Establishment of a Shear Strength Prediction Model for Asphalt Mixtures with Raw Materials Properties and Design Parameters

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Shear strength is one of the important mechanical properties of asphalt mixtures, which is affected by a combination of various parameters such as asphalt property, gradation, and asphalt content, so it often requires a large number of tests to obtain a satisfactory asphalt mix design result. Therefore, a shear strength prediction model considering the effects of various factors is proposed to guide the design of asphalt mixes. Firstly, on the foundation of analyzing the factors affecting the shear strength of asphalt mixtures, composed bulk specific gravity of mineral materials, aggregate surface energy, nonrecoverable creep compliance Jnr3.2, gradation index, aggregate specific surface area, asphalt content, and gyratory compaction number were selected as the input parameters for modeling. Secondly, the effects of modeling parameters on shear strength were analyzed, and an appropriate model was established using the software Origin with 101 set of test results. In the end, the prediction model was verified using extra 18 sets of test data. The result showed that the correlation coefficient between the predicted and measured value reached 0.8 or more, indicating that the model has satisfactory prediction accuracy. This prediction model proposed in this article can be used to reduce the workload for designing asphalt mixes and promote the establishment of the performance-based design method of asphalt mixes.

1. Introduction

Lots of studies have shown that the rutting of asphalt pavements mainly originates from the shear deformation of asphalt mixtures [1–3]; thus, many researchers have tried to establish a link between the rutting depth and the shear resistance of asphalt mixtures, as a part of performance-based asphalt mixture design method. Yu and Li [4], Lu and Sun [5], and Kim et al. [6] proposed rutting prediction models, including the shear performance of asphalt mixes, respectively. In such models, the predicted rutting depth is obtained by inputting the shear strength of the asphalt mixture and other parameters. Similarly, for the pavement rutting depth to meet certain requirements, a minimum limit must be set for the shear resistance of asphalt mixtures. Therefore, making the shear resistance meet certain requirements becomes one of the important goals in the asphalt mixture design process. However, this goal is hard to achieve because of the numerous factors affecting the shear strength of asphalt mixtures, such as gradation, asphalt content, and the bonding strength between asphalt and aggregate [7]. Project A-318 in SHRP Program summarized the factors affecting the shear strength of asphalt mixtures into three major categories [8]: (1) asphalt related, which mainly refers to the stiffness modulus of asphalt; (2) aggregate related, which includes aggregate shape, size, angularity, and gradation; (3) mixture related, including asphalt content, VV, VMA, and molding method. A large number of studies have been conducted by scholars on the above influencing factors [9–11], but most of these studies were performed on a single factor, which has led to different conclusions from different scholars. For example, Brown argued that the VV of asphalt mixture should not be less than 3% to prevent excessive rutting [12], while Peng Yong's...
study showed that the smaller the VV of the mixture, the higher the shear strength [13]. Ei-Baseyoum and Mamlouk [14], Kandhal and Cooley [15], and Buttlar et al. [16] have very different views on which gradation, coarse or fine, has better rutting resistance. This suggests that the current study may have overlooked the complex interactions that exist between different factors, which have been confirmed in the authors’ previous works [17]. So, it has to constantly adjust the gradation and asphalt content by trial and error to make the shear strength of the asphalt mixture meet certain requirements, which is a time-consuming and labor-intensive process. If the shear strength can be predicted at the beginning of the mixture design process, then the shear strength can be modified to achieve the design goal quickly. Therefore, the objective of this article is to propose a shear strength prediction model that can guide the design of asphalt mixes.

At present, there are three principal methods to estimate the performance of asphalt mixtures. (1) The artificial neural network method: many researchers used this method to estimate the triaxial shear strength or low-temperature bending strain of asphalt mixtures [18]. The key step in this method is the network training process. However, not only is the training speed slow, but also the network training may fail due to the unsuitable training sample. Therefore, it is rarely used in engineering projects. (2) The theory of viscoelastic-plastic mechanics: some researchers attempted to establish a constitutive model of asphalt mixtures with viscoelastic-plastic mechanics theory and then derived a theoretical performance prediction model of asphalt mixtures with the constitutive model [19]. However, proposing an accurate constitutive model because of the complex composition of asphalt mixtures using this method is challenging. Thus, it is currently difficult to apply this method. (3) Numerical fitting method: the key point of this method is to select the appropriate function model and modeling parameters. Although this method is empirically related, it is suitable for engineering applications due to its simplicity. For example, in the asphalt pavement design specifications of the United States and China, the mathematical model is used to estimate the dynamic modulus of asphalt mixtures. Therefore, this article adopts the numerical fitting method to predict the shear strength of asphalt mixtures. After an appropriate model form and modeling parameters were selected, the shear strength of 101 sets of asphalt mixtures was fitted, and the prediction model was verified by extra test data. This model plays a guiding role in the rapid realization of asphalt mixture design objectives and promotes the establishment of a performance-based asphalt mixture design method.

2. Selection of the Modeling Parameters

As noted above, raw material characteristics, aggregate gradation, asphalt content, and volume parameters have an impact on the shear strength of asphalt mixtures. It is necessary to choose reasonable modeling parameters for mathematical fitting. As the asphalt mixture is produced by mixing some raw materials according to some design methods, the factors affecting the shear strength of asphalt mixtures are summarized into two categories: the raw material characteristics and the design parameters. The former includes the properties of the aggregate and asphalt binder, and the latter includes aggregate gradation, asphalt content, and the molding parameters. In this article, these two categories of factors are discussed as follows to choose suitable modeling parameters.

1. Aggregates properties: This article chose composed bulk specific gravity (Gsb) and aggregate surface energy to reflect aggregates properties.

   In theory, the shape, texture, and lithology of the aggregate affect the movement resistance between aggregate particles and the adhesion between particles and asphalt and further affect the shear strength of asphalt mixtures. In terms of aggregate shape indicators, some scholars argued that the content of needle and plate particles plays an important role in affecting the performance of the mixture [20], while others thought that different particle shapes should be considered, not just the needle and plate particles. So, they used imagery methods to characterize the shape of aggregate particles [21]. This method is accurate but complicated and needs lots of work to handle particle pictures as well. In terms of aggregate texture indicators, rougher textures generate more friction between aggregate particles. Typically, crushed faces have more texture than noncrushed faces. Usually, the more crushed a particle is, the more surface texture it will have, but not always. NCHRP Report 567 used Gsb to distinguish different types of aggregates when studying the effect of volume parameters on the anti-rutting performance of asphalt pavements [22]. The research conclusions of NCHRP Report 567 have shown that Gsb is a convenient parameter. So, this article chose Gsb to characterize different types of aggregates. However, since Gsb cannot reflect the adhesion between aggregate and asphalt, this article selected aggregate surface energy as another parameter to present aggregate properties. This parameter is commonly used in the study of moisture stability of asphalt mixtures [23], which can reflect the quantitative adhesion force between aggregates and asphalt from the energy aspect.

2. Asphalt binder properties: The unrecoverable creep compliance (Jnr3.2) was chosen to reflect asphalt binder properties in this article.

   The stiffer the binder, the higher the shear strength of the asphalt mixtures. Common indicators such as penetration, softening point, and viscosity can all reflect the stiffness of asphalt in different degrees. The Strategic Highway Research Program (SHRP) proposes the rutting factor to characterize the high-temperature performance of asphalt. However, some studies have shown that these indicators can effectively distinguish virgin asphalt, but it is difficult to
The aggregate gradation: This article used Grading Index (GI) and specific surface area (SA) to reflect the characteristics of aggregate gradation.

Aggregate gradation has an important effect on the shear strength of asphalt mixtures. A gradation analysis method was proposed by Bailey in 2001 [26]. In this method, coarse aggregate particles are placed in a unit volume to create voids and fine aggregate particles that can fill the voids are created by the coarse aggregate in the mixture. Some new indicators such as CA, Fac, and FAA were defined to evaluate the gradation characteristic. Roque proposed a dominant aggregate size range (DASR) model to describe the influence of gradation structure on asphalt mixture performance [27]. The model considers that the aggregate particle sizes within DASR make up the primary structure or “skeleton” of the mixture. Particles larger than the DASR will be “float” in the skeleton, and particles finer than the DASR will fill the skeleton voids. Archilla [28] defined GI to analyze the gradation characteristics. GI refers to the sum of percent deviation away from the maximum density line (the 0.45 power line) at each sieve size. It is calculated according to equation (1):

$$GI = \sum |P_i - P_{i\text{-theory}}|,$$  \hspace{1cm} (1)

where GI is Grading Index; $P_i$ is the percentage passing for a specific gradation (%); $P_{i\text{-theory}}$ is the percentage passing for the maximum density line, which is determined by equation (2):

$$P_{i\text{-theory}} = \left(\frac{d_i}{D}\right)^{0.45} \times 100,$$ \hspace{1cm} (2)

$d_i$ is sieve size (mm); $D$ is the minimum sieve size of that gradation (mm).

Archilla adopted GI to study the effect of aggregate gradation on the antirut property of asphalt mixture at WesTrack, indicating that GI exhibited satisfactory applicability for such research. Considering that two different gradation curves may have the same GI, the author proposed SA as another parameter. SA is critical to determine the asphalt film thickness, which is closely related to mixture properties. In this paper, SA is calculated according to JTG E20-2011 Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering of China.

The asphalt content: This article used the asphalt-aggregate ratio to characterize the asphalt content in asphalt mixtures.

The molding parameters: Both the fabrication manner (Marshall blow, static pressing, kneading, gyratory, etc.) and the mixing process (mixing time, mixing temperature, compaction effort, etc.) affect the shear strength of asphalt mixtures, but it is difficult to involve all these factors in a mathematical model currently. In this article, the asphalt mixtures were designed with the Superpave method. Thus, the SGC (Superpave Gyratory Compactor) number of gyrations was used to represent the molding parameters.

3. Test Scope and Method

In this article, two coarse aggregates (basalt and sandstone), two fine aggregates (limestone and sandstone), two asphalt kinds (70-PEN unmodified asphalt and polymer modified asphalt), seven gradations, four gyratory numbers, and four asphalt contents were adopted for the test. Overall, there were 101 sets of asphalt mixtures with different variable combinations. The percentage passing of seven aggregate gradations was shown in Table 1, and other values required for modeling were presented in Tables 2 and 3.

In this article, the shear strength of asphalt mixtures was determined with Uniaxial Penetration Test (UPT). This test method was involved in JTG D50-2017 Specification for Design of Highway Asphalt Pavement of China. The test principle of UPT was illustrated in Figure 1. A cylindrical specimen, with a height of 100 mm and a diameter of 150 mm, manufactured by SGC, was loaded with a cylindrical steel indenter at a speed of 1 mm/min at 60°C. The diameter of the steel indenter was 42 mm so that the surrounding portion of the specimen would provide confining stress for the loaded portion to simulate the actual confining stress in the pavement. The shear strength is expressed by

$$\tau_0 = \frac{f \times F}{A_c},$$ \hspace{1cm} (3)

where $\tau_0$ is shear strength (MPa), $F$ is the maximum load (N), and $A_c$ is the cross-section area ($\text{mm}^2$), $f = 0.350$, representing the sample dimension correction coefficient.

4. Initial Analysis of Test Results

The test results of the shear strength of asphalt mixtures are shown in Table 4. Four parallel specimens were taken for each test.

First, analysis of variance (ANOVA) was performed on the test results to verify whether the selected modeling parameters were reasonable. The SPSS software was used for ANOVA in this part. The results of ANOVA are shown in Table 5.

It can be seen from Table 5 that all the modeling parameters have significant effects on the shear strength of asphalt mixtures.
asphalt mixtures (significance < 0.05), illustrating that the modeling parameters selected in this article are valid and can be used for the establishment of shear strength prediction model. Besides, ANOVA results in Table 5 demonstrate the complex interactions between different modeling parameters and further illustrate the necessity of establishing a shear strength prediction model concerning the effects of multiple parameters.

This article further analyzed the effects of the modeling parameters on shear strength based on the test data in Tables 1–4. The result was expressed in Figure 2. When the effect of a specific parameter is analyzed, other modeling parameters remain unchanged. The analysis results with all the data are not given here, but are illustrated with partial data as an example.

From Figure 2, it can be observed that the shear strength is influenced by the modeling parameters to different degrees. Based on the result in Figure 2, this article divided the effects of modeling parameters on the shear strength of asphalt mixtures into three categories: (i) the shear strength increases monotonously with the change of modeling parameters, such as the effect of the gyratory compaction number; (ii) the shear strength decreases monotonously with the variation of modeling parameters, as in the effect of the GI; (iii) the shear strength varies nonlinearly with the change of modeling parameters, demonstrated by the effect of the asphalt-aggregate ratio. Upon the foregoing analyses, a practical prediction model for shear strength can be proposed.

5. Establishment and Verification of the Prediction Model for the Shear Strength of Asphalt Mixtures

5.1. Establishment of the Prediction Model. Based on previous analyses, a simple and clear prediction model for the shear strength of asphalt mixtures was established after many trials. It is presented as equation (4).

$$R_t = G_{sb} [n_1 \times (Pa/SA)^{n_2} \times r_1/SA + n_3] \times GI^n \times N^m \times \gamma^n \times f_{3.2}^2 \times$$

(4)
Table 4: Shear strength of 101 sets of asphalt mixtures.

| Grading  | Gyratory number | Asphalt type | Asphalt-aggregate ratio (%) | Shear strength (MPa) |
|----------|-----------------|--------------|----------------------------|----------------------|
| Sup13-1  | 50              | 70#          | 4.3                        | 0.423                |
| Sup13-1  | 50              | 70#          | 4.7                        | 0.463                |
| Sup13-1  | 50              | 70#          | 5.1                        | 0.499                |
| Sup13-1  | 50              | 70#          | 5.5                        | 0.777                |
| Sup13-1  | 75              | 70#          | 4.1                        | 0.514                |
| Sup13-1  | 75              | 70#          | 4.4                        | 0.537                |
| Sup13-1  | 75              | 70#          | 4.7                        | 0.563                |
| Sup13-1  | 75              | 70#          | 5.0                        | 0.801                |
| Sup13-1  | 100             | 70#          | 4.1                        | 0.541                |
| Sup13-1  | 100             | 70#          | 4.4                        | 0.586                |
| Sup13-1  | 100             | 70#          | 4.7                        | 0.668                |
| Sup13-1  | 125             | 70#          | 5.0                        | 0.916                |
| Sup13-1  | 125             | 70#          | 4.1                        | 0.609                |
| Sup13-1  | 125             | 70#          | 4.4                        | 0.695                |
| Sup13-1  | 125             | 70#          | 4.7                        | 0.813                |
| Sup13-1  | 125             | 70#          | 5.0                        | 1.110                |
| Sup13-1  | 50              | Polymer      | 4.7                        | 0.895                |
| Sup13-1  | 75              | Polymer      | 4.7                        | 1.102                |
| Sup13-1  | 100             | Polymer      | 4.7                        | 1.205                |
| Sup13-1  | 125             | Polymer      | 4.7                        | 1.273                |
| Sup13-2  | 50              | 70#          | 4.3                        | 0.495                |
| Sup13-2  | 50              | 70#          | 4.7                        | 0.527                |
| Sup13-2  | 50              | 70#          | 5.1                        | 0.570                |
| Sup13-2  | 50              | 70#          | 5.5                        | 0.789                |
| Sup13-2  | 75              | 70#          | 4.3                        | 0.600                |
| Sup13-2  | 75              | 70#          | 4.7                        | 0.668                |
| Sup13-2  | 75              | 70#          | 5.1                        | 0.853                |
| Sup13-2  | 75              | 70#          | 5.5                        | 0.978                |
| Sup13-2  | 100             | 70#          | 4.1                        | 0.564                |
| Sup13-2  | 100             | 70#          | 4.4                        | 0.692                |
| Sup13-2  | 100             | 70#          | 4.7                        | 0.851                |
| Sup13-2  | 100             | 70#          | 5.0                        | 0.956                |
| Sup13-2  | 125             | 70#          | 4.1                        | 0.754                |
| Sup13-2  | 125             | 70#          | 4.4                        | 0.850                |
| Sup13-2  | 125             | 70#          | 4.7                        | 1.014                |
| Sup13-2  | 125             | 70#          | 5.0                        | 1.141                |
| Sup13-2  | 50              | Polymer      | 4.7                        | 1.032                |
| Sup13-2  | 75              | Polymer      | 4.7                        | 1.170                |
| Sup13-2  | 100             | Polymer      | 4.7                        | 1.260                |
| Sup13-2  | 125             | Polymer      | 4.7                        | 1.350                |
| Sup13-5  | 75              | Polymer      | 4.3                        | 1.130                |
| Sup13-5  | 75              | Polymer      | 4.7                        | 1.160                |
| Sup13-5  | 100             | Polymer      | 4.7                        | 1.347                |
| Sup13-5  | 125             | Polymer      | 4.7                        | 1.487                |
| Sup13-5  | 75              | Polymer      | 5.1                        | 1.310                |
| Sup13-5  | 75              | Polymer      | 5.5                        | 1.290                |
| Sup13-5  | 75              | 70#          | 4.7                        | 0.640                |
| Sup13-6  | 100             | Polymer      | 4.3                        | 1.177                |
| Sup13-6  | 75              | Polymer      | 4.7                        | 0.950                |
| Sup13-6  | 100             | Polymer      | 4.7                        | 1.247                |
| Sup13-6  | 125             | Polymer      | 4.7                        | 1.370                |
| Sup13-3  | 50              | 70#          | 4.7                        | 0.427                |
| Sup13-3  | 50              | 70#          | 5.1                        | 0.434                |
| Sup13-3  | 50              | 70#          | 5.5                        | 0.451                |
| Sup13-3  | 50              | 70#          | 5.9                        | 0.572                |
| Sup13-3  | 75              | 70#          | 4.3                        | 0.446                |
| Sup13-3  | 75              | 70#          | 4.7                        | 0.496                |
| Sup13-3  | 75              | 70#          | 5.1                        | 0.597                |
| Sup13-3  | 75              | 70#          | 5.5                        | 0.730                |
| Sup13-3  | 100             | 70#          | 4.3                        | 0.738                |
where $R_t$ is shear strength (Pa); $n_1$-$n_7$ are undetermined coefficients; other parameters have the same meaning as before.

Substituting the relevant data in Tables 2-4 into equation (4) and using Origin software, we can get the regression values of $n_1$-$n_7$. The final form of equation (4) is shown as

$$R_t = G \left[ 5.25 \times \left( \frac{\text{Pa}}{\text{SA}} \right)^2 + 11.23 \times \left( \frac{\text{Pa}}{\text{SA}} \right) + 23.11 \right] N^{0.56} \times G^{0.35} \times J^{0.17} \times f_{n_r}^{0.28}, \quad R^2 = 0.841.$$  

All the parameters have the same meaning as before. The comparison between measured and predicted shear strength of asphalt mixtures is shown in Figure 3. The oblique line in the figure is the isoline of measured and predicted values.

As can be seen from Figure 3, the accuracy of the prediction model is generally satisfactory, and the correlation coefficient between the predicted and measured values reaches 0.841, indicating that the form and parameters of the prediction model are available.

5.2. Verification of the Prediction Model. To verify the applicability of the model shown in equation (4), this article used extra test data to verify the model. The data used for verification are shown in Table 6. These data come from other projects of our research group.

The predicted shear strength can be obtained by substituting the data in Table 6 into equation (4). The comparison between the measured values and the predicted values is presented in Figure 4. It can be seen from the figure that measured and predicted values are well correlated, and

| Table 4: Continued. | Gyratory number | Asphalt type | Asphalt-aggregate ratio (%) | Shear strength (MPa) |
|---------------------|----------------|--------------|-----------------------------|---------------------|
| Sup13-3 100         | 70#            | 4.7          | 0.793                       |
| Sup13-3 100         | 70#            | 5.1          | 0.951                       |
| Sup13-3 125         | 70#            | 4.4          | 0.700                       |
| Sup13-3 125         | 70#            | 4.7          | 0.921                       |
| Sup13-3 125         | 70#            | 5.0          | 1.256                       |
| Sup13-3 50          | Polymer        | 4.7          | 0.902                       |
| Sup13-3 75          | Polymer        | 4.7          | 1.088                       |
| Sup13-3 100         | Polymer        | 4.7          | 1.238                       |
| Sup13-3 125         | Polymer        | 4.7          | 1.302                       |
| Sup13-4 50          | 70#            | 4.7          | 0.296                       |
| Sup13-4 50          | 70#            | 5.1          | 0.482                       |
| Sup13-4 50          | 70#            | 5.5          | 0.578                       |
| Sup13-4 50          | 70#            | 5.9          | 0.626                       |
| Sup13-4 75          | 70#            | 4.7          | 0.448                       |
| Sup13-4 75          | 70#            | 5.1          | 0.739                       |
| Sup13-4 75          | 70#            | 5.5          | 0.855                       |
| Sup13-4 75          | 70#            | 5.9          | 0.962                       |
| Sup13-4 100         | 70#            | 4.3          | 0.602                       |
| Sup13-4 100         | 70#            | 4.7          | 0.655                       |
| Sup13-4 100         | 70#            | 5.1          | 0.804                       |
| Sup13-4 100         | 70#            | 5.5          | 1.083                       |
| Sup13-4 125         | 70#            | 4.3          | 0.753                       |
| Sup13-4 125         | 70#            | 4.7          | 0.882                       |
| Sup13-4 125         | 70#            | 5.1          | 1.006                       |
| Sup13-4 125         | 70#            | 5.5          | 1.248                       |
| Sup13-4 50          | Polymer        | 4.7          | 0.856                       |
| Sup13-4 75          | Polymer        | 4.7          | 0.992                       |
| Sup13-4 100         | Polymer        | 4.7          | 1.221                       |
| Sup13-4 125         | Polymer        | 4.7          | 1.369                       |
| Sup13-6 100         | Polymer        | 4.7          | 1.180                       |
| Sup13-6 100         | Polymer        | 5.1          | 1.380                       |
| Sup13-6 100         | Polymer        | 5.5          | 1.250                       |
| Sup13-6 100         | 70#            | 4.7          | 0.710                       |
| Sup13-7 125         | Polymer        | 4.3          | 1.253                       |
| Sup13-7 75          | Polymer        | 4.7          | 0.720                       |
| Sup13-7 100         | Polymer        | 4.7          | 1.030                       |
| Sup13-7 125         | Polymer        | 4.7          | 1.363                       |
| Sup13-7 125         | Polymer        | 5.1          | 1.500                       |
| Sup13-7 125         | Polymer        | 5.5          | 1.313                       |
| Sup13-7 125         | 70#            | 4.7          | 0.770                       |
Table 5: ANOVA results with the test data.

| Sources                                      | df | Square of the average | $F$    | Sig.   |
|----------------------------------------------|----|-----------------------|--------|--------|
| Modified model                               | 101| 0.273                 | 70.408 | 0.000  |
| Intercept                                    | 1  | 77.693                | 20058.881 | 0.000 |
| Aggregate surface energy                     | 1  | 0.043                 | 11.136 | 0.001  |
| Asphalt-aggregate ratio                      | 8  | 0.377                 | 97.408 | 0.000  |
| Rotating times                               | 3  | 1.317                 | 339.961 | 0.000 |
| Jnr3.2                                       | 1  | 4.389                 | 1133.090 | 0.000 |
| GI                                           | 3  | 0.205                 | 52.925 | 0.000  |
| Aggregate surface energy * compaction number | 2  | 0.056                 | 14.500 | 0.000  |
| Aggregate surface energy * Jnr3.2            | 1  | 0.018                 | 4.550  | 0.034  |
| Aggregate surface energy * GI                | 2  | 0.045                 | 11.550 | 0.000  |
| Asphalt-aggregate ratio * compaction number  | 16 | 0.009                 | 2.381  | 0.003  |
| Asphalt-aggregate ratio * GI                 | 16 | 0.016                 | 4.137  | 0.000  |
| Compaction number * Jnr3.2                   | 3  | 0.020                 | 5.254  | 0.002  |
| Compaction number * GI                       | 9  | 0.019                 | 4.989  | 0.000  |
| Jnr3.2 * GI                                  | 3  | 0.007                 | 1.762  | 0.156  |
| Error                                        | 201| 0.004                 |        |        |
| Total                                        | 303|                      |        |        |
| Corrected total                              | 302|                      |        |        |

a. $R^2$ square = 0.973 (square of adjusted $R = 0.959$)

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**Figure 2: Continued.**

(a) 
(b) 
(c) 
(d)
Figure 2: Effects of different modeling parameters on the shear strength. (a) Effects of aggregate surface energy on the shear strength. (b) Effects of Jnr3.2 on the shear strength. (c) Effects of GI on the shear strength. (d) Effects of specific surface area on the shear strength. (e) Effects of asphalt-aggregate ratio on the penetration strength. (f) Effects of the gyratory number on the shear strength.

Figure 3: Comparison between the measured and predicted values.

Table 6: Data for validating the prediction model.

| Asphalt-aggregate ratio (%) | GI     | Gyratory number | Jnr3.2 (kPa⁻¹) | SA (m²/kg) | Surface energy (mJ/m²) | Gsb   | Shear strength (MPa) |
|-----------------------------|--------|-----------------|-----------------|------------|------------------------|-------|----------------------|
| 4.8                         | 41.5   | 50              | 1.44            | 4.70       | 45.06                  | 2.775 | 1.218                |
| 4.7                         | 47.0   | 75              | 1.44            | 4.59       | 45.01                  | 2.776 | 1.320                |
| 4.6                         | 52.6   | 100             | 1.44            | 4.14       | 44.91                  | 2.776 | 1.386                |
| 4.6                         | 63.3   | 125             | 1.44            | 3.81       | 44.74                  | 2.778 | 1.454                |
| 4.6                         | 41.5   | 50              | 3.62            | 4.70       | 45.06                  | 2.775 | 1.129                |
| 4.5                         | 47.0   | 75              | 3.62            | 4.59       | 45.01                  | 2.776 | 1.194                |
| 4.5                         | 52.6   | 100             | 3.62            | 4.14       | 44.91                  | 2.776 | 1.263                |
| 4.5                         | 63.3   | 125             | 3.62            | 3.81       | 44.74                  | 2.778 | 1.334                |
| 4.7                         | 41.5   | 50              | 6.34            | 4.70       | 45.06                  | 2.775 | 1.034                |
| 4.6                         | 47.0   | 75              | 6.34            | 4.59       | 45.01                  | 2.776 | 1.112                |
| 4.5                         | 52.6   | 100             | 6.34            | 4.14       | 44.91                  | 2.776 | 1.118                |
| 4.5                         | 63.3   | 125             | 6.34            | 3.81       | 44.74                  | 2.778 | 1.228                |
| 4.7                         | 66.6   | 75              | 1.44            | 4.55       | 44.15                  | 2.782 | 1.420                |
| 4.6                         | 82.6   | 100             | 1.44            | 4.16       | 44.02                  | 2.783 | 1.589                |
| 4.7                         | 66.6   | 75              | 6.34            | 4.55       | 44.15                  | 2.782 | 1.145                |
| 4.6                         | 82.6   | 100             | 6.34            | 4.16       | 44.02                  | 2.783 | 1.196                |
| 4.7                         | 66.6   | 75              | 3.62            | 4.55       | 44.15                  | 2.782 | 1.298                |
| 4.6                         | 82.6   | 100             | 3.62            | 4.16       | 44.02                  | 2.783 | 1.395                |
the correlation coefficient reaches 0.827, which shows the satisfactory applicability of the prediction model.

6. Conclusions and Further Works

In this article, the prediction model of the shear strength of asphalt mixtures was established based on the characteristics of raw materials and the design parameters. The model was obtained by fitting 101 sets of asphalt mixture test data and validated with other 18 sets of data. The result proved that the prediction model established in this article has good prediction accuracy. It can be utilized to reduce the test workload and guide the design of asphalt mixtures.

It should be noted that the prediction model proposed in this article is not perfect. It has to be optimized in further work. In the future, more types of materials should be used for verification and other new parameters should be adopted for optimization. Apart from this, the balance between shear property and other performances of asphalt mixtures also should be concerned in the future.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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