An investigation of the heat generated during cyclic loading of ultra-high performance concrete

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In this paper, the mechanism of heat generation in concrete due to cyclic loading is studied, in which the development of load-induced temperature is modelled using a heat transfer equation. The heat generation rate is theoretically determined and the calculation is experimentally validated. The influence of the maximum size of aggregate of concrete on the temperature development is also taken into account. It is shown that the load-induced temperature is generated by conversion of dissipate energy, which mainly occurs at the interfacial transition zone between binders and concrete aggregates and can be described by the plastic work of concrete material.

1 Introduction

Ultra-high performance concrete (UHPC) shows a very high compressive strength $f_{c}$, but also a sensitive fatigue behaviour for high load cycles and high load frequencies. In previous fatigue studies with experimental works, e.g. [1], a temperature increase was observed in the concrete sample. Higher concrete strengths, especially for concretes with small maximum grain size, showed a higher temperature increase [2]. The load-induced temperature can cause internal stresses in concrete sample, which are not uniformly distributed. This leads to high local stresses in concrete, which reduces the fatigue strength. Although some phenomena of the fatigue behaviour of UHPC and HPC have been experimentally identified, e.g. in [2], an explanation of the mechanism of heat generation in concrete under cyclic loading is still open. In this paper, a hypothesis of energy conversion is used to explain the heat generation, which assumes that the thermal energy is generated by conversion of dissipate energy induced by crack formation and fracture of concrete material. In order to study the mechanism of heat generation, mathematical formulations for a heat transfer problem in a concrete cylinder are developed, which can be validated experimentally. As a main influencing parameter on the heat generation, the aggregate sizes is also taken into account.

2 Strain development of concrete due to fatigue load

In experimental work it is only possible to measure the strain, but not the stress in structures. Structures react to the load by showing deformations. The analysis of the strain behaviour helps to understand the load-bearing behaviour of structures. In concrete structures under fatigue load, the concrete strain develops in different manners depending on load characteristics. Under load and time effects, concrete is deformed with different components of strain, which can be described as follows:

$$\varepsilon_c = \varepsilon_e + \varepsilon_p + \varepsilon_{cr} + \varepsilon_{sh} + \varepsilon_T$$  \hspace{1cm} (1)

in which $\varepsilon_e$, $\varepsilon_p$, $\varepsilon_{cr}$, $\varepsilon_{sh}$ and $\varepsilon_T$ are the elastic strain, the load-induced plastic strain, the creep strain, the shrinkage strain and thermal strain, respectively. The individual strain components depend on the age and properties of concrete, the load level, the load duration as well as load cycles and the load frequency.

3 Heat transfer in a concrete cylinder

3.1 General

Under load, concrete shows a complex response with multi-axial stress and strain states. This influences the thermal energy generation rate and thus the temperature development in concrete. In order to reduce the complexity of concrete behaviour to allow a convenience in studying the mechanism of thermal generation in concrete, a uni-axial behaviour of concrete is considered. Therefore, cylindrical samples are used in both theoretical and experimental analyses. It should be noted that due to an uneven temperature distribution in concrete samples, internal stresses are also expected. For a simplification, average values of radial strains and stresses are considered, which introduce a uniform heat generation rate in the concrete specimen.
3.2 Heat equation in cylindrical coordinate system

Consider a cylinder with a radius $r_0$ much smaller than the length $L$ heating up from inside. In this case, a temperature gradient occurs only in the radial direction. Under the assumption that the thermal source is uniformly distributed in the cylinder, the environment temperature $T_f$ is constant and the heat dissipation coefficient $\alpha$ does not change over the entire surface, see Fig. 1, the general heat equation in cylindrical coordinate system is presented as follows.

$$ \rho c_p \frac{dT}{dt} = \lambda \left( \frac{d^2T}{dr^2} + \frac{1}{r} \frac{dT}{dr} \right) + q_v $$

(2)

where $\rho$ is specific weight, $c_p$ is specific heat capacity and $q_v$ is heat generation rate of the considered material. In the steady state the temperature in the cylinder remains unchanged and the heat equation can be simplified. With the temperature $T_0$ in the middle of cylinder, $T_w$ on the cylinder surface and $T_f$ in the environment, the heat generation rate can be determined by one of the following equations, depending on whether the thermal conductivity $\lambda$ or the heat dissipation coefficient $\alpha$ is given.

$$ q_v = (T_0 - T_w) \frac{4\lambda}{r_0^2} $$

(3)

$$ q_v = (T_w - T_f) \frac{2\alpha}{r_0^2} $$

(4)

It is noted that concrete is deformed due to the temperature change. Therefore, the rate of the deformation energy of thermal strains may also be taken into account in the left side of Eq. (2), which can be described as $\beta = \frac{\rho c_p T}{C \sigma \varepsilon_p}$, where $\beta$ is the rate of plastic strain depending on the load frequency and the load levels.

3.3 Determination of the heat generation rate

3.3.1 Energy conversion

The thermal energy $W_T$ is generated by transformation of the energy $W_f$ released due to internal friction and fracture of material, which can be assumed to be a linear function of the plastic work $W_p$ of concrete material, $W_f = C \cdot W_p$. The fraction of the dissipate energy converted into heat can be described by a factor $\beta = W_T / W_f \leq 1$ as presented in Eq. (5), in which $\sigma$ is the acting stress and $\varepsilon_p$ is the rate of plastic strain of concrete. The constant $C$ depends the fracture characteristics of material and is determined experimentally. For brittle materials like steel, a value of 1 may be used for $C$. For brittle materials like concrete, a larger value of $C$ is expected. It is noted that in the steady state the first term in Eq. (5) equals zero.

$$ \beta = \frac{\dot{q}_v}{C \sigma \varepsilon_p} \approx \frac{\rho c_p T + \alpha T E_\sigma \Delta T \dot{\varepsilon}_e + (T_0 - T_w) \cdot 4\lambda/r_0^2}{C \sigma \varepsilon_p} $$

(5)

3.3.2 Influence of aggregate size

As two main material elements of concrete, aggregates and binders show an almost linear behaviour with different modulus of elasticity, see Fig. 3. When they are combined to form a composite material, the resulting concrete exhibits non-linear behaviour. It can therefore be said that the plastic deformation is mainly caused by the damage of the contact between aggregates and binders. The friction work and fracture energy of material, which is caused by formation of cracks and relative sliding of material particles especially in the interfacial transition zone (ITZ) between binders and aggregates, is assumed to be the source of heat generation in concrete. Since aggregates dominate about 70% of the concrete material in volume, the plastic strain is mainly determined by the deformation at the ITZ, the weakest part of the concrete matrix. As a result, the plastic strain depends on the area of the interfacial transition zone, the contact area between binders and aggregates. Assuming that each aggregate has a spherical shape with a radius $R$, the surface area and the volume of the sphere are $A = 4\pi R^2$ and $V = 4/3\pi R^3$, respectively. The ratio $k$ between $A$ and $V$ of the sphere is $3/R$. For the same total volume of aggregates in
concrete, the smaller aggregate exhibits a larger ratio $k$ than the larger aggregate. This means that the concrete with smaller aggregates has a larger area of the interfacial transition zone, and thus a higher potential to generate thermal energy by plastic work. Taking into account two concretes with an equal volume of aggregate, but with two different aggregate sizes, the following equation is obtained, in which $A_{ITZ1}$ and $A_{ITZ2}$ are the areas of the ITZ corresponding to concretes with the maximum aggregate sizes $a_g1$ and $a_g2$.

$$A_{ITZ1} \cdot a_g1 = A_{ITZ2} \cdot a_g2$$

(6)

Under the assumption that the generated heat energy is proportional to the total area of the ITZ, the energy conversion fraction $\beta(a_g) \leq 1$ for concrete with the maximum aggregate size $a_g$ in mm is determined on the basis of Eq. (6) as follows:

$$\beta(a_g) = \frac{\beta_1}{a_g}$$

(7)

here, $\beta_1$ is the reference value of the energy conversion fraction, which corresponds to the aggregate size $a_g = 1$ mm. It should be noted that the heat energy generated due to the friction between binder material and aggregate also depends on the strength of aggregate as well as of binder material. A larger generated heat energy is expected by concrete with a higher strength.

![Fig. 3: Stiffness of materials](image1)

![Fig. 4: Development of temperature in cylinders](image2)

4 Experimental validation

4.1 General

In order to validate the hypotheses of the thermal generation mechanism presented in Section 3, experimental work is carried out. For a detailed experimental program and test results, it is referred to [1]. Based on the results of fatigue tests, the plastic strain in concrete samples is analysed and the thermal energy generation rate is calculated. The influence of aggregate size on the heat energy generation rate is also investigated.

4.2 Experimental program

The examined UHPC without fibres has a water-cement ratio $w/c$ of 0.24 and a maximum aggregate size $a_g$ of 1 mm. The tested concrete cylinders have the same geometry with $d/h = 60/180$ mm. To eliminate the shrinkage, creep and hardening effects of concrete, fatigue tests are performed on concrete samples with at least 90 days, when the compressive strength $f_c$ remains constant with the mean value of 183 MPa. In order to measure the temperature development inside the concrete, a temperature sensor is embedded in the centre of the test specimens. The aim is to detect temperature gradients in the concrete by determining the temperature difference between the outside and the centre of the cross-section. In addition to the temperature, the longitudinal strain is also measured. The samples are divided into three groups corresponding to three load frequencies: $f_P = 3$ Hz, 10 Hz and 20 Hz. In all fatigue tests, the lower stress level $S_{min}$ is fixed by 10 % of the mean compressive strength $f_{com}$, while the upper stress level $S_{max}$ is varied by 0.6, 0.7 and 0.8. In this paper, only the results of the first 3 samples with a load frequency of 20 Hz are analysed, since the other tests are still in progress. In order to evaluate the results of fatigue tests, thermal parameters of UHPC should be determined experimentally. Due to the lack of experimental results, they are assumed in this paper based on the reference of literature, e.g. [3], as follows: specific weight $\rho = 2300$ kg/m$^3$, specific heat capacity $c_p = 1000$ J/(kg K), thermal expansion coefficient $\alpha_T = 1.2 \cdot 10^{-5}$ K$^{-1}$, heat dissipation coefficient $\alpha = 10$ W/(m$^2$-K) and thermal conductivity $\lambda = 1.1$ W/(m-K).

4.3 Plastic strain

As presented in Section 3.3.1, the heat generation rate $q_h$ is related to the rate of plastic strain $\dot{\varepsilon}_p$, which can be determined on the basis of the plastic strain evolution. A typical development of the measured strain concrete in a fatigue test is shown.
in Fig. 2. Since the measured strain $\varepsilon_{\text{mea}}$ includes the plastic strain $\varepsilon_p$, the elastic strain due to load $\varepsilon_e$ and the elastic strain due to temperature $\varepsilon_T$, the plastic strain is calculated from the strain $\varepsilon_{\text{mea}}$ as $\varepsilon_p = \varepsilon_{\text{mea}} - \varepsilon_e - \varepsilon_T$. The elastic strain $\varepsilon_e$ is determined from the ratio between the acting stress (lower or upper stresses) and the effective elastic modulus of concrete $E_{c,e,f}$. The thermal elastic strain $\varepsilon_T$ is calculated as $\alpha_T \Delta T$. From the relationship between the plastic strain $\varepsilon_p$ and the load frequency $f_P$ as well as the time, the plastic strain rate $\dot{\varepsilon}_p$ is determined. The obtained results of plastic strain rate $\dot{\varepsilon}_p$ are then used to determine the plastic work rate $W_p$, which is needed for the calculation of the energy conversion fraction $\beta$ according to Eq. (5), see also Section 4.4.

4.4 Thermal energy generation rate

The fatigue tests show that the load-induced temperature in concrete develops with two different curves depending on load level. When testing with a low load level, the temperature rises continuously up to a certain time and then remains constant or drops slightly. For specimens with a higher load level, e.g. $S_{\text{max}} = 0.7$, there is a strong temperature increase until the sample fails, see Fig. 4. Based on the measured strain and temperature in concrete cylinders, the heat generation rate $\dot{q}_v$ is calculated for each test at the time of the maximum temperature summarised in Table 1. Assuming that $C = 1000$, a reasonable result of the energy conversion fraction $\beta$ can be seen for the studied samples. This confirms that the heat generation rate $\dot{q}_v$ is a linear function of the plastic work rate $W_p$.

4.5 Influence of aggregate size

Since the tests for concrete with other aggregate sizes have not yet been completed, the experimental results of the fatigue tests for high strength concrete carried out by [2] are used for validation. In this test program, the aggregate size $a_g$ was varied while keeping the same compressive strength. The concrete samples were tested with the same load frequency $f_P$ of 10 Hz and with stress levels $S_{\text{min}} = 0.05$ and $S_{\text{max}} = 0.75$. Based on the temperature development, the heat generation rates at the temperature increase of $\Delta T = 13$ K are determined for 3 concretes with maximum aggregate sizes $a_g = 1$, 2 and 5 mm and shown in Table 2. It is shown that the ratios of heat generation rates in theoretical and experimental analyses agree very well, see columns (2) and (6) in Table 2. This directly confirms the accuracy of Eq. (7).

Table 1: Heat generation at $\Delta T_{\text{max}}$ of samples in [1]

| Sample       | $a_g$ (mm) | $S_{\text{max}}$ | $f_P$ (Hz) | $\dot{q}_v$ (J/s) | $\beta$ |
|--------------|------------|------------------|------------|------------------|--------|
| UHPC1-80-20-b| 1          | 0.8              | 20         | 1.16 · 10^4      | 0.82   |
| UHPC1-70-20-b| 1          | 0.7              | 20         | 7.88 · 10^4      | 0.81   |
| UHPC1-60-20-b| 1          | 0.6              | 20         | 2.90 · 10^4      | 0.98   |

Table 2: Heat generation rate at $\Delta T = 13$ K of samples in [2]

| Sample       | $a_g$ (mm) | $S_{\text{max}}$ | $f_P$ (Hz) | $\dot{q}_v$ (J/s) | $\beta/\alpha$ |
|--------------|------------|------------------|------------|-------------------|----------------|
| VB1          | 1          | 0.75             | 10         | 1.53 · 10^6       | 1.00           |
| VB2          | 2          | 0.75             | 10         | 7.65 · 10^4       | 2.00           |
| VB3          | 5          | 0.75             | 10         | 3.92 · 10^4       | 3.90           |

5 Conclusions

Ultra-high performance concrete shows a temperature increase under cyclic compressive loading with high load frequency. Through experimental work and theoretical analysis it can be concluded that most dissipate energy caused by fatigue loading is converted into heat. The fraction of dissipate energy converted into thermal energy strongly depends on the size of the aggregates used in the concrete. The smaller the aggregate, the greater the heat generation. Taking into account the interfacial transition zone between binders and aggregates, the energy conversion factor can be formulated as a function of the maximum aggregate size $a_g$. The accuracy of this proposed formula is confirmed by experimental results. In the next step, further experimental results of fatigue tests on UHPC samples are evaluated, in which the influence of load frequency and the critical strain regard to failure state are also studied.

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