Time Response-Based Synchronous Calibration of the Pavement Asphalt Softening Point Tester

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Abstract. The asphalt softening point reflects the temperature sensitivity and high-temperature stability of asphalt pavement and is an important quality assessment indicator of asphalt pavement. The detection method of asphalt softening point commonly used in China is the asphalt softening point ring and ball tester. In JJG 057-2004 Verification Regulation of Apparatus for Softening Point of Bitumen, the partial calibration method of the tester was proposed. The partial calibration method cannot realize the synchronous calibration of softening point and various definitions of the softening point are significantly different. Therefore, in order to achieve synchronous calibration of the asphalt softening point tester, a standard verification device was established in this study to simulate asphalt dropping and record response time and temperature simultaneously. The circuit composition, working principle, main technical indicators and influencing factors of key devices were explored and the uncertainty of response results obtained in warming water was evaluated. The evaluation results showed that it was feasible to realize the synchronous calibration of asphalt softening point tester with the verification device.

1. Introduction
Asphalt pavement plays an extremely important role in Chinese roads in terms of both use and quantity. Different asphalt materials are different in temperature stability. When the temperature of asphalt materials reaches a certain value, a softening phenomenon will occur. Asphalt materials become soft and further melts into a liquid. This phenomenon will seriously affect the performance of asphalt materials. At present, the asphalt softening point ring and ball tester (hereafter referred to as “softening point tester”) is used to determine the softening point of pavement asphalt [1]. The working principle of softening point tester is described as follows. In a metal ring with a specified size, a steel ball of a predetermined size and weight is placed on water or glycerin, and heated at a speed of $5 \pm 0.5 \, ^\circ\text{C}/\text{min}$. When the steel ball drops onto the upper surface of the lower support plate, the temperature at this moment is recorded as the softening point of the asphalt. Asphalt softening point tester is generally composed of a heating device, a thermometer (or temperature sensor), a time system and other components. In JJG 057-2004 Verification Regulation of Apparatus for Softening Point of Bitumen, stopwatch and thermometer are respectively adopted in the time system and the temperature system for time and temperature measurements, but the softening point is not directly measured [2].

According to the definition of softening point, its measurement involves two main technical indicators, the time when a ball drops to a certain point and the temperature at this moment. When the steel ball drops to the bottom plate of the device, the recently developed automatic asphalt softening point tester automatically records this moment, which is transmitted to the temperature acquisition system, records the temperature at this moment, and outputs the softening point of the tested asphalt.
The whole measurement process with the automatic asphalt softening point meter may involve various factors, such as working environment and response time, which directly affect the output of softening point. The softening point is not measured synchronously and the measurement time system cannot take into account environmental factors and response lag. Therefore, the accuracy of automatic softening point tester is still uncertain.

The synchronous calibration method is not available in current standard verification regulation (JJG 057-2004). In this study, in order to solve the problem, a verification device was established for the softening point tester. The device can simulate the dropping process after asphalt softening, and sends a signal command to the time system when the device falls to the specified height position. The time system records the response time while the temperature system records the temperature. In this way, the synchronous calibration of the softening point tester can be achieved. In the study, key circuit components, working principle, main measurement indicators and their influencing factors of the standard verification device were analyzed and the uncertainty of response results obtained in warming water were evaluated [3]. The uncertainty evaluation results proved that it was feasible to realize the synchronous calibration of asphalt softening point tester with the verification device. Therefore, it is suggested that the standard verification device should be added in Verification Regulation of Apparatus for Softening Point of Bitumen.

2. Standard tester and experimental schemes

![Schematic diagram of a standard tester.](image)

1. Thermometer in the tester to be calibrated; 2. Time system in the tester to be calibrated; 3 Standard temperature collector; 4. Standard time recording and main control system; 5. Standard asphalt dropping simulation system; 6. Upper plate in the tester to be calibrated; 7. Lower plate in the tester to be calibrated;

The standard tester consists of three parts: a standard temperature collector, a standard time recording and master control system, and a standard asphalt dropping simulation system. The experimental scheme is described as follows. The standard temperature collector shares the same standard time recording system, which is connected with the main control system, with the standard asphalt dropping simulation system. The standard asphalt dropping simulation system is designed as a system with its own
counterweight and integrated with a proximity displacement device and it achieves a vertical drop in water by balancing its own weight and the buoyancy force in water. When the distance between the standard asphalt dropping simulation system and the lower bottom plate of the tester to be calibrated (approximate size is 2 mm × 2 mm × 1 mm) is close to a certain value, the electrical signal is output to the main control system, which commands the standard time recording system to record the current time. At the same time, the main control system commands the standard temperature collector to record the temperature at the moment. Finally, the experiment ends.

In the proximity displacement device, an inductive proximity sensor (Ø, hereinafter referred to as the sensor) is adopted and the nominal motion distance is 1.5 mm. The inductive proximity sensor, as a metal detector, can recognize an object and output the signal based on the sensitivity to the approaching object [4]. In the standard temperature collector, a standard temperature sensor with a resolution of 0.05 °C is adopted.

3. Mathematical model for the temperature calibration of asphalt softening point tester
The mathematical model for temperature indication error of the standard verification device of asphalt softening point tester [5] is provided as follows:

$$\Delta T = T_t + T_M$$

where $\Delta T$ is the temperature indication error of the standard verification device of asphalt softening point tester; $T_t$ is the temperature error introduced by the standard asphalt dropping simulation system; $T_M$ is the temperature error introduced by the standard temperature acquisition system.

3.1. Temperature error introduced by the standard asphalt dropping simulation system $T_t$
The temperature error introduced by the standard asphalt dropping simulation system is mainly caused by its time response deviation, which is composed of two parts: time error and signal response time error caused by the change in its motion distance [6]. The calculation model of the temperature error is provided as follows:

$$T_t = T_s \times \Delta t = T_s \times (\Delta t_1 + \Delta t_2) = T_s \times \frac{\alpha}{v_y} + T_s \times \Delta t_2,$$

where $T_t$ is the temperature error introduced by the standard asphalt dropping simulation system; $T_s$ is the change in the heating rate of water where the device is calibrated (assuming that water is heated at a uniform rate according to the regulation); $v_y$ is the dropping speed of the standard asphalt dropping simulation system in water (the subscript indicates the dropping height); $\Delta t$ is the time response deviation of the standard asphalt dropping simulation system; $\Delta t_1$ is the time response deviation caused by the change in the motion distance of the standard asphalt dropping simulation system; $\Delta t_2$ is the signal response time error; $\Delta \alpha$ is the change in the motion distance. The values of the parameters in Eq. (2) are analyzed below.

i. Calculation of $T_s$. According to the requirements of the verification regulation, the heating rate of the tester to be calibrated should be within 5±0.5 °C/min. The maximum temperature change $T_{smax}=5.5$ °C/min, which can be converted to 0.0917 °C/s. $T_{smax}$ can be regarded as a constant.

ii. Calculation of $v_y$. According to Newton's second law, the following differential equation is obtained.

$$m \frac{d^2y}{dt^2} = W - B - k \frac{dy}{dt},$$

where $m = \frac{w}{g}$ ($g = 9.8 (m^2/s^2)$ is the gravitational acceleration). Eq. (3) is the second-order differential equation with $t$ as the independent variable and $y$ as the unknown function. The relationship between the dropping displacement and velocity of an object in water is obtained by computer simulation as follows [7]:

$$y = y(v) = 203.619v - 44219.2595 \ln(1 + 0.0046v).$$
When the dropping device drops from the upper bottom plate to the lower bottom plate shown in Figure 1 (the distance between the upper and lower bottom plates is 25 mm), Eq. (4) can be used to calculate the distance. When the dropping device drops to the vicinity of the motion distance, its dropping speed is calculated. The velocities of the dropping device with different distances away from the starting point (18.5 mm, 19.25 mm and 25 mm):

\[ y_1 = 18.5 \text{ mm}, \quad v_1 = 0.195 \text{ (m/s)}; \quad (5) \]
\[ y_2 = 19.25 \text{ mm}, \quad v_2 = 0.199 \text{ (m/s)}; \quad (6) \]
\[ y_3 = 25.00 \text{ mm}, \quad v_3 = 0.203 \text{ (m/s)}. \quad (7) \]

It can be seen that within a short distance, the dropping velocity varies little. Therefore, in the range of the motion distance, the dropping device can be regarded as a constant-velocity dropping device. The average value of the three velocities \( v_\text{avg} = 0.199 \text{ (m/s)} \) is taken as the dropping velocity \( v_y \), so \( v_y \) can be regarded as a constant.

iii. Calculation of \( \Delta t_2 \). \( \Delta t_2 \) is related to the proximity sensor response frequency \( f \) and response time is not greater than \( 1/f \). The indication error can be obtained from a calibration certificate.

iv. Calculation of \( \Delta h \). The motion distance error of the standard asphalt dropping simulation system is calculated as follows:

\[ \Delta h = h_0 + h_1 + h_2 + h_3, \quad (8) \]

where \( h_0 \) is the motion distance error introduced by the proximity displacement device itself; \( h_1 \) is the motion distance error introduced by operation personnel; \( h_2 \) is the motion distance error introduced by the metal material to be calibrated; \( h_3 \) is the motion distance error caused by the increase in water temperature.

Then Eq. (2) can be rewritten as:

\[ T_t = \Delta T \times \Delta t = \Delta T \times \frac{\Delta h}{v_y} + \Delta T \times \Delta t_2 = \frac{0.0917 \text{C}}{s} \times \left( 0.199 \frac{\text{m}}{s} \right) \times \Delta h + \frac{0.0917 \text{C}}{s} \times \Delta t_2, \]

\[ = 0.461\Delta h + 0.0917\Delta t_2 \quad (9) \]

3.2. Temperature error introduced by the standard asphalt dropping simulation system \( T_M \)[8]

This error is mainly caused by the standard temperature acquisition device itself and can be obtained by analyzing the resolution and other technical indicators of the device.

4. Uncertainty analysis of the calibrated temperature indication value of asphalt softening point tester

Based on Eq. (1), we get [9]:

\[ u_\Delta T = \sqrt{u_{T_1}^2 + u_{T_M}^2}, \quad (10) \]

where \( u_\Delta T \) is the temperature indication error uncertainty introduced by the standard verification device of asphalt softening point tester; \( u_{T_1} \) is the temperature error uncertainty introduced by the standard asphalt dropping simulation system; \( u_{T_M} \) is the temperature error uncertainty introduced by the standard temperature acquisition system.

4.1. Calculation of \( u_{T_1} \)

According to Eq. (9), the uncertainty can be calculated as follows:

\[ u_{T_1}^2 = (0.461u_{\Delta h})^2 + (0.0917u_{\Delta t_2})^2, \quad (11) \]

where \( u_{\Delta h} \) is the uncertainty of the motion distance error of the standard asphalt dropping simulation system and \( u_{\Delta t_2} \) is the standard uncertainty of the signal response time error.

i. Calculation of \( u_{\Delta h} \). According to Eq. (8), the indication error \( \Delta h \) consists of four independent parts:
\[ u_{\Delta 0} = u_{h0} + u_{h1} + u_{h2} + u_{h3}, \]  

where \( u_{h0} \) is the motion distance error uncertainty introduced by the proximity displacement device itself; \( u_{h1} \) is the motion distance error uncertainty introduced by operation personnel; \( u_{h2} \) is the motion distance error uncertainty introduced by the metal material to be calibrated; \( u_{h3} \) is the motion distance error uncertainty caused by the increase in water temperature.

I) Motion distance error uncertainty introduced by the proximity displacement device \( u_{h0} \)

In the experimental scheme, an inductive proximity sensor (hereinafter referred to as a sensor), which met relevant requirements in GB/T14048.10 [10], was adopted. The switch is composed of an induction head (or a detection coil), a high-frequency oscillation circuit, a detection circuit, an amplification circuit, a wave shaping circuit, and an output circuit, as shown in Figure. 2 [11]. The sensitive component is the detection coil, which is an integral part of the oscillation circuit. When the metal object is close to the detection coil with the AC signal, an eddy current is generated to absorb the energy, so that the oscillation of the oscillation circuit is weakened and the vibration even stops. The two states of oscillation and oscillation stoppage are converted into switching signal by the detection circuit and output [12].

It can be seen from the circuit composition of the proximity switch that the uncertainty caused by the switch itself is composed of the uncertainty introduced by the induction head, the uncertainty introduced by the high-frequency oscillation circuit, the uncertainty introduced by the detection circuit, the uncertainty introduced by the amplification circuit, the uncertainty introduced by the wave shaping circuit, and the uncertainty introduced by the output circuit. In the experiment, a cylindrical induction head, a tank type ferrite magnet core, was adopted. When the magnetic core was placed in a tubular metal shell, the magnetic flux lines outside the magnetic core were shielded and the metal demagnetization range was reduced. Therefore, the working distance was shorter than that of other open induction heads. In the oscillation circuit, the feedback resistance of the oscillating circuit can be adjusted to change the feedback depth, thereby achieving the purpose of setting the motion distance. Feedback depth settings of each manufacturer are different, but the feedback depths of various devices by the same manufacturer are similar. In addition, after a device is manufactured, the detector circuit, the amplifier circuit, and the wave shaping circuit are solidified and remain unchanged in the service life of the device [13]. Therefore, the uncertainty can be analyzed with the B-class assessment method and acquired through the calibration certificate. When the materials are the same and the environment is stable, the extension uncertainty of the motion distance, \( U \), is \( 0.1 \, d \), where \( d \) is the nominal motion distance. The nominal motion distance of this proximity sensor is 1.5 mm. Therefore, the standard uncertainty of the motion distance introduced by the proximity sensor itself is

\[ u_{h0} = \frac{U}{2} = 0.1 \times \frac{1.5}{2} = 0.075 \, \text{mm}. \]  

II) Motion distance error uncertainty introduced by operation personnel \( u_{h1} \)

This uncertainty is mainly due to the dispersion of measurement results caused by the process of opening and closing the switch and pushing the switch to the object under normal room temperature conditions [14]. Therefore, under the repeatability conditions, the same metal to be tested was measured 10 times and the uncertainty was analyzed with the A-class assessment method. The 10 measurements (unit: mm) were respectively 1.02, 1.02, 1.04, 0.98, 1.06, 0.98, 1.04, 0.98, 1.06, and 1.04. The average value of the measurement results is: \( \bar{X} = 1.022 \, \text{mm} \).

The standard deviation of a single measurement is calculated with the Bessel Equation:
where $S$ indicates the standard deviation (%); $n$ is test times.

$$S(x_i) = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_i - \bar{x})^2} = 0.0319 \text{ mm}. \quad (15)$$

The standard uncertainty introduced by operation personnel is:

$$u_{h1} = \frac{S(x_i)}{\sqrt{n}} = \frac{0.0319}{\sqrt{10}} = 0.00998 \text{ mm}. \quad (16)$$

III) Motion distance error uncertainty introduced by the metal material to be calibrated $u_{h2}$

The lower bottom plate of the metal to be tested is approximately regarded as a rectangular plate. The equivalent impedance of the switching coil affected by eddy currents is [15]:

$$Z = R + j\omega L \quad (17)$$

The equivalent resistance $R$ is

$$R = R_1 + \frac{\omega^2 M^2}{R_2^2 + (\omega L_2)^2} R_2. \quad (18)$$

The equivalent inductance $L$ is

$$L = L_1 - \frac{\omega^2 M^2}{R_2^2 + (\omega L_2)^2} L_2 \quad (19)$$

where $R_1$ and $L_1$ are respectively the resistance and inductance of the coil; $R_2$ and $L_2$ are the equivalent resistance and equivalent inductance of the measured object; $\omega$ is the angular frequency of oscillation; $M$ is the mutual inductance between the coil and the measured object [16]. When $(\omega L_2) \gg R_2$, both the resistivity and the equivalent resistance are large, indicating that the motion distance is large. The measurement repeatability data of different materials under the same inductor switch are provided in Table 1.

| Materials           | Motion distance data (mm) | Means | Standard deviations |
|---------------------|---------------------------|-------|---------------------|
| Aluminum            | 0.4 0.36 0.38 0.38 0.44 0.42 0.38 0.36 0.42 0.394 0.027 |
| Copper alloy        | 0.6 0.64 0.56 0.58 0.64 0.56 0.58 0.62 0.64 0.56 0.598 0.035 |
| Bottom plate alloy a| 0.82 0.84 0.86 0.78 0.78 0.78 0.8 0.86 0.8 0.8 0.818 0.035 |
| Bottom plate alloy b| 0.82 0.84 0.84 0.84 0.82 0.84 0.83 0.78 0.86 0.86 0.833 0.023 |
| Iron 1              | 1.02 1.02 1.04 0.98 1.06 0.98 1.04 0.98 1.06 1.04 1.022 0.032 |
| Other alloys a      | 0.82 0.8 0.82 0.8 0.78 0.8 0.81 0.8 0.78 0.78 0.8 0.016 |
| Iron 2              | 0.98 1.02 0.94 0.96 0.98 1.02 1.02 1.02 0.96 1.02 0.992 0.032 |
| Iron 3              | 1.02 1.04 0.98 1.00 1.06 1 0.98 1.04 1.04 1.04 1.02 0.028 |
| Steel               | 1.24 1.22 1.28 1.26 1.26 1.2 1.22 1.28 1.28 1.2 1.244 0.032 |

The standard deviation of the motion distance among the alloys 3, 4, and 6 0.033

Standard deviation of the motion distance among different materials 0.252

The standard deviation of the motion distance among different materials was 10 times larger than that of the same material. The standard deviation of the motion distance among similar materials was similar to that of the same material. The standard deviation of the motion distance among different materials was calculated with Bessel's Equation, whereas the standard deviation of the motion distance among the alloys 3, 4, and 6 was calculated with the range method. Therefore, the analysis of the uncertainty introduced by the metal material to be inspected was limited to the comparison among similar metals. The bottom plate of the softening point tester is an alloy, so the uncertainty caused by the difference in the proportion of the material composition in the alloy is calculated as:

$$u_{h2} = \frac{S(x)}{\sqrt{n}} \sqrt{\frac{0.033}{3}} 0.019 \text{ mm}. \quad (20)$$

IV) Motion distance error uncertainty caused by the increase in water temperature $u_{h3}$ [17]
The tests were carried out with the same material at room temperature and different water temperatures to measure the motion distance. The test data are shown in Table 2 and Table 3. With the increase in water temperature, the motion distance gradually increased. The standard deviation of the motion distance in the whole water body was 0.061. However, if water temperature was controlled within a certain range (10 °C~30 °C), the standard deviation was 0.015; in medium- and high-temperature water (30 °C~70 °C), the standard deviation was 0.017. It can be seen that the influence of the temperature rise on the motion distance is much reduced when the test is performed respectively in segmented water with different temperature intervals. In addition, the standard deviations of the motion distance of the proximity sensor in air and water showed no significant difference.

Therefore, the test with the proximity sensor should be performed in segmented water with different temperature intervals and the uncertainty assessment should be carried out in several stages to control the increase in the uncertainty caused by the change in the motion distance. The maximum value (0.017 mm) of the standard deviation among the segmented water with different temperature intervals (the temperature interval did not exceed 40 °C) was used as the calculation basis. Then, the uncertainty caused by the change in water temperature can be calculated as:

\[
u_{\text{h}3} = \frac{s_3}{\sqrt{3}} = 0.00981 \text{ mm},
\]

V) Calculation of \(u_{\text{h}h}\)
Based on the above calculation, \(u_{\text{h}h}\) can be calculated as [18]:

\[
u_{\text{h}h} = \sqrt{u_{\text{h}0}^2 + u_{\text{h}1}^2 + u_{\text{h}2}^2 + u_{\text{h}3}^2} = 0.0786 \text{ mm}
\]

ii. Calculation of \(u_{\Delta t_2}\).
}\(u_{\Delta t_2}\) is the standard uncertainty of signal response time error and can be obtained from the calibration certificate as:

\[
u_{\Delta t_2} = \frac{0.00125}{\sqrt{10}} = 6.25 \times 10^{-4} \text{ s.}
\]

Table 2 Motion distance data obtained in low-temperature water.

| Temperature | Materials | Motion distance data (mm) | Means | Standard deviations |
|-------------|-----------|---------------------------|-------|--------------------|
| 20°C        | Air       | 0.78 0.74 0.72 0.7 0.74 0.76 0.74 0.74 0.7 0.72 0.734 | 0.025 |
| 20°C        | Water     | 0.78 0.82 0.78 0.76 0.8 0.76 0.74 0.76 0.8 0.76 0.776 | 0.026 |
| 13°C        | Water     | 0.78 0.8 0.84 0.8 0.76 0.72 0.7 0.74 0.78 0.76 0.767 | 0.044 |
| 13°C        | Water     | 0.78 0.76 0.78 0.8 0.8 0.82 0.8 0.76 0.8 0.84 0.796 | 0.026 |
| 30°C        | Water     | 0.86 0.86 0.88 0.84 0.88 0.84 0.86 0.82 0.86 0.88 0.858 | 0.021 |
| 30°C        | Water     | 0.86 0.84 0.86 0.86 0.86 0.86 0.86 0.82 0.82 0.8 0.844 | 0.028 |

Table 3 Motion distance data obtained in high-temperature water.

| Temperature | Materials | Motion distance data (mm) | Means | Standard deviations |
|-------------|-----------|---------------------------|-------|--------------------|
| 30°C        | Water     | 0.86 0.86 0.88 0.84 0.88 0.84 0.86 0.82 0.86 0.88 0.858 | 0.021 |
| 30°C        | Water     | 0.86 0.84 0.88 0.86 0.88 0.86 0.86 0.82 0.82 0.8 0.844 | 0.028 |
| 46°C        | Water     | 0.9 0.9 0.9 0.9 0.88 0.88 0.88 0.92 0.9 0.92 0.92 0.93 | 0.096 | 0.018 |
| 46°C        | Water     | 0.9 0.92 0.88 0.89 0.9 0.88 0.89 0.89 0.88 0.9 0.892 | 0.013 |
| 61°C        | Water     | 0.9 0.88 0.92 0.94 0.96 0.92 0.9 0.94 0.98 0.94 0.931 | 0.030 |
| 61°C        | Water     | 0.9 0.9 0.9 0.92 0.9 0.9 0.9 0.9 0.9 0.9 0.902 | 0.007 |

iii. Calculation of \(u_{\text{R}}[19]\).

\[
u_{\text{R}}^2 = (0.461u_{\text{h}h})^2 + (0.0917u_{\Delta t_2})^2 = (0.461 \times 0.00981)^2 + (0.0917 \times 0.00125)^2 = 0.0362 \text{ °C}.
\]

4.2. Calculation of \(u_{\text{T}_M}\)

The resolution of the temperature acquisition sensor is 0.05 °C, so the half-width of the uncertainty interval is 0.05 °C. The uncertainty interval can be treated as the uniform distribution. Its unreliability is estimated to be 20% and the degree of freedom is 12.
\( u_{TM} = 0.05/\sqrt{3} = 0.0289^\circ C \)  

(25)

4.3. Uncertainty of indication values of the verification device of softening point tester

\[ u_{\Delta T} = \sqrt{u_{T_1}^2 + u_{T_2}^2} = \sqrt{(0.0362)^2 + (0.0289)^2} = 0.0463 \]  

(26)

5. Conclusion

According to the above uncertainty analysis, through the synchronous calibration with the standard verification device, the uncertainty of the indication error of the softening point tester was small, indicating that the standard verification device standard device was applicable to calibrate the tester. In addition, based on the characteristics of core components in the standard verification device, it is suggested that:

i. When a different material is inspected, the uncertainty should be re-evaluated;
ii. When the water temperature range exceeds 40 \(^\circ\)C, the uncertainty should be re-evaluated;
iii. A synchronous calibration standard device should be added in the verification procedure of the asphalt softening point tester.

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