High-Temperature Effect on the Physical and Dynamic Compressive Properties of Pre-Stressed Cement Mortar

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Abstract

Cement mortars are extensively used in tunnels and underground facilities, where the risk of high temperatures due to fires and explosions triggered by traffic accidents, earthquakes or electrical malfunctions cannot be ruled out. It is necessary, therefore, to know the mechanical properties of cement mortars at high temperature in both static and dynamic conditions. The dynamic mechanical behavior of pre-stressed cement mortars at high temperature is investigated in this research project, from 25 to 300°C, by means of the Hopkinson bar. The microstructure of cement mortars is also studied via Scanning Electron Microscopy-SEM. The properties under investigation are: density, coefficient of thermal expansion, dynamic compressive strength, peak strain, dynamic elastic modulus and damage variables, as well as the longitudinal wave velocity. The tests indicate that the physical and dynamic mechanical properties of cement mortars are significantly affected by high temperature. In the range 25 - 300°C, because of the increasing number and size of microdefects (microcracks), the density and the longitudinal wave velocity exhibit a gradual less-than-linear decline, while the decline of the compressive strength and elastic modulus is more marked (roughly linear), the peak strain and damage almost increase linearly.

1. Introduction

It is well known that structural damages caused by natural or human causes are inevitable, especially in the cases of fire and earthquakes. However, a growing number of structures are subjected to high temperature, which leads the physical and dynamic mechanical properties of cement mortar materials to weaken. The improvement of material property and the change of structure stress distribution can reduce the damage to a certain extent. Therefore, to improve fire and impact resistances of the structures, it is necessary to obtain the physical and mechanical properties of cement mortar materials at high temperature.

Up to now, many researches on behaviors of structural materials after a thermal treatment have been conducted, concentrating on physical properties, compressive and tensile strength under quasi-static loading condition (Phan and Carino 1998; Phan and Carino 2002; Černý et al. 2003; Husem 2006; Demir and Keleştemur 2010; Monte and Gambarova 2014; Georgali and Tsakiris 2015; Ahn et al. 2016; Yin et al. 2016). For example, Ismail et al. (2011) stated that the compressive strength and mass decrease with the increasing temperature in the concrete experiment containing palm oil fuel ash. Mydin et al. (2012) discovered that the tensile strength, compressive strength and density all decrease with the increasing temperature, while the porosity increases as the temperature increases. Besides, the experiment was conducted by exposing foamed concrete from ambient temperature to 600°C. Keleştemur et al. (2014) carried out experiments of cement mortars containing marble dust and glass fiber under different temperatures, ranging from 400 to 800°C, and concluded that static compressive strength of cement mortar gradually decreases with the increasing temperature even at different contents of marble dust and glass fiber; while the porosity sharply increases with the increasing temperature. By carried out the experiment on geopolymer mortar exposed from 25 to 700°C, Zhang et al. (2016) pointed out that both the tensile and static compressive strengths of geopolymer mortars increase when the temperature increases from 25 to 100°C, while it decreases gradually when the temperature increases from 100 to 700°C. Similar phenomenon was occurred to cement mortars containing nanosilica and heavy-weight aggregates. Horszczaruk et al. (2017) confirmed that, before 100°C, the compressive strength increases with the increasing temperature; after 100°C, the compressive strength decreases with the increasing temperature. From the previous studies, it is clear that the temperature greatly affects both physical and static mechanical properties of structural materials. Since impact loads and the heating occur more frequently in structures, dynamic mechanical properties of engineering materials have been investigated (Yin et al. 2015, 2018a, 2018b; Li et al. 2016; Fu et al. 2017), as well as those

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subjected to the heat treatment (Li et al. 2012; Huo et al. 2013). For example, Yang et al. (2013) discovered that the dynamic compressive strength decreases with the increasing temperature by carried out the dynamic experiment on heat-treated concrete, indicating that dynamic mechanical properties also are obviously influenced by the temperature.

Considering that engineering structures are often subjected to high temperature and impact loads simultaneously, a few of engineering material experiments at elevated temperature have been carried out (He et al. 2011). By split Hopkinson pressure bar experiment of concrete under temperatures ranging from room temperature to 800°C, Su et al. (2014) discovered that the dynamic compressive strength of concrete at 400°C is increased by nearly 14% compared to that under the room temperature. However, it decreases at 200°C, 600°C and 800°C with the decrease of 20%, 16% and 48%, respectively. Besides, the dynamic elastic modulus decreases largely with the increasing temperature. In another reference of Su et al. (2016), the weight loss is remarkable when temperature ranges from room temperature to 200°C, as well as from 600 to 800°C. The dynamic compressive strength of geopolymer concrete grow largely at 200°C than that at room temperature, but suffers a sharp drop at 800°C. The above researches are significant to the practical engineering, showing that both temperature and impact loads are important factors for the engineering safety and stability.

In fact, the temperature and impact loads cannot separately affect the structural materials. Hence, dynamic experiments on structural materials at high temperature are more suitable than those after thermal treatment, and few studies has involved cement mortars. It should be noted that structural materials may have already subjected to static stress which caused by structure gravity. Thus, a study on structural materials under static stress, high temperature and impact load is necessary. Through dynamic experiments of pre-stressed cement mortars under high temperature, dynamic compressive properties of pre-stressed cement mortar were studied, including dynamic compressive strength, peak strain, dynamic elastic modulus and damage. Moreover, physical properties of cement mortar under the temperature effect were obtained and analyzed.

2. Materials and methods

2.1 Specimens preparation

As shown in Fig. 1, cement mortar specimen was processed into a cylinder which is 50 mm in diameter and 25 mm in length. Both ends of specimens were polished, and the parallelism controlled within ±0.05 mm and surface flatness within ±0.02 mm for the parallelism, flatness and finish. The cement mortar specimen consists of 30% cement, 50% fine sand and 20% water. Furthermore, specimens have been stored in constant temperature and controlled-environment chamber for 28 days. Noteworthy, the temperature and humidity of the constant temperature and controlled-environment chamber is 20°C and 90% respectively. The cement mortar specimens with similar wave velocities were chosen for experiment. Then, physical properties of specimens were obtained by measuring no less than three times. Specimens were classified into 5 groups, and no less than 5 specimens in each group. Because the underground structures may bear static stress, here the static stress was set at 5 MPa. Finally, the prepared specimens were used for the dynamic experiment at high temperature and 5 MPa static stress.

2.2 Experimental apparatus

The improved split Hopkinson pressure bar (SHPB) and scanning electron microscope (SEM) are main apparatus in this test, as shown in Figs. 2(a) and 2(b). The dy-
Dynamic compressive experiment under high temperature and static stress was carried out by improved SHPB experimental system. It is primarily composed of a spindle punch, an emission cavity, a gas gun, a φ 50 mm × 2000 mm incident bar, a φ 50 mm × 1500 mm transmission bar, a φ 50 mm × 500 mm absorbing bar, a signal recording and data-processing device, a temperature–pressure coupling device and a static stress device. The ultimate strength, wave velocity and density of bar are 800 MPa, 5400 m/s and 7810 kg/m³, respectively. The complete stress-strain curve can be obtained due to the higher stiffness of high-strength alloy bar compared to that of cement mortar specimens. A stable strain rate of half the sinusoidal stress wave was produced by spindle punch. The incident, reflection and transmission waves were measured by recorded signals by strain gauges which are fixed on the incident and transmission bar. Correspondingly, the stress σ(t), strain ε(t), and strain rate ε̇(t) can be calculated through the cross-sectional area \( A_s \) of the specimen, the cross-sectional area \( A_0 \) of the pressure bar, the wave velocity \( C_0 \) of the pressure bar, the length \( L_s \) of the specimen, the elastic modulus \( E \) of the specimen, the incident strain \( \varepsilon_i \), the reflection strain \( \varepsilon_r \) and the transmission strain \( \varepsilon_t \) by Equations (1), (2) and (3), respectively.

\[
\sigma(t) = \frac{A_0}{2A_s} E (\varepsilon_i + \varepsilon_r + \varepsilon_t) \tag{1}
\]

\[
\varepsilon(t) = \frac{C_0}{L_s} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt \tag{2}
\]

\[
\dot{\varepsilon}(t) = \frac{C_0}{L_s} (\varepsilon_i - \varepsilon_r - \varepsilon_t) \tag{3}
\]

2.3 Experimental technique and methods

The experiment could be carried out by the improved experimental technique of split Hopkinson pressure bar, as is shown in Fig. 3. The same air pressure was used to ensure a same impact load in each test. Here, the temperature–pressure coupling device can not only ensure specimen on the heat source, but also guarantee the precise alignment of the incident bar, specimen and transmission bar, as well as avoid crushed specimen blocks from breaking the heating bonnet; in addition, the static stress device could apply axial static stress to specimen. Due to the technical restriction, the test temperature was classified into 5 groups: 25, 50, 100, 200 and 300°C. Each group was equipped with no less than 5 specimens. Because the underground structures may bear static stress, here the static stress was set at 5 MPa. Before the heating, physical properties were measured, including mass, volume and longitudinal wave velocity. After the measurement of physical properties, the specimen was put into the temperature–pressure coupling device and heated to the target temperature with a low heating rate of 2°C/min; once the target temperature was reached, the temperature was kept to be constant for 2 h to ensure the uniform heating of specimen. Then, the specimen was taken out by high temperature gloves and the physical properties were measured as fast as possible to avoid heat loss. After that, the incident bar and transmission bar were pushed into the heating cavity body after the specimen was put into the temperature–pressure coupling device. The insulation bin gate was closed after ensuring the fine alignment of the specimen and bar. Upon the former step, the axial pressure was set to 5 MPa. Finally, the dynamic experiment could be carried out. In addition, the internal structure of cement mortar specimens can be observed by scanning the fragment by using an electron microscope.

![Fig. 3 Sketch of experimental technique.](image-url)
3. Results

3.1 High-temperature effect on physical properties and internal structures

(1) High-temperature effect on physical properties

Figure 3 shows the change of physical properties of cement mortar specimens under different temperatures, including the mass, volume, density and longitudinal wave velocity. For mass, density and longitudinal wave velocity, although these values all gradually decrease with the increasing temperature, there are still some differences in the change degrees. The density and longitudinal wave velocity are more sensitive than mass subjected to the thermal effect. As shown in Figs. 4 and 5, when the temperature increases from 25 to 300°C, the mass decreases from 94.53 to 89.34 g, only decreased by 5.49%; the density reduces from 1854.21 to 1629.70 kg/m³, decreased by nearly 12.11%; while the longitudinal wave velocity decreases from 2691.60 to 1699.85 m/s with a large decline of 36.86%. However, the volume gradually increases with the increasing temperature. This is mainly caused by the bound water evaporation and crack extension when the specimen is heated. As the temperature ranges from 25 to 300°C, the volume of cement mortar increases from 5.10 × 10⁻⁵ to 5.45 × 10⁻⁵ m³, increased by about 7.53%. According to the volume change, the cubic expansion coefficient of cement mortar at different temperatures are obtained after linearly fitted the values of volumes by using Equation (4), as shown in Fig. 5. The cubic expansion coefficient of cement mortar is about 1.26 × 10⁻⁴, which is a small value.

\[ \alpha_v = \frac{\tan(\theta)}{V_0} = \frac{\Delta V}{\Delta T V_0} = \frac{V_b - V_a}{(T_b - T_a)V_0} \]  

(4)

where \( \alpha_v \) is the cubic expansion coefficient of cement mortar, \( \Delta V \) and \( \Delta T \) are the thermal expansion capacity and temperature change, respectively. \( V_a \) and \( V_b \) are volumes corresponding to \( T_a \) and \( T_b \), respectively, as shown in Fig. 6. \( V_0 \) is the volume of the specimen at the temperature of 25°C.

To visually describe the change of defects under thermal treatment, the schematic diagram is drawn in Fig. 7. As shown in Fig. 7, the volume of cement mortar increases after the heating, resulting from the increasing defects caused by the expansion of the original and generated cracks and holes. In details, as the temperature increases, the number and size of defects in regular and irregular cracks and holes increase to some extent, eventually leading to an enlarging volume.

(2) High-temperature effect on internal structures

By using scanning electron microscopy, the microstructures of cement mortar specimens subjected to different temperatures were obtained, as shown in Fig.8. In Fig. 8, as the temperature increases, the specimens show some differences at different temperatures, mainly focusing on the defect size, such as the size of the crack. Figs. 8(a), 8(b), 8(c), 8(d), 8(e) and 8(f) are SEM images at the temperatures of 25°C, 100°C, 100°C, 200°C, 200°C and 300°C, respectively, and the corresponding amplifications are 1000, 200, 1000, 500, 1000 and 500, respectively. As shown in Fig. 8(a), the specimen at 25°C is relatively dense with some inconspicuous micro cracks and original cracks caused by the working process. Even at high amplification, the micro crack is hardly to be observed. As the temperature increases to 100°C, a...
few micro cracks can be observed at low amplification, as shown in Fig. 8(b). While many interconnected micro cracks can be observed at high amplification, as shown in Fig. 8(c). When the temperature continuously increases to 200°C, some large cracks connected with some micro cracks can be observed at low amplification, so does it at high amplification, as shown in Figs. 8(d) and 8(e), respectively. When the temperature is 300°C, the micro cracks expand, generating more large cracks, as shown in Fig. 8(f). In addition, more large cracks through the large holes and micro cracks at 300°C, even at low amplification.

As illustrated in Fig. 9, the size of the largest crack increases with the increasing temperature. When the temperature increases from 25 to 300°C, the size of the largest crack ranges from 1.6 to 22.5 μm, almost increased 20.9 μm. Certainly, the number of cracks also increases to some extent, as the temperature increases. Hence, it is clear that, based on SEM images, cracks under different temperatures are much diverse from each other, such as the number, size and distribution modes of cracks. As the temperature increases, cracking evolves from few isolated microcracks to large interconnected cracks accompanied by holes and microcracks. With the increasing temperature, the damage caused by the thermal effect increases gradually, finally leading to the deterioration of physical and mechanical properties.
3.2 High-temperature effects on dynamic compressive properties

As shown in Table 1, dynamic mechanical properties of pre-stressed cement mortar under different temperatures are obtained. AV stands for an average value in Table 1. The dynamic compressive strength is no more than 39 MPa and decreases with the increasing temperature obviously. In other words, the cement mortar is not too compact, and the dynamic compressive strength is actually affected by thermal. Experimental complete stress-strain curves are given in Fig. 10. The stress-strain curves at different temperatures clearly show that the mechanical properties are markedly affected by the temperature.

Based on the experimental results, the complete stress-strain curve can be divided into five stages, namely compression stage (stage. I), elastic stage (stage. II), microcrack evolution and propagation stage (stage. III), strain softening stage (stage. IV) and rapid failure stage (stage. V), as shown in Fig. 11. Based on the above stages, the stress-strain curves at different temperatures show great differences at the experimental temperature ranging from 25 to 300°C. When the temperature is lower, namely before 200°C, the compression stage is short and not too obvious; when the temperature reaches 300°C, the stage becomes longer and more obvious than others. The slope of the elastic stage gradually reduces with the increasing temperature. At the same time, the microcrack evolution and propagation stage are more obvious with the increasing temperature. In addition, as the temperature increases, more than 200°C, the strain softening stage occurs, in which the strain increases largely while the stress does not change. An apparent phenomenon on the amplitude of curves is appeared. Namely the peak of curve decreases gradually with the increasing temperature. When the temperature is high such as 300°C, the peak of curve is far lower than that of curve at 25°C.

### Table 1 Dynamic compressive properties of cement mortar at different temperatures and under a static stress of 5 MPa.

| Temperature (°C) | Number | Dynamic compressive strength (MPa) | Strain rate (s⁻¹) | Peak strain (10⁻³) | Dynamic elastic modulus (GPa) | Damage index |
|------------------|--------|-----------------------------------|------------------|------------------|-------------------------------|--------------|
| 25               | 1-1    | 35.74                             | 60.25            | 4.99             | 13.11                         | 0.00         |
|                  | 1-2    | 34.86                             | 65.58            | 5.33             | 13.18                         | 0.00         |
|                  | 1-3    | 37.62                             | 59.54            | 5.86             | 13.62                         | 0.00         |
|                  | 1-4    | 38.17                             | 61.58            | 6.44             | 13.51                         | 0.00         |
|                  | 1-5    | 37.33                             | 66.24            | 6.24             | 13.55                         | 0.00         |
|                  | AV     | 34.97                             | 62.87            | 6.02             | 11.47                         | 0.073        |
| 50               | 2-1    | 36.12                             | 65.58            | 5.84             | 11.81                         | 0.078        |
|                  | 2-2    | 37.24                             | 69.45            | 5.08             | 11.99                         | 0.098        |
|                  | 2-3    | 34.5                              | 60.89            | 5.96             | 11.42                         | 0.057        |
|                  | 2-4    | 35.53                             | 66.12            | 6.05             | 11.44                         | 0.005        |
|                  | 2-5    | 35.67                             | 65.38            | 5.79             | 11.63                         | 0.049        |
|                  | AV     | 29.28                             | 64.25            | 6.92             | 8.56                          | 0.214        |
| 100              | 3-1    | 27.53                             | 61.84            | 6.77             | 8.17                          | 0.053        |
|                  | 3-2    | 28.68                             | 58.45            | 6.82             | 8.28                          | 0.357        |
|                  | 3-3    | 27.24                             | 67.34            | 6.14             | 8.01                          | 0.259        |
|                  | 3-4    | 26.15                             | 59.78            | 7.18             | 7.95                          | 0.182        |
|                  | 3-5    | 27.78                             | 62.33            | 6.76             | 8.19                          | 0.217        |
|                  | AV     | 19.92                             | 60.98            | 7.81             | 7.25                          | 0.46         |
| 200              | 4-1    | 17.14                             | 55.38            | 7.63             | 7.12                          | 0.446        |
|                  | 4-2    | 20.99                             | 64.85            | 7.94             | 7.71                          | 0.556        |
|                  | 4-3    | 18.05                             | 59.31            | 7.55             | 7.19                          | 0.513        |
|                  | 4-4    | 19.04                             | 59.08            | 7.69             | 7.32                          | 0.492        |
|                  | AV     | 15.08                             | 64.38            | 8.03             | 4.22                          | 0.611        |
| 300              | 5-1    | 13.25                             | 61.34            | 8.22             | 4.11                          | 0.639        |
|                  | 5-2    | 14.13                             | 63.89            | 8.06             | 4.21                          | 0.624        |
|                  | 5-3    | 11.95                             | 56.89            | 7.83             | 3.88                          | 0.627        |
|                  | 5-4    | 11.28                             | 53.89            | 8.72             | 3.71                          | 0.536        |
|                  | 5-5    | 13.14                             | 60.08            | 8.17             | 4.03                          | 0.608        |

3.2 High-temperature effects on dynamic compressive properties

As shown in Table 1, dynamic mechanical properties of pre-stressed cement mortar under different temperatures are obtained. AV stands for an average value in Table 1. The dynamic compressive strength is no more than 39 MPa and decreases with the increasing temperature obviously. In other words, the cement mortar is not too compact, and the dynamic compressive strength is actually affected by thermal. Experimental complete stress-strain curves are given in Fig. 10. The stress-strain curves at different temperatures clearly show that the mechanical properties are markedly affected by the temperature.

Based on the experimental results, the complete stress-strain curve can be divided into five stages, namely compression stage (stage. I), elastic stage (stage. II), microcrack evolution and propagation stage (stage. III), strain softening stage (stage. IV) and rapid failure stage (stage. V), as shown in Fig. 11. Based on the above stages, the stress-strain curves at different temperatures show great differences at the experimental temperature ranging from 25 to 300°C. When the temperature is lower, namely before 200°C, the compression stage is short and not too obvious; when the temperature reaches 300°C, the stage becomes longer and more obvious than others. The slope of the elastic stage gradually reduces with the increasing temperature. At the same time, the microcrack evolution and propagation stage are more obvious with the increasing temperature. In addition, as the temperature increases, more than 200°C, the strain softening stage occurs, in which the strain increases largely while the stress does not change. An apparent phenomenon on the amplitude of curves is appeared. Namely the peak of curve decreases gradually with the increasing temperature. When the temperature is high such as 300°C, the peak of curve is far lower than that of curve at 25°C.

(1) High-temperature effects on dynamic compressive strength

The correlation between the dynamic compressive strength and temperature is given in Fig. 12. It shows that the dynamic compressive strength approximately linearly decreases with a slope of $9.05 \times 10^{-2}$ when the temperature rises. The dynamic compressive strength decreases from 38.17 to 11.28 with the amplitude of 0 to 70.45% when the temperature ranges from 25 to 300°C. In details, the dynamic compressive strength is 38.17 MP at 25°C, which is not too large. When the tempera-
ture increases to 50°C, the value decreases into 35.53 MPa, reduced by 6.93%. As the temperature reaches to 100°C, it is 26.15 MPa with a larger decrease of 31.49%. When the temperatures are higher, the values of dynamic compressive strength decrease to 18.05 and 11.28, decreased by 52.72% and 70.46%. The dynamic compressive strength is sensitive to the temperature. The correlation between dynamic compressive strength and temperature can be linearly described by Equation (5). The main reason for the change of dynamic compressive strength is the increase of defects, including cracks and holes.

\[
\sigma = 38.81 - 9.05 \times 10^{-3} T, \quad 25 \leq T \leq 300 \tag{5}
\]

where \(\sigma\) is dynamic compressive strength and \(T\) is the temperature.

(2) High-temperature effects on peak strain
The correlation between peak strain and temperature is given in Fig. 13. On the contrary to dynamic compressive strength, the peak strain linearly increases with the slope of \(9.32 \times 10^{-6}\) as the temperature increases. When the temperature increases from 25 to 300°C, the peak strain increases from \(6.24 \times 10^{-3}\) to \(8.72 \times 10^{-3}\), in-

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**Fig. 10** Stress-strain curves of cement mortar at different temperatures and under a static stress of 5 MPa: (a) The stress-strain curves varying from temperatures; (b) 25°C; (c) 50°C; (d) 100°C; (e) 200°C; and (f) 300°C.
creased by 39.72%. Compared to lower temperature, the increasing number and size of cracks, holes, the softening of specimen composition caused by the higher temperature lead to the larger deformation of specimens. Hence, the peak strain increases with the increasing temperature.

The correlation between peak strain and temperature is linearly described by Equation (6).

\[ \varepsilon = 5.58 \times 10^{-3} + 9.32 \times 10^{-4} T, \quad 25 \leq T \leq 300 \]  

where \( \varepsilon \) and \( T \) are peak strain and the temperature, respectively.

(3) High-temperature effect on dynamic elastic modulus

The cement mortar dynamic elastic modulus can describe the elastic deformability of cement mortar under impact load. In this paper, the dynamic elastic modulus is obtained by Equation (7), as shown in Fig. 11.

\[ E_d = \tan(\beta) = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \]  

where \( E_d \) is the dynamic elastic modulus of cement mortar; \( \sigma_1 \) and \( \sigma_2 \) are the stresses under the elastic stage, respectively; \( \varepsilon_1 \) and \( \varepsilon_2 \) are the strain corresponding to \( \sigma_1 \) and \( \sigma_2 \), respectively.

The correlation between dynamic elastic modulus obtained from the linear stage of the stress-strain curve and temperature is shown in Fig. 14.

An obvious phenomenon can be observed that the dynamic elastic modulus almost decreases linearly at a slope of \( 3.10 \times 10^{-3} \) with the increasing temperature. Under different temperatures ranging from 25 to 300°C, the decreased amplitude increases from 0 to 69.90%.

When the temperature is 25°C, the average value is about 13.39 GPa. The value decreases to 11.63 GPa at the temperature of 50°C with an amplitude of 13.14%. As the temperature continuously increases to 100, 200 and 300°C, the dynamic elastic modulus decreases to 8.19, 7.32 and 4.03 GPa with a decline of 38.83%, 45.33% and 69.90%, respectively. Besides, the correlation between dynamic elastic modulus and temperature is concluded as Equation (8).

\[ E_d = 13.09 - 3.10 \times 10^{-2} T, \quad 25 \leq T \leq 300 \]
(4) High-temperature effects on damage characteristic
The damage of cement mortar is described as a value of the cement mortar weakening status under a certain state. The damage index of cement mortar under different thermal treatments is obtained by wave velocity as Equation (9). In this paper, the cement mortar specimen at 25°C is considered to be relatively intact and undamaged, namely the damage value of which is zero. The values of damage index at different temperatures are given in Table 1.

\[ D = 1 - \frac{v^2}{v_0^2} \]  

(9)

where \( D \) is the damage index described by the longitudinal wave velocity, \( v \) and \( v_0 \) are the longitudinal wave velocity at any temperature and at 25°C, respectively.

As Fig. 15 shows, the damage index of cement mortar varies sharply with the increasing temperature, showing a linear upward trend generally.

When the temperature ranges from 25 to 300°C, the average value of damage index increases from 0 to 0.608. High temperature indeed makes a large influence on the property of cement mortar, especially at 300°C. The changing law of damage can be described as the linear Equation (10) in the range of the experimental temperature. When the temperature rises, the damage index of cement mortar increases at a speed of 2.32 \times 10^{-3}/°C.

\[ D = 2.32 \times 10^{-3}T - 4.01 \times 10^{-2}, \quad 25 \leq T \leq 300 \]  

(10)

4. Analysis and discussion
From the change of physical properties of cement mortar, such as mass loss, longitudinal wave velocity and the change of internal structure, the changes of dynamic mechanical properties can be clearly explained, including dynamic compressive strength, peak stress, dynamic elastic modulus and damage. The mass loss, the increasing number and size of cracks and holes are main reasons for the weakening of dynamic compressive properties.

The change of dynamic compressive properties can be explained from the view of energy. Based on the one-dimensional stress wave theory and the energy conservation law, the incident energy, reflected energy and transmitted energy are obtained through the incident stress, reflected stress and transmitted stress as follows:

\[ W_i = \frac{A_0}{\rho_0 C_0} \int_0^t \sigma_I^2(t) dt \]  

(11)

\[ W_R = \frac{A_0}{\rho_0 C_0} \int_0^t \sigma_R^2(t) dt \]  

(12)

\[ W_T = \frac{A_0}{\rho_0 C_0} \int_0^t \sigma_T^2(t) dt \]  

(13)

where \( W_i, W_R \) and \( W_T \) are the total incident, reflected and transmitted energy during the experimental process, respectively. \( A_0, \rho_0 \) and \( C_0 \) are the cross-section area, density and the wave velocity of bars, respectively. \( \sigma_I, \sigma_R \) and \( \sigma_T \) are the incident, reflected and transmitted stress, respectively.

Regardless the other energy dissipation, based on energy conservation law, the dissipated energy \( W_d \), which is used to destroy specimen, can be expressed as:

\[ W_d = W_i - (W_R + W_T) \]  

(14)

Correlation curves among the incident energy, reflected energy, transmitted energy, absorbed energy and temperature are drawn in Fig. 16. The same impact load is applied to every experiment to ensure the same incident energy, and the total incident energy is around 50 J. As Fig. 16 shows, when the temperature increases, the reflected energy approximately increases linearly; on the contrary, the transmitted and absorbed energy nearly show a linear decrease trend. From 25 to 300°C, the reflected energy increases from 40.57 to 50.37 J with an increase of about 24.16%; the transmitted and absorbed
energy decrease from 2.00 J and 7.81 J to 0.71 J and 2.05 J with a large decrease of around 64.50% and 73.75%, respectively. Because of the increase number and size of cracks caused by the increasing temperature, the interface of the internal structure of specimen increases accordingly. Hence, the reflected energy increases gradually. During the propagation of stress wave, because the cracks and holes of specimens increase when temperature increases, the stress wave is kept from propagating to transmitted bar, and is largely reflected back to the incident bar. Therefore, the higher the temperature, the smaller the transmitted energy. Certainly, owing to the increasing cracks and holes, the internal structure of specimen is weakened gradually as the temperature increases, finally resulting in that the specimen can be destroyed by the smaller energy. The changing law of energy in the experimental process well explains the changing situation of the internal structure of specimens. Thereby the change of dynamic compressive properties of cement mortar is clearly explained.

The correlations among the reflected energy, transmitted energy, absorbed energy and temperature are expressed as follows:

$$R = 40.48 + 3.29 \times 10^{-2} T, \quad 25 \leq T \leq 300$$  \hspace{1cm} (15)

$$W_I = 2.07 - 4.83 \times 10^{-3} T, \quad 25 \leq T \leq 300$$  \hspace{1cm} (16)

$$W_A = 8.12 - 2.13 \times 10^{-2} T, \quad 25 \leq T \leq 300$$  \hspace{1cm} (17)

In addition, the energy absorbed by the thermal energy could be calculated by the following formula:

$$Q = c \Delta T V = c(T - T_0)V$$  \hspace{1cm} (18)

where $Q$ is the absorbed thermal energy of cement mortar, $c$ is the specific heat capacity of cement mortar, and $c$ is constant when the material is given. $\Delta T$ is the change of temperature, $T$ and $T_0$ are temperature and the temperature at 25°C, respectively. $V$ is the volume of specimen.

The absorbed thermal energy per cubic meter of cement mortar, $Q_P$, is obtained as:

$$Q_P = c \Delta T = c(T - T_0) \times 1 \text{m}^3$$  \hspace{1cm} (19)

Because the specific heat capacity $c$ of cement mortar is considered as constant, the correlation between the dynamic compressive strength loss $\Delta \sigma$, and the absorbed thermal energy $Q_P$ in per cubic meter of cement mortar is shown in Fig. 17. As shown in Fig. 17, $c$ is the specific heat capacity of cement mortar. It is visual to understand the change of dynamic compressive strength in the point view of energy. The increasing temperature weakens the internal structure of specimen, resulting in more reflected energy. Finally, the dynamic compressive strength decreases gradually.

According to the above results, the correlation between dynamic compressive properties and temperature is expressed by a linear equation as:

$$N = J + kT, \quad 25 \leq T \leq 300$$  \hspace{1cm} (20)

where $N$ is dynamic compressive properties of cement mortar, $T$ is the temperature, $J$ and $k$ are parameters related to materials. When the experimental temperature ranges from 25 to 300°C, the dynamic compressive properties almost show a linear change with the increasing temperature.

In fact, the specimen is subjected to both static and dynamic stress in the process of dynamic experiment under high temperature and static stress, as shown in Fig. 18. The total energy consists of incident energy $W_I$ caused by the spindle punch, elastic energy $W_E$ caused by the static stress, and thermal energy $Q$ caused by the heating.

In the process of experiment, the total energy is divided into three parts expect for other energy dispassion. The correlation is described as:

$$W_I + W_E + Q = W_I + W_E + W_A$$  \hspace{1cm} (21)

The absorbed energy is expressed as:

$$W_A = W_I + W_E + Q - W_E - W_I$$  \hspace{1cm} (22)

Compared to Equation (14), the absorbed energy obtained before is smaller than the actual value. However, the change rule of absorbed energy described by the previous value is still reliable because the static stress is constant.
5. Conclusions

The conclusions including physical properties, dynamic compressive strength, peak strain, dynamic elastic modulus and damage characteristic were drawn throughout the investigation and discussion as follows.

(1) Physical properties of thermal treated cement mortar are different compared with the untreated one; when temperature increases from 25 to 300°C, the mass, density and longitudinal wave velocity of cement mortar specimen decreases by 5.49%, 12.11%, 36.86% respectively; the volume increases by 7.53%. In addition, the density and longitudinal wave velocity are more sensitive to the temperature.

(2) The internal structure of cement mortar specimen is seriously affected by the temperature, which is mainly characterized in the increase of the number and size of cracks and holes with the increasing temperature; 25 to 300°C, the size of the largest crack increases from 1.6 to 22.5 μm; and the damage almost increases linearly.

(3) When the temperature increases from 25 to 300°C, the dynamic compressive strength and dynamic elastic modulus of pre-stressed cement mortar almost decrease linearly, almost a loss of 70.46% and 69.90% respectively; on contrary, the peak strain almost increases linearly, an increase of 39.72%.

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