Research on prediction of WMA mixing temperature or additive dosage using digital image recognition of coating rate

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Abstract
It is difficult to determine a reasonable mixing temperature for WMA based solely on the viscosity-temperature relationship of the binder, as is the case for HMA, and it is a more reasonable solution to determine the mixing temperature of WMA by the state of the mix. This paper proposes to use the coating rate as an index for determining the mixing temperature of WMA, to analyze the reliability and sensitivity of this index using a digital image recognition method, and to analyze the influence law of this method based on the coating rate recognition test. The study shows that: The precision of the digital image coating rate recognition test can meet the requirements of calculating the mixing temperature; in a certain range, the coating rate of WMA is positively correlated with the mixing temperature or additive dosage; the sensitive variation of the coating rate with mixing temperature and additive dosage can be used to predict the engineering mixing temperature or additive dosage for WMA; the slope of the coating rate contour also has some common trends and can be used to illustrate the effect of warm mix additives (or warm mix technology) on the effectiveness or efficiency of warm mix.

1. Introduction
Warm mix asphalt (WMA) is an effective and environmentally friendly technology in the field of road engineering. It is a technical measure to reduce the mixing temperature during the construction phase without affecting (or significantly affecting) the serviceability of the asphalt mix after paving. The mixing temperature of WMA is usually 20 ~ 30 °C lower than that of hot mix asphalt (HMA) due to factors such as dust removal from aggregate drying and temperature loss in subsequent construction operations. Currently, the technical mechanisms of WMA can be broadly classified into four categories: foam viscosity reduction, dilution viscosity reduction, high melting point paraffin viscosity reduction and surfactant interfacial lubrication. As with conventional HMA, the engineer needs to determine the appropriate mixing temperature during the mix design and construction phase of WMA. However, determining a reasonable mixing temperature is more difficult for WMA than for HMA because the flow state of WMA binders is not only influenced by temperature, but also by other factors such as foam state (foaming viscosity-reducing type), diluent evaporation (dilution viscosity-reducing type) and aggregate contact relations (surfactant lubrication type). In addition, the additive dosage of WMA and the mixing temperature are a pair of interrelated influences within a certain range. These effects are felt throughout the entire process from mixing (hot state) to compaction (cooling), making it difficult to determine a reasonable mixing temperature for WMA based solely on the viscosity-temperature relationship of the binder, as is the case for HMA, and a more reasonable solution would be to determine the mixing temperature of WMA based on the state of the mix. To this end, we have carried out a study of an experimental method for determining the reasonable mixing temperature or additive dosage of WMA based on the quantified state of the mix coating rate. For common petroleum asphalt as the binder of HMA, due to the binder in relatively high temperature conditions show Newtonian fluid properties, mobility (viscosity) is only affected by temperature changes,
generally through the asphalt viscosity temperature curve to determine the mix reasonable mixing temperature, this method of determining the construction operating temperature of the mix was first derived from the 1960s AI research results, and proposed 0.17 ± 0.03 Pa*s 0.02 Pa*s and 0.28 ± 0.03 Pa*s viscosity as the standard for mixing and compaction temperature, has been widely recognized around the world [1]. Similar to WMA, polymer modified asphalt exhibits non-Newtonian fluid properties at high temperatures, and usually a reasonable mixing temperature for modified asphalt HMA cannot be obtained simply from the viscosity-temperature curve. Yildirim [2], Bahia [3], Shenoy [4], Zhang [5] and Ji [6] used the viscosity-temperature relationship or viscosity-temperature curve at a specific shear rate to determine the mixing (or compaction) temperature based on the relationship between the state of the mix and the shear rate of the asphalt film during the mixing (or compaction) process. The viscosity-temperature relationship of asphalt mastic at a specific shear rate has also been proposed by Azari [7] to determine the mixing (or compaction) temperature. The above mentioned methods for common and modified asphalt can be extended to some WMAs, e.g. when using high melting point paraffin waxes like Sasobit to reduce viscosity, the viscosity temperature curve of the bitumen only shows a sudden change around the melting point of the paraffin wax (about 105 °C) and remains parallel to the original curve at higher or lower temperatures without fundamental changes in rheological properties, so that it is still reasonable to use the test methods for common and modified asphalt methods to determine the mixing temperature [8, 9]. However, for most other mechanisms of WMA, it is difficult to determine the mixing or compaction temperature directly from the binder [1].

It is a common practice in WMA to infer the mixing temperature from the void ratio or compaction curve of the formed specimens immediately after mixing at variable temperature, and Wang [10], Yan [11] and He [12] have argued that this method is more convenient when designing engineering mixes. However, this method ignores the inhomogeneous changes in the state of the mix during and after mixing, which essentially reflects the compactability or the state of the compacted object, corresponding precisely to the compaction temperature (rather than the mixing temperature). Some studies have also pointed out that the variable temperature mixing followed by immediate forming method is insensitive to intermittent and open grading and that the temperatures determined do not correspond to empirical mixing temperatures [13]. Due to the dominant influence of temperature on the viscosity of the binder, different mixing temperatures must correspond to specific workability of the mix. The workability index is used directly to characterize the state of the mix, and the temperature corresponding to the specific workability is then used as the reasonable mixing or compaction temperature. Wang Liming [13], Wang Chun [14] and Sukhija [15] determined the compaction or mixing temperature by mix workability. They used penetration resistance from penetration tests, agitator torque and agitator motor load as characteriztion indicators of workability, respectively, but these methods all require the resistance indicator to be calibrated first by ordinary asphalt, while the tests to obtain both indicators are subject to large variability.

Complete and uniform coating of the aggregate by the asphalt without excessive ageing is the basic objective of asphalt mix condition control, which is usually used to control the mixing time at a given mixing temperature, but mixing temperature and time are conjugate indicators for the percentage of coating under certain conditions, as explained in ASTM D2489/D2489M-16 and in the literature [1] and [14], the mixing time changes when the mixing temperature changes and vice versa. Therefore, mixing temperature, like time, can be regarded as a sensitive factor affecting the rate of coating within a certain range. When the mixing time is fixed, a coating rate of exactly 100% can correspond to a specific mixing temperature, which may be a reasonable mixing temperature or be highly correlated with it. In this study, a digital image analysis method was introduced as a means of coating rate identification, and the method and process of using digital image recognition of coating rate to predict WMA mixing temperature or additive dosage was investigated experimentally.
2. Research program

Two research objectives were addressed: (1) Checking the reliability or variability of digital image recognition coating rate tests; (2) Test whether the coating rate indicator is sensitive to mixing temperature or additive dosage. A study flow for the multiple WMA based mix coating rate identification test was designed as shown in figure 1.

3. Experiment material

3.1. Asphalt and aggregate

The test used 90# common petroleum asphalt, SBS modified asphalt and basalt aggregate, the basic technical index parameters were tested according to Chinese technical standard JTG F40 as shown in table 1 and table 2. The basic properties of the materials used are in accordance with the relevant technical requirements of JTG F40.

3.2. Warm mix additives

(1) Asphalt foaming and viscosity reduction additive - EC-130

EC-130 (abbreviated EC) is a zeolite powder containing crystalline water, manufactured by Shenzhen Ocean Power (Opmaterial, China). The water contained can be released continuously during mixing, and the hot asphalt acts as a foaming agent, which improves the workability of the mix due to the lubricating effect of the foam. The basic parameters are shown in table 3.

(2) Surface active mechanism additive - Evotherm DAT

Evotherm DAT (abbreviated EV) is an ionic surfactant manufactured by Medvisvaco, USA. By indicating the combined effect of the active agent and the introduction of a small amount of water, the surface tension of the asphalt or aggregate interface is reduced, making the asphalt easier to spread on the surface of the aggregate and the asphalt film potential is increased and more lubricious, while the high concentration of water-in-oil emulsion formed by the part of the asphalt coating on the surface of the particles also has a certain viscosity.

### Table 1. Basic performance parameters of binders.

| Characteristics                  | 90# petroleum asphalt | SBS modified asphalt |
|----------------------------------|-----------------------|----------------------|
| Penetration at (25 °C,5 s, 100 g)/0.1 mm | 82                    | 74                   |
| PI                               | 0.749                 | −0.31                |
| Softening point from 5 °C        | 44.2                  | 76                   |
| Ductility at 5 °C cm−1           | /                     | 49                   |
| Ductility at 15 °C cm−1          | >100                  | /                    |
| 135 °C viscosity/ pa s           | /                     | 1.205                |

### Table 2. Basic performance parameters of aggregate.

| Characteristics                  | Test results            |
|----------------------------------|-------------------------|
| Crush value/%                   | 15.8                    |
| Los Angeles abrasion loss/%      | 17.5                    |
| Water absorption/%              | 0.6                     |
| Polishing value                  | 52.2                    |
| Adhesion grade to asphalt        | 5                       |

### Table 3. EC-130 basic physical and chemical parameters.

| Abbreviated symbol | Exterior | Bulk density/(g·cm⁻³) | PH value | Water content/% |
|--------------------|----------|-----------------------|----------|-----------------|
| EC                 | Pink powder | 0.78                  | 9.9      | 22.1            |
reduction benefit, thus reducing the mixing temperature. The EV dosage is 1/9 of the asphalt quality indoors, and 1/19 of the asphalt quality during construction. The basic parameters are shown in table 4.

(3) High melting point paraffin viscosity reducing additive—Sasobit

Sasobit (abbreviated S) is a long-chain saturated aliphatic hydrocarbon, a high melting point paraffin wax made from coal by the Fischer-Tropsch method, produced by Sasol-Wax, Germany. This paraffin has a melting point of around 105 °C and is completely soluble in asphalt at 115 °C to 135 °C, thereby lubricating the asphaltene gum mass and reducing the viscosity of the asphalt. Its basic parameters are shown in table 5.

(4) Surface active mechanism additive—BMH

BMH (abbreviated B) is an oil-soluble, non-ionic surfactant based blend with some paraffin and performance compensating components, manufactured by Xi’an Yonghe Technology, China. The paraffin in this additive promotes compatibility with asphalt and viscosity reduction of the asphalt, and has similar spreading and lubricating effects to Evotherm DAT in promoting asphalt films. The basic parameters are shown in table 6.

3.3. The basic ratio of the mixture

The basic mix ratio of the test was AC-13 specified by JTG F40. Considering that it is desirable to avoid the interference of excessive coarse particles on the mix coating and the temperature sensitivity of compaction in
subsequent studies, making it slightly finer relative to the specification median, with the composition shown in figure 2. The optimum amount of base asphalt for HMA was determined by Marshall testing to be 5.1% and the optimum amount of SBS modified asphalt to be 5.2% by standard sieve staging step by step back-mixing of the aggregate. As the dosage of additives used was in trace amounts, the study assumed that the optimum asphalt dosage for WMA was the same as that for HMA, where the EC-130 additive was based on out-mixing relative to the mix and the other additives were based on out-mixing relative to the asphalt.

4. Coating rate identification test method

4.1. Test equipment
The main equipment used for the mixing test was a 20L mixer, as shown in figure 3(a). This apparatus is the standard mixing equipment specified in the Chinese standard JTG E20, which allows stable control of the mixing temperature in the range from room temperature to 200 °C.

The main equipment used for the coating rate identification test was a high pixel digital camera with tripod and an ALPHA-1501 cold light source, where the cold light source was arranged as shown in figure 3(b), with the incident light angle controlled at 45° on both sides to eliminate natural light shadow areas.

4.2. Specimen preparation method
The test specimens are prepared according to ASTM D2489. After mixing the mix under set conditions, the hot mix is passed through a 9.5 mm sieve and the particles on the sieve are taken and placed randomly and without overlap on clean paper as the object of image recognition.

Mixing time is also one of the conditions that affects the coating rate, with ASTM specifying a laboratory mixing time of between 90–120s and Chinese JTG E20 specifying a standard mixing time of 180s for mix design. To avoid the interference of grade variation on the coating rate, the mix was back-mixed with standard sieved
aggregates of the same material source. In order to avoid the influence of the mixing time factor on the coating rate, a progressive test with variable mixing time at a fixed high temperature (163 °C for the base asphalt and 175 °C for the modified asphalt) was first carried out based on the HMA, and the combination of two mixing times before and after the mineral powder input was selected as 90s + 30s by observing the degree of coating and taking complete coating as the standard. All subsequent mixes are controlled by this grading and time condition standard.

4.3. Digital image processing methods

A 2D digital image recognition process similar to this problem consists of four typical steps as in figure 4: image acquisition, image enhancement, image segmentation, and image target feature extraction [16]. It is worth pointing out that the application of digital recognition techniques in the study of the surface morphology of materials or structures has become more common and mature, and the above 4-step recognition process digital image recognition process is also applicable to any adoption of other image recognition software, such as the commonly used Matlab. However, due to differences in research needs, the 2 steps of image enhancement and image segmentation vary considerably in different application areas, often also depending on the means of digital image perception (acquisition) [17]. The digital image processing software Image-Pro Plus (IPP) was used in this study. The most prominent feature of IPP compared to other processing software is the automatic extraction of the AOI of the region of interest, which simplifies the process of identifying the test and reduces the difficulty of using the software. As shown in figure 4 for both image enhancement and image segmentation, the manual calibration method is used in this study, i.e. the software parameters for these two steps are set based on experimental progressive calibration, which ultimately makes the machine recognition results stable and identical to the manual recognition results under the boundary conditions.

4.4. Coating rate indicator definition

ASTM D2489 defines the coating rate as the percentage of the number of completely coated particles to the total number of particles tested, this indicator does not easily reflect the continuous change of the coating degree, due to the introduction of digital image technology, this study defines the coating rate indicator as the ratio of the coating area to the measured area, the coating rate CR formula is expressed as follows.

$$CR = \left(1 - \frac{S_r}{S_t}\right) \times 100$$

In the formula: $S_r$—Relative exposed area of measured particles, dimensionless; $S_t$—Relative total area of measured particles, dimensionless.

5. Analysis of test results

5.1. Reliability of CR tests for digital image recognition of coating rates

The base asphalt WMA mixed at 115 °C was investigated and six parallel coating rate identification tests were carried out for 1% dosage S and B additives respectively. Due to the small sample size and the lack of test method precision comparison objects, this paper estimates the reliability of the test method by judging the data as outliers, using a simple Gurbbs test, the test results are shown in table 7.

| Parallel test number | S additive CR/% | B additive CR/% |
|----------------------|----------------|----------------|
| 1                    | 82.47          | 82.95          |
| 2                    | 83.91          | 84.28          |
| 3                    | 79.65          | 81.86          |
| 4                    | 85.21          | 80.82          |
| 5                    | 85.65          | 86.11          |
| 6                    | 82.60          | 82.17          |
| Average value $\bar{X}$ | 83.25          | 82.95          |
| Standard deviation $\sigma$ | 2.19          | 1.90            |
| Maximum relative error | 3.60%          | 3.16%            |
| G                    | 1.64           | 1.66            |
| $G_{0.05}$ (6)       | 1.729          | 1.729          |

The Gurbbs test is an outlier discrimination method that assumes that the number of outliers is one, and is recommended by ISO, ASTM and China’s GB/T4883. The test value G is the ratio of the most suspicious value and the difference between the mean and the standard deviation: $G = \left| \text{Most suspicious value — Average value} / \text{Standard deviation} \right|$. The threshold value $G_{0.05}$ corresponding to the Gurbbs table is found according to the
number of measurements $n$ and the confidence level $\alpha$. When $G > G_\alpha(n)$, the most suspicious value can be considered as an outlier at the confidence level, and vice versa, the most suspicious value can be considered as not an outlier at the confidence level or the group of data meets the normal distribution with confidence level $\alpha$. If the most suspicious value is judged to be an outlier, the Gurbbs test can be applied again to determine whether there are any outliers in the remaining samples after the outliers have been removed [18].

As can be seen from table 7, the G-value tests for both sets of parallel tests were no greater than the closest critical values $G_{0.05}(6)$ in the table, i.e. the assumption of outliers was rejected and the data from the six parallel tests were of high accuracy. The prediction of the mixing temperature from the coating rate-temperature relationship is the derivation of an indirect indicator from a direct measurement, a process that is logically consistent with the derivation of the mixing temperature from the asphalt viscosity-temperature relationship, the permissible error for the repeatability test of the viscosity test in China’s JTG E20 is 3.5% (confidence level 95%), while the results of the coating rate parallel test are 3.60% and 3.16%, average of approximately 3.40%.

Table 8. Bivariate crossover test results of CR.

| Types of additives | Dosage $^\ast /\%$ | Mixing temperature of common asphalt $^{\circ}\text{C}$ | Mixing temperature of modified asphalt $^{\circ}\text{C}$ |
|--------------------|-----------------|------------------|------------------|
|                    |                 | 115 | 125 | 135 | 145 | 155 | 130 | 140 | 150 | 160 | 170 |
| EC                 | 0.1             | 71.56 | 78.87 | 86.06 | 76.74 | 100 | 73.92 | 81.35 | 90.62 | 96.23 | 100 |
|                    | 0.2             | 75.23 | 86.31 | 91.71 | 100 | 100 | 78.83 | 86.19 | 95.54 | 100 | 100 |
|                    | 0.3             | 79.43 | 90.77 | 100 | 100 | 100 | 83.17 | 91.41 | 100 | 100 | 100 |
|                    | 0.4             | 82.17 | 93.58 | 100 | 100 | 100 | 87.47 | 94.47 | 100 | 100 | 100 |
| EV                 | 1               | 80.54 | 91.09 | 96.22 | 100 | 100 | 84.24 | 92.89 | 100 | 100 | 100 |
|                    | 2               | 84.65 | 94.78 | 100 | 100 | 100 | 88.19 | 94.62 | 100 | 100 | 100 |
|                    | 3               | 89.13 | 97.88 | 100 | 100 | 100 | 90.73 | 97.48 | 100 | 100 | 100 |
|                    | 4               | 93.26 | 100 | 100 | 100 | 100 | 93.05 | 99.3 | 100 | 100 | 100 |
| S                  | 1               | 73.24 | 80.66 | 86.78 | 98.86 | 100 | 75.04 | 82.51 | 91.87 | 98.34 | 100 |
|                    | 2               | 77.55 | 85.82 | 94.24 | 100 | 100 | 80.34 | 87.82 | 97.45 | 100 | 100 |
|                    | 3               | 82.48 | 94.93 | 100 | 100 | 100 | 86.53 | 92.23 | 100 | 100 | 100 |
|                    | 4               | 86.33 | 96.47 | 100 | 100 | 100 | 89.16 | 95.05 | 100 | 100 | 100 |
| B                  | 1               | 83.03 | 93.62 | 98.91 | 100 | 100 | 87.33 | 93.71 | 100 | 100 | 100 |
|                    | 2               | 87.13 | 96.01 | 100 | 100 | 100 | 91.18 | 96.35 | 100 | 100 | 100 |
|                    | 3               | 91.39 | 100 | 100 | 100 | 100 | 93.42 | 98.45 | 100 | 100 | 100 |
|                    | 4               | 95.62 | 100 | 100 | 100 | 100 | 95.06 | 100 | 100 | 100 | 100 |
| Blank group        | 70.32           | 76.74 | 84.03 | 91.47 | 100 | 71.44 | 79.20 | 88.6 | 93.26 | 100 |

Note: The additive dosage for the EC group is external relative to the mass of the mix, the others are external relative to the amount of asphalt used.
which is not very different from the requirements of the viscosity test. The precision of the coating rate test in this paper can meet the requirements of the projected mixing temperature, and the reliability of the test method is on par with that of the viscosity test.

### 5.2. Additive dosage-mixing temperature effect on the CR of coating rate

A bivariate cross-over comprehensive test of additive dosage and mixing temperature was designed, with parallel control tests of four WMAs at variable temperature mixing conditions from 115 to 155 °C for the base asphalt, and from 130 to 170 °C for the modified asphalt. In addition to the mixing temperature variation, the additive dosages of the four WMAs were also arranged at four levels of variation, together with a blank control group for both asphalts, resulting in a total of 170 sets of digital images and comparable test data including the blank test, each set of data being the average of two parallel tests. The data in table 8 were plotted as a contour plot of the coating rate and marked with interpolated integer CR, suggesting that the effect of these two additives on the effectiveness of warm mixing varies consistently over the range of dosages tested.

| Types | Mixing conditions in this study                                  | Other studies                                                                 | Producer experience                        |
|-------|-----------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------|
| EC    | Common asphalt: 0.2%−145 °C, 0.3%−135 °C, 0.3%−150 °C, Modified asphalt: 0.2%−160 °C, 0.3%−150 °C | Common asphalt: 0.3%−153 °C  [19] Modified asphalt: 0.3%−150 °C  [20, 21] | 0.3%, Reduce mixing temperature by 30 °C |
| EV    | Common asphalt: 1.0%−145 °C, 2.0%−135 °C, Modified asphalt: 1.0%−150 °C | Common asphalt: 5.0%−130 °C  [14] Modified asphalt: 10.0%−160 °C  [22] :1:9 water dilution | 1.0%, Reduce mixing temperature by 20 to 30 °C |
| S     | Common asphalt: 2.0%−145 °C, 3.0%−135 °C, Modified asphalt: 2.0%−160 °C, 5.0%−150 °C | Common asphalt: 1.5 ∼ 2.5%−145 ∼ 160 °C  [8] Modified asphalt: 2.0%−150 °C  [9] | 1.5 ∼ 2.5%, Reduce mixing temperature by 20 °C−40 °C |
| B     | Common asphalt: 2.0%−135 °C, 3.0%−125 °C, Modified asphalt: 1.0%−150 °C, 4.0%−140 °C | Common asphalt: 1.0%−140 °C  [23] Modified asphalt: 1.0%−150 °C  [21] | 1.0%−3.0%, Reduce mixing temperature by 30 °C−40 °C |

The mixing temperatures and additive dosages corresponding to the time when the coating rate reaches 100% (critical) in table 8 were observed and compared extensively with research literature and empirical data from additive manufacturers based on the working characteristics of the mixes, the results of which are presented in table 9.

In actual engineering, it is more common to use only a 20 °C−30 °C reduction relative to the HMA as the temperature losses from aggregate drying and de-dusting and subsequent operations are also taken into account. It can be seen that the additive dosage - mixing temperature corresponding to the 100% adhesion threshold is consistent with the results of established studies based on working characteristics and engineering experience.

The data in table 8 were plotted as a CR contour plot of the coating rate and marked with interpolated integer contours of the coating rate as in figure 5. Where (a) (b) (c) (d) are the test results for common asphalt with different additives, while (e) (f) (g) (h) are the test results for SBS modified asphalt with different additives.

In figure 5, we note that the mixing temperature (y-axis) in all eight plots causes the rate of coating (area) to vary continuously, regardless of the type of asphalt or the additives used. This trend indicates that the rate of coating (area) is sensitive to changes in mixing temperature over a range, confirming the inference in the introduction that ‘mixing temperature, like time, can be regarded as a sensitive factor affecting the rate of coating over a range.’ Similarly, the additive dosages (x-axis) in figure 5 all resulted in a continuous increase in the coating rate, indicating that the coating rate was also sensitive to changes in the dosage of the warm mix additive within the range set by the test.

In the equal scale figure 5, the 100% contours are taken from the measured data and the arrangement of the dependent variable spacing makes the high coating rate region vary unevenly in the plot, but the interpolated contours in the low coating rate interval have a good regularity. This regular variation in the low inclusion rate zone can, on the one hand, indicate that the use of digital image recognition tests can reflect the sensitivity of coating rate variation and, on the other hand, evaluate the effect of warm mix additives (or warm mix technology) on the effectiveness of warm mix based on these regularities. For example, additives EV (figures. (b), (f)) and B (figure. (d), (h)) show a turning zone in the low coating rate interval, indicating that the dosage of both additives has a more significant effect on the coating rate or warm mix effect at lower levels (<1%), after which the sensitivity decreases. Similarly, the variation in EC (figures. (a), (e)) and S (figures. (c), (g)) is more linear, suggesting that the effect of these two additives on the effectiveness of warm mixing varies consistently over the range of dosages tested.
For the same EV, S and B additives put into the asphalt, the relationship between mixing temperature and additive dosage to achieve the target coating rate can be compared on the basis of contours, thus comparing the effectiveness of the warm mix additives. The smoother interpolated contour of $CR = 98\%$ in figure 5 was extracted for comparative analysis and is plotted in figure 6.

In figure 6, the B additive results in the lowest coating rate contour and the S additive results in the highest coating rate contour for both the common and modified asphalt. This indicates that of the three additives at the same dosage, B has the highest warm mix efficiency, S has the lowest and EV is in between.

6. Conclusions

A method for predicting WMA mixing temperature or additive dosage using a digital image recognition coating rate test was investigated and the following conclusions were obtained.

(1) The prediction of WMA mixing temperature and additive dosage by coating rate is an isostatic temperature method, using digital image recognition as a technical tool and coating area rate as a state indicator, consisting of the preparation of a single variable (temperature or additive dosage) of the mix specimen, digital image recognition of the coating area rate and contour analysis of the coating area rate;

(2) The repeatability of the digital image coating rate recognition test has an average test error of approximately 3.40% and has the accuracy required to derive the mixing temperature.

(3) Digital image recognition of the coating rate varies sensitively with both the WMA mixing temperature and the additive dosage, and the critical 100% coating rate can be used to predict the mixing temperature or additive dosage that will satisfy the warm mixing conditions. The predicted values are consistent with established research and engineering experience based on working characteristics.

(4) The coating rate contour has certain common trends and can also be used to illustrate the effect of different mixing additives (or different warm mixing techniques) on the effectiveness or efficiency of warm mixing.

(5) The process of predicting WMA mixing temperatures or reasonable additive dosages based on coating rates is still relatively cumbersome and its use is currently more suited to research than engineering applications, and future integration with engineering is needed to build up application experience. At the same time, the digital image recognition should also be optimized automatically with the aid of algorithms to reduce the uncertainty associated with manual calibration.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Conflicts of interest

The authors declare no conflict of interest.

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