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Experimental study on the thermal convection behaviour of concrete material in service environments

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Abstract

Concrete is a kind of common building material with many advantages and widely used in civil infrastructures. Concrete has the qualities of uneven, anisotropic, large dispersion and thermal inertia, therefore, it is very difficult to accurately determinate its thermophysical properties. The lab testing conditions are much different to the service environments of structures. The inverse method using field measurements affected by so many factors and uncertainties decreases the reliability of results. In this study, the heat convection behaviour of concrete in natural service environments is investigated using specimen experiments. A special testing system is designed and established. It includes a small size thermal insulated cuboid tank, concrete specimens, temperature and wind speed measuring and collection. The heat convection coefficient of concrete in natural environments is investigated taking account of different wind speed and roughness of concrete surface. The results indicate that the roughness of specimen surface has considerable effects on the heat convection coefficient. Based on the measurements, the relationship between heat convective coefficient and wind speed of concrete is regressed using linear equation. Comparing with other literature, the results of this study is reasonable and reliable.

1. Introduction

Concrete is a kind of common building material with many good properties. It has been widely used for civil infrastructures such as buildings and bridges. For high-rise buildings and large long-span bridge, the thermal behaviour is one of the most important issues should be seriously concerned. The analysis of thermal effects on structures is very important for structural design, construction and management. The determination of thermophysical properties of building materials is the basics for the thermal analysis and assessment of structures.

The determination method of concrete surface heat convection coefficient (h_c) can be divided into two types: 1) lab testing using precise instruments and following rigorous procedures; 2) field measurements of structural temperature and inversely calculate the thermal parameters of materials. Zhu (1999) proposed the inversion analysis method for thermal conductivity, heat convection coefficient and solar radiant heat of concrete based on the field measurements of mass concrete temperatures. Song et al (2010) obtained the thermal parameters of concrete through analysing the thermal behaviour of concrete slabs using the measurements of temperature, strain and meteorological data. Liu (2000) proposed the formula for calculating the heat convection coefficient of the outer surface of medium roughness solid and building structure. Zhang and Liu (2006) obtained the convective heat transfer coefficient through fitting the test results from wind tunnel experiments. Kehlbeck (1981) provided a formula for calculating the heat convection coefficient (wind speed less than 5 m/s) using field measurements. Mirambell and Aguado (1990) concluded a formula for calculating the heat convection coefficient of the outer surface of bridge beam. Saetta, et al (1995) concluded a regression formula for heat convection coefficient of concrete structure surface through studying the stress of concrete structure under the action of temperature difference.

Concrete has the qualities of uneven, anisotropic, large dispersion and hot inert materials, therefore, it is very difficult to accurately determinate its thermophysical properties, especially in natural environments. The lab testing conditions are much different to the service environments of structure. The inverse method using field measurements affected by so many factors and uncertainties decreases the reliability of results. In this study, the heat convection coefficient of concrete is investigated using specimen experiments. A testing system is particularly designed and fabricated. The effects of wind speed and concrete surface roughness on the heat convection behaviour are experimented and analysed.

2. The basic principle of the experiment

Usually, the building materials exchange heat with the surrounding environment by way of heat radiation and convection simultaneously. The total exchanged heat Q can be expressed as:

$$Q = Q_c + Q_R \tag{1}$$

where Q_c is the convection heat and Q_R is the radiation heat, respectively.

Thermal convection is the process of energy exchange between the solid surface and the surrounding air. It can be divided into two types: natural convection (atmospheric molecules moved according to thermodynamics) and forced convection (atmospheric molecules moved by environmental wind) (Arpaci, and Larsen, 1984; Bejan, 2013). The convective heat transfer can be expressed using Newton cooling formula:

$$Q_c = h_c(T_w - T_f)A \tag{2}$$

where h_c is the heat convection coefficient; A is the area; T_w and T_f is the temperature of solid and the air temperature, respectively.

The radiation heat transfer can be calculated [6]:

$$Q_R = \varepsilon C_o\left[(T_w/100)^4 - (T_f/100)^4\right]A \tag{3}$$

where ε is the emissivity coefficients of the solid surface; C_0 is the Stefan–Boltzmann constant.

In this experimental study, a specific testing device is designed and fabricated to measuring the total exchanged heat, the temperature of the specimen and surrounding air. The environmental wind is simulated according to real situation and controllable. The convective heat transfer coefficient of concrete is investigated.

3. Experimental study

The heat convection coefficient of concrete is investigated taking account of the effects of wind speed and concrete surface roughness. The experimental system includes testing device, concrete specimen, generating the environmental wind, temperature and wind speed collection, as is shown in Fig. 1.

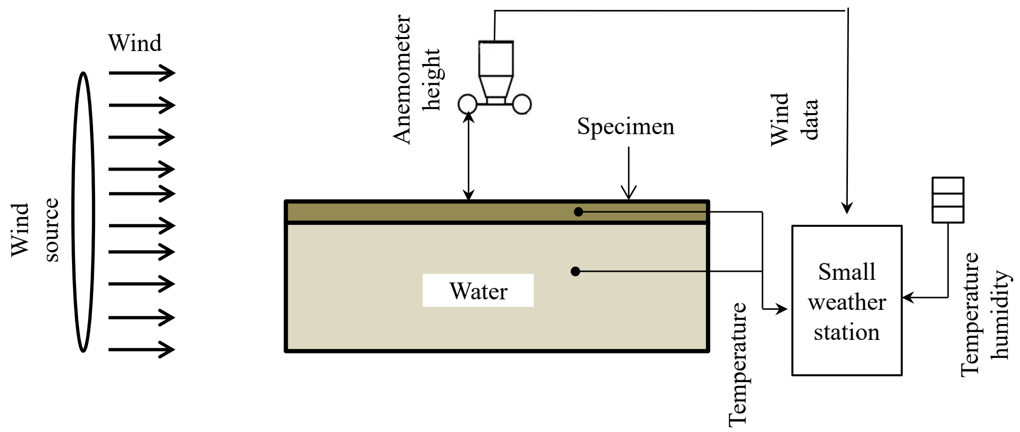
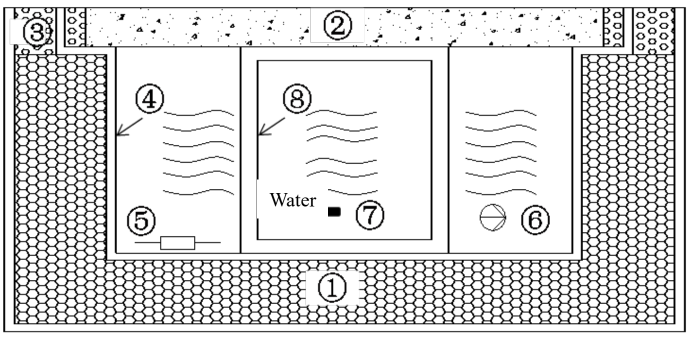


Fig.1. Schematic diagram of the experimental system

3.1 The testing device

A specific testing device is developed, as shown in Fig. 2. A small size thermal insulated cuboid tank is fabricated using insulation material. The upper side of tank can be replaced with the testing specimen. The inside of tank is full of water and using electric heater to warm the water. Besides, a small water pump is placed on the bottom of tank to circulate the water, then, the water temperature is almost even. The specimen is placed on the top of tank with one side exposing to natural environment and the other side immersing in the water of tank. The water can provide a stable heat source and apply a First-type thermal boundary condition on the surface of the testing specimen.

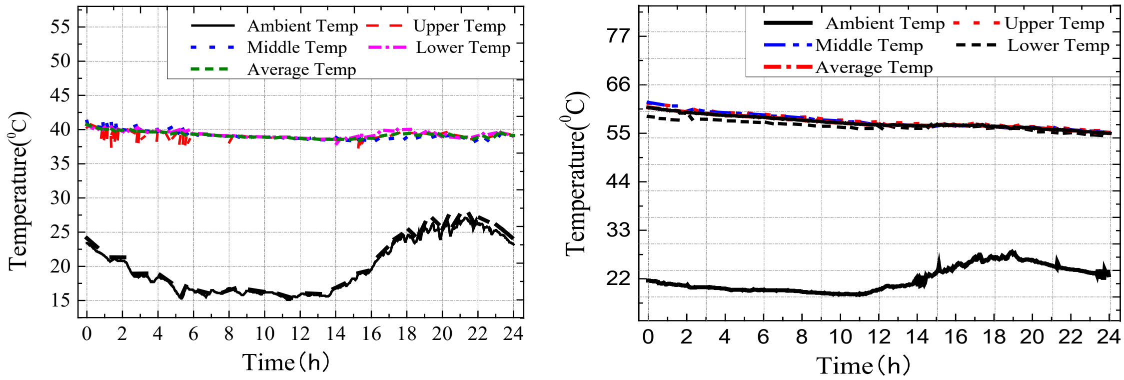


①-Foam board
②-Specimen
③-Blowing agent
④-Plexiglass
⑤-Electric heater
⑥-Circulating water pump
⑦-Thermocouple
⑧-Steel support

Fig. 2. Profile of thermal insulated cuboid tank

3.2 Measuring the heat loss of the insulation tank system

The insulation tank cannot be absolute heat insulation. In order to accurately calculate the convective heat transferring via the specimen, the amount of heat loss not passing the specimen should be estimated. The cooling tests of the tank are carried out from different initial temperature of water. Three thermocouples are placed at upper, middle and bottom of the tank inside along the depth. The average temperature of the three thermocouples is utilized to calculate the heat loss. The temperature drop curves are shown in Fig. 3. The performance of the heating and insulation of the testing system is good. The heat loss is almost linear and can be easily compensated in the experiments.



a）Initial temperature of 40°C b）Initial temperature of 60℃

Fig. 3. Temperature drop curves of thermal insulation tank

Two concrete specimens with different surface roughness are fabricated, as shown in Fig. 4. The specimen is 70cm length, 50cm width and 5cm thickness. The concrete axial compressive strength was designed to be 26.8 N/mm^2. The immersing surfaces of the concrete specimen were treated with a flexible waterproof coating to prevent the water penetrating into the concrete slab specimen. The temperature of specimen is measured using T-type thermocouples, and the data is collected by a small automatic weather station. The layout of thermocouples is shown in Fig. 4. Three thermocouples were installed at the center of the specimen (Point-1) along the depth. Another three thermocouples were installed on the specimen surface at the Point-2, 3 and 4, respectively. The surface thermocouples were buried inside specimen with a depth about 1 mm below the concrete surface.

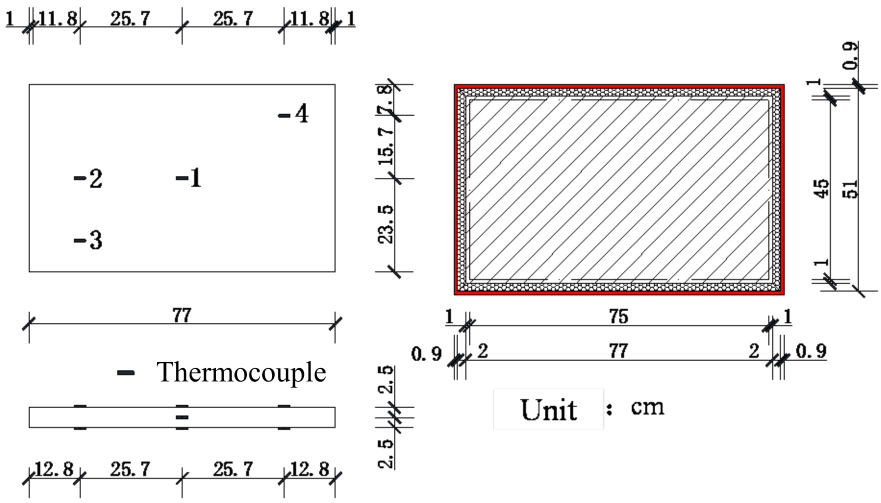


Fig.4. Specimen and the layout of the thermocouples

3.2 Wind field generating

Several industrial fans are used to generate the continuous wind field with controllable wind speed. Figure 5 shows the measured wind speed nearing the specimen surface. It can be seen that the average wind speed of ten minutes is very close to the total average wind speed. The industrial fans can provide stable wind field. Therefore, wind speed in 10 minutes average is used for thermal analysis.

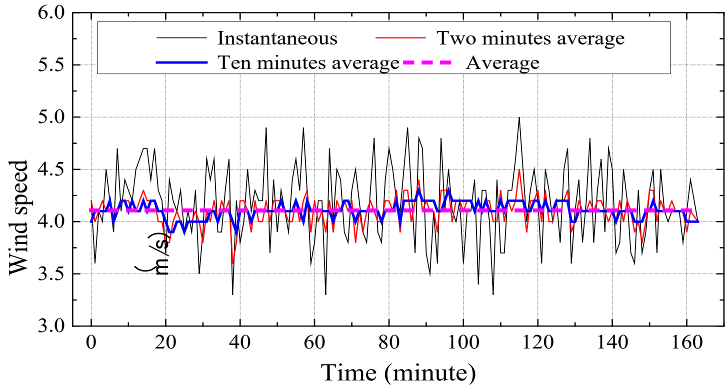


Fig.5 Wind field for experiment

4. Experimental results and analysis

In the natural environment, concrete specimens with different roughness are experimented. The concrete specimen is plastered cement mortar to generate smooth surface. The rough surface is the casted concrete slab without any further processing. The heat convection coefficient h_c of concrete surface is obtained according to different wind speed. The results are listed in Table 1. The difference of h_c between the rough surface and the smooth surface is very small in the natural convective heat transfer condition (wind speed is 0 m/s), however, the difference is significantly increased with the increasing of wind speed.

Table.1. Heat convection coefficients at different wind speed

Wind speed（m/s） / h_c（W/(m^2·°C)）	0	1.17	3.92	4.11	1.07	4.01
Smooth	5.66	×	×	×	10.09	19.95
Rough	5.31	12.56	20.43	23.20	×	×

Using the least squares method, the relationship between heat convection h_c coefficient and wind speed v of concrete surfaces with different roughness can be fitted as:

$$h_{cS}=3.929v+6.378 \quad (W/(m^2 \cdot °C)) \qquad \text{(smooth)} \tag{4}$$

$$h_{cR}=3.519v+5.941 \quad (W/(m^2 \cdot °C)) \qquad \text{(rough)} \tag{5}$$

The relative difference of heat convection coefficient between rough and smooth surface ($C=(h_{cR}-h_{cS})/h_{cS}$) is shown in Fig. 6. The relative difference rapidly increases to 10% when the wind speed changes from 0 to 4.5 m/s.

The energy exchange of heat convection between the solid and surrounding air is very complicated and deeply affected by many factors. It is not easy to identify the heat convection coefficient (h_c) of concrete using experiments, especially in natural environments. In this study, the discrepancy of the concrete material, the temperature loss of the testing system and other uncertainties will influence the results. The identified heat convection coefficients are compared with the existing conclusions from other literatures, as shown in Fig.7. The rough surface of concrete definitely has the largest h_c since there are more contact area between solid and air. The surface roughness engineering structures is obvious different. It is meaningful taking account of the roughness for thermal analysis of structures.

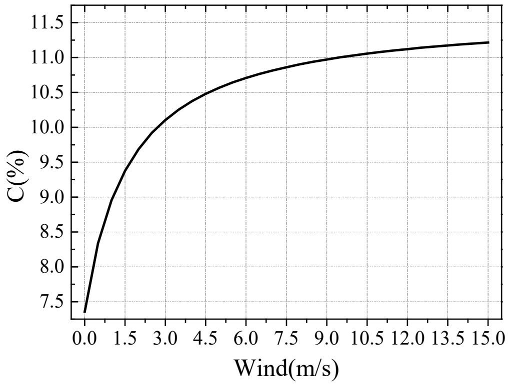


Fig. 6. Discrepancies of h_c between rough and smooth surfaces

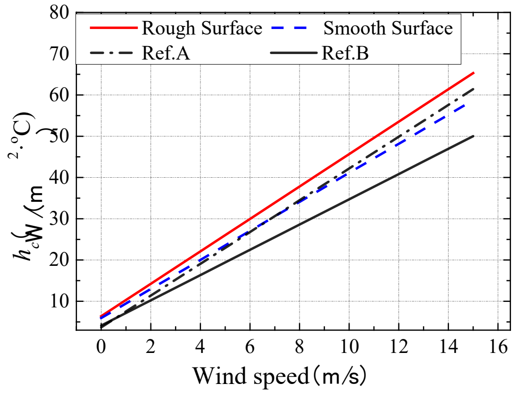


Fig. 7. Comparison of h_c (Ref. A –Bejan, 2013; Ref. B –Mirambell and Aguado, A 1990)

4. Conclusion

In this paper, the heat convection coefficient of concrete in natural environment is investigated. The wind speed and roughness of concrete surface are discussed.

The roughness of concrete surface shows little influence on the natural convection heat transfer process, however, it is significantly impact on the heat convection coefficient of forced convection heat transfer. The relative difference of h_c between rough and smooth rapidly increases to 10% when the wind speed changed from 0 to 4.5 m/s.

Under the condition of forced convection heat transfer, the wind speed has a significant effect on the surface convective heat transfer coefficient. Based on the experimental data, the relationship between the heat convection coefficient h_c and the wind speed v can be regressed as h_c=3.929v+6.378 for rough surfaces and h_c=3.519v+5.941 for smooth surfaces.

ACKNOWLEDGMENTS

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