{\overline{R}_{T3}}{\overline{R}_{T1}} \times 100 \quad (5)$$

In the formulas:

$TSR_1$—The indirect tensile strength ratio under freeze–thaw cycle (%);

$TSR_2$—The indirect tensile strength ratio under freeze–thaw–boil cycle (%);

$\overline{R_{T1}}$—Average value indirect tensile strength of the first set of effective specimens under normal conditions (MPa);

$\overline{R_{T2}}$—Average value of indirect tensile strength of the second set of effective specimens after a freezing and thawing cycle (MPa);

$\overline{R_{T3}}$—Average value of indirect tensile strength of the third set of effective specimens under long-term aged after a freeze-thaw-boil cycle (MPa).

Long-term aging treatment of the third set of specimens is required to assess the long-term water stability of the mixture (refer to test method T 0734-2000 in "Testing Procedures for Asphalt and Asphalt Mixtures for Highway Engineering"; loose mix 135 °C/4 h, compacted test specimen 85 °C/5 d) [46]. After aging, the freeze–thaw–boiling–splitting test for the third set of test specimens as described above was carried out on this specimen to obtain the splitting strength ratio, which was recorded as $TSR_2$. At present, the Chinese standard generally uses an unaged asphalt mixture for freeze–thaw split testing to evaluate water stability, while AASHTO tests the long-term aged mixture in America. For an ordinary asphalt mixture, the impact of the implementation of the Chinese standard is not significant, but considering the special mechanical characteristics and the complex working environment experienced by the crumb rubber–asphalt mixture, this study proposes that it is necessary to carry out the above-mentioned freeze–thaw boiling procedure on a long-term aged test specimen.

(2) Cántabro Abrasion Test under water-immersion

The Cántabro test is usually used for assessing the water damage resistance of the porous mixtures, of which the main distress is aggregate stripping. Thus, because the main distress of crumb rubber–asphalt pavement is also aggregate stripping, we here introduce it as an auxiliary evaluation method. A water immersion test was carried out by immersing the specimens in the water at 60 °C for 48 h. The main objective of the Cántabro abrasion test [46] under water immersion was to investigate the expansion of rubber crumbs in hot water. The pressure of the Marshall specimen in the test machine was used to simulate its stability after instantaneous extrusion and elastic recovery of the mixture under dynamic traffic load.

## 3. Results and Discussion

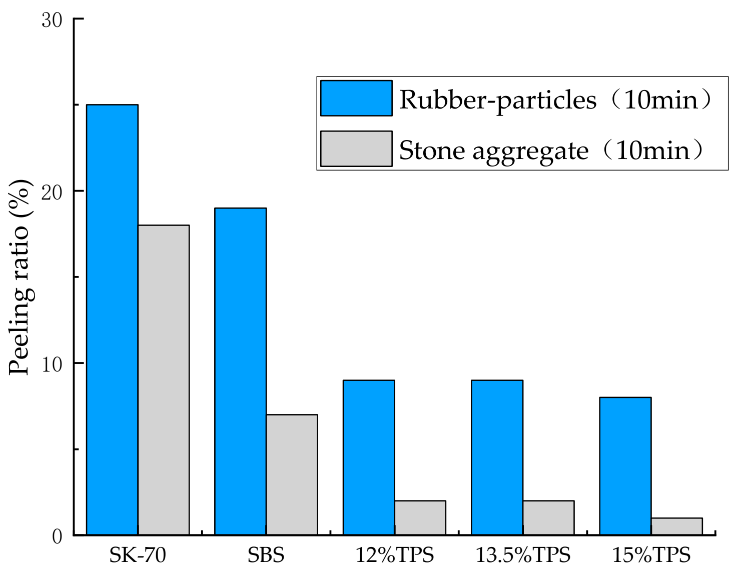
The durability evaluation method proposed herein was verified using the following laboratory tests. In order to verify the effectiveness of the evaluation method mentioned above, this study used the standard method and the method proposed in this study to investigate crumb rubber–asphalt mixture (CR-reinforced SMA-16) [52] mixed with five different asphalts [36,53]. The following test results mainly refer to the three aspects of durability evaluation mentioned in Section 2.2.

(1) The results of the water-boiling test for adhesion evaluation of asphalt and coarse aggregates are shown in Table 4 and Figure 5.

**Table 4.** Results of water-boiling test.

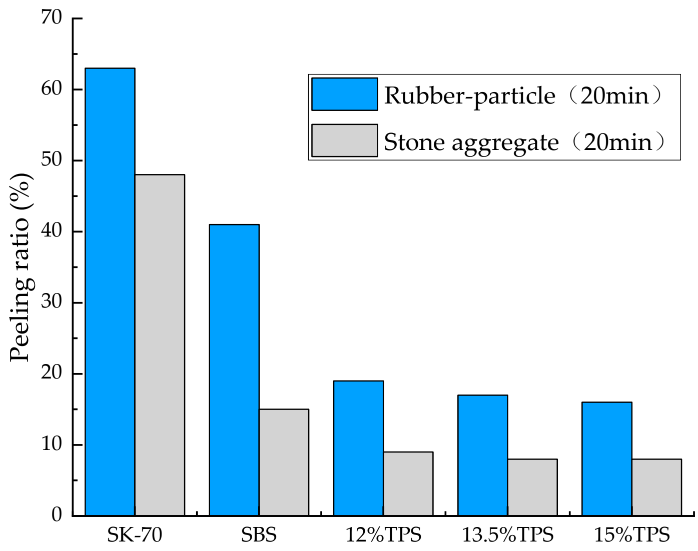
| Aggregate Type | Asphalt Type | First-Time Oil Bubble Time (min) | 3 min (T 0616) | | 10 min (D 3625) | | 20 min | |
|---|---|---|---|---|---|---|---|---|
| | | | Adhesion Grade [46] | Peeling Ratio (%) | Adhesion Grade | Peeling Ratio (%) | Adhesion Grade | Peeling Ratio (%) |
| Stone aggregate | SK-70 | 2 | 4 | 7 | 3 | 18 | 2 | 48 |
| | SBS | 4 | 5 | 1 | 4 | 7 | 3 | 15 |
| | TPS (12%) | 7 | 5 | 0 | 5 | 2 | 4 | 9 |
| | TPS (13.5%) | 9 | 5 | 0 | 5 | 2 | 4 | 8 |
| | TPS (15%) | 9 | 5 | 0 | 5 | 1 | 4 | 8 |
| Rubber particles | SK-70 | 2 | 4 | 8 | 3 | 25 | 2 | 63 |
| | SBS | 2 | 4 | 6 | 3 | 19 | 2 | 41 |
| | TPS (12%) | 5 | 5 | 0 | 4 | 9 | 3 | 19 |
| | TPS (13.5%) | 5 | 5 | 0 | 4 | 9 | 3 | 17 |
| | TPS (15%) | 6 | 5 | 0 | 4 | 8 | 3 | 16 |

Table 4 shows that 1–5 characterize the adhesion grade corresponding to the degree of peeling off of the bitumen film from the aggregate surface after boiling. The determination of the adhesion grade was carried out by referring to the T 0616 method [46] in "Specifications and Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering ". As summarized in Table 4, when the boiling time reaches 10 min, the adhesion grade of rubber and stone particles begins to differ. Extending the boiling time to 20 min causes little change in the asphalt film on the surface of the stone material, but causes significant detachment of the asphalt film from the surface of the rubber crumbs. Figure 5 shows that the adhesion of stone and rubber particles to all of the asphalts can reach grade 4 or higher at 3 min of boiling. Therefore, the method in the specification (boiling for 3 min) cannot effectively evaluate the adhesion of rubber particles. The test results prove that the proposed adhesion evaluation method for asphalt and crumb rubber coarse aggregate is intuitive and effective.




**(a)**

**Figure 5.** *Cont.*




(**b**)

**Figure 5.** Adhesion test results of aggregate with different asphalt: (**a**) boiled for 10 min; (**b**) boiled for 20 min.

(2) Asphalt and fine aggregate adhesion evaluation by the boiling–sieving method:

The values recorded in the boiling–sieving test are listed in Table 5. Referring to the blended proportions of raw materials, $a_1$ is 80% and $a_2$ is 10%.

**Table 5.** Test results from the boiling–sieving method.

| Asphalt Type | Mixing Temperature (°C) | $M_1$ (g) | $M_C$ (g) | $M_2$ (g) | $M_3$ (g) | $\triangle L$ (%) |
|---|---|---|---|---|---|---|
| SK-70 | 170 | 505 | 448.9 | 476.3 | 456.6 | 71.9 |
| SBS | 170 | 512 | 455.1 | 491.1 | 472.2 | 52.5 |
| 12% TPS | 170 | 507 | 450.7 | 481.1 | 469.4 | 38.5 |
| | 185 | 516 | 458.7 | 492.3 | 482.4 | 29.5 |
| 13.5% TPS | 170 | 520 | 462.2 | 493.6 | 480.8 | 40.8 |
| | 185 | 510 | 453.3 | 485.2 | 475.2 | 31.3 |
| 15% TPS | 170 | 514 | 456.9 | 491.9 | 476.5 | 44.0 |
| | 185 | 508 | 451.6 | 482.6 | 472.8 | 31.6 |

The crumb rubber–asphalt mixture using SBS-modified asphalt (and SK-70 asphalt) has a test result of 52.5% (and 71.9%), which is higher than the results with TPS-modified asphalt. The high-viscosity TPS-modified asphalt can effectively improve the adhesion of the aggregate to the bitumen, and has good compatibility with crumb rubbers [54,55]. The test results in Table 5 and Figure 6 show that the proposed method can be used to effectively distinguish the adhesion properties of asphalt and fine aggregates in crumb rubber–asphalt mixture.

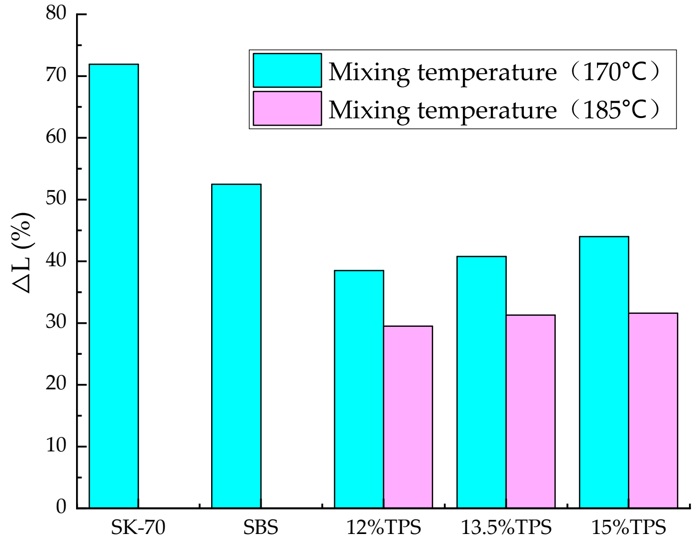



**Figure 6.** Test results from the boiling–sieving method with different asphalts.

(3) Crumb rubber–asphalt mixture water stability evaluation:

The splitting strength ratios recorded for the different specimen types within the freeze–thaw–boiling split testes are listed in Table 6, and Table 7 summarizes the results of the Cántabro abrasion test under water-immersion.

**Table 6.** Results of indirect tensile tests under a freeze–thaw–boil cycle [56,57].

| Asphalt Type | Mixing Temperature (°C) | Void Ratio (%) | Indirect Tensile Strength Ratio (%) | | Technical Requirement (%) [58] |
|---|---|---|---|---|---|
| | | | $TSR_1$ (Unaged and Freeze–Thaw) | $TSR_2$ (Long-Term Aged and Freeze-Thaw–Boil Cycle) | |
| SK-70 | 170 | 4.3 | 85.6 | 76.3 | ≮75 |
| SBS | 170 | 4.2 | 86.9 | 77.4 | |
| 12% TPS | 185 | 4.5 | 95.6 | 86.3 | ≮80 |
| 13.5% TPS | 185 | 4.2 | 96.8 | 86.5 | |
| 15% TPS | 185 | 4.6 | 95.8 | 85.7 | |

**Table 7.** Results of Cántabro test under water-immersion.

| Asphalt Type | Mixing Temperature (°C) | Standard Flying Loss Ratio (%) | Water Immersion Loss Ratio (%) | Technical Requirement (%) [58] |
|---|---|---|---|---|
| SK-70 | 170 | 19.4 | 36.2 | ≯20 |
| SBS | 170 | 14.4 | 25.9 | |
| 12% TPS | 185 | 11.5 | 14.4 | |
| 13.5% TPS | 185 | 11.0 | 14.8 | ≯15 |
| 15% TPS | 185 | 12.9 | 15.2 | |

Table 6 and Figure 7 shows that $TSR_1$ (Unaged and Freeze–Thaw) under the standard test method all meet the technical requirements, and the difference of the rubber particle asphalt mixture with different asphalt types on moisture stability cannot be directly and effectively distinguished. However, $TSR_2$(Long-term aged and Freeze–Thaw–Boil cycle) of the test method proposed in this study can directly assess that the mixture with SBS-modified asphalt does not meet the technical requirements, and the long-term performance of crumb rubber–asphalt mixture with TPS high-viscosity-modified asphalt is obviously superior to other types.

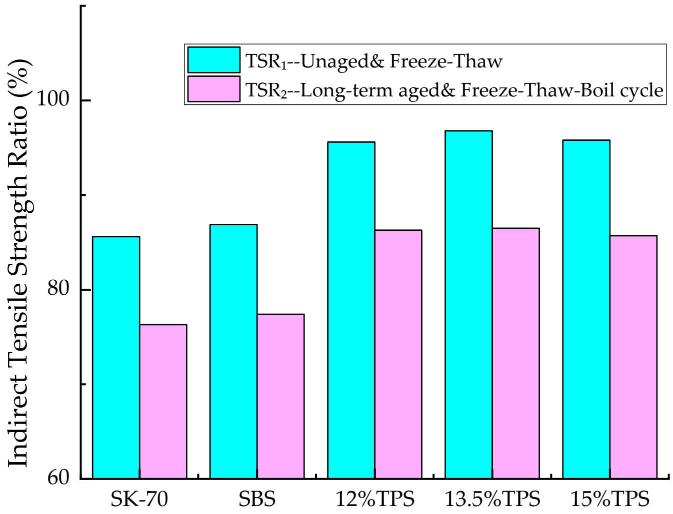



**Figure 7.** Results of indirect tensile tests under a freeze–thaw–boil cycle.

Data presented in Table 7 and Figure 8 indicate that the experimental evaluation method proposed in this study is significantly different from the conventional water stability evaluation method. For example, the mixture with SK-70 and SBS modified asphalt can meet the technical requirements under normal test conditions, but it is completely unsatisfactory under water immersion. It is proved that the durability evaluation method proposed in this study can more effectively evaluate the long-term moisture stability of crumb rubber–asphalt pavement.

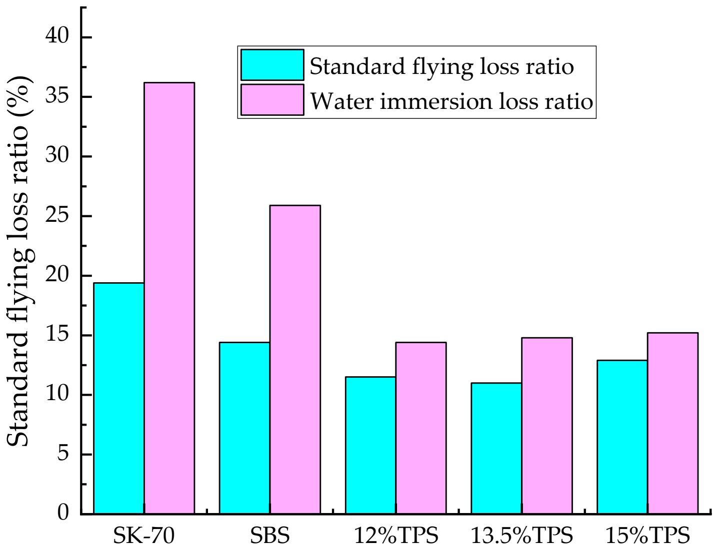



**Figure 8.** Results of indirect tensile tests under Freeze-Thaw-Boil cycle.

The above-mentioned test results indicate that it is necessary to adopt the moisture stability evaluation system proposed in this study to account for the specific characteristics of crumb rubber–asphalt mixture. The analysis shows that the durability evaluation method for crumb rubber–asphalt mixtures proposed in this study has greater pertinence and operability than pre-existing methods.

## 4. Conclusions

The main contributions of this study are as follows:

(1) Analysis of the failure mechanism of crumb rubber–asphalt pavement based on the surface properties of constituent materials and the combined effects of the working environment.

(2) Proposal for a durability evaluation system based on the failure mechanism. The system includes adhesion evaluation methods for asphalt and crumb rubber coarse/fine aggregate, and crumb rubber–asphalt mixture moisture stability evaluation method.

(3) Verification by performing laboratory tests to ensure that the durability evaluation system can be used more scientifically and effectively to evaluate the durability of crumb rubber–asphalt pavement than the conventional test method.

(4) The experimental method used in the study contributes to better knowledge of the mechanical and durability characteristics of the materials that comprise crumb rubber–asphalt pavement, as well as a proposal for the development of new test methods and standards.

**Author Contributions:** X.W. and Z.F. designed the experiments and revised the manuscript; Z.F. performed the experiments\analyzed the data\wrote the paper; L.L. and H.W. contributed reagents/materials/analysis tools; M.H. revised the manuscript.

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