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A Tool for Experimental Analysis of Behavior of Solidifying Concrete inside Massive Structures

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In massive concrete structures, the heat generated by hydration reaction is the main cause of defects in homogeneity of the structure as the rate of hydration itself depends on temperature, which results in uneven temperature field distributions throughout the structure and subsequent cracking. This effect, which occurs during solidification and further hardening of concrete, influences the integrity and thus durability of the entire structure, therefore, it is analyzed beforehand by means of various numerical methods. This paper presents a simple heating system for curing concrete specimens under prescribed temperature history so that material parameters in arbitrary locations inside massive structure can be experimentally obtained, providing relevant input data necessary in the numerical methods. The controlling unit of the heating system is constructed very simply, based on the fuzzy logic techniques.

Keywords: solidifying concrete, massive structure, temperature history, fuzzy logic, thermal analysis.

1. INTRODUCTION

The majority of the very early age defects in concrete is attributed to the incapability of the hardening concrete to cope with the increasing differences in stress distributions, mainly caused by the non-uniform temperature fields. This effect becomes of importance in massive concrete structures where the heat generated by the hydrating cement is constrained by the surrounding mass. To prevent the detrimental effects of increased temperature some precautionary measures can be applied, such as embedded cooling pipes. Since massive concrete structures are usually unique in shape, direct measurements of temperature and other measurable quantities acquired from precedent cases are not available, therefore, it is desired to develop a system for simulating a temperature history at arbitrary position in the concrete structure on a specimen which can provide valuable experimental information on the effects related to the hydration of mass concrete. In an analysis of a massive concrete structure the effect of elevated temperature due to hydration can be taken into account by applying, e.g., the equivalent age concept using the Arrhenius reaction-rate equation whose parameters are available for commonly used cements. However, in the case of special structures new materials may be used for which relevant experimental data are not at hand, such as time-dependent deformation of solidifying concrete at elevated temperature which come into play with the considerable self weight of the concrete mass. Further, acquiring experimental data on the specimens obtained directly from the actual structures has its limitations regarding the retrieval of the specimens, where especially the core-drilling technique is not feasible in the case of massive concrete structures. Therefore, it seems reasonable to prepare a test specimen outside the actual structure by curing the specimen under the same conditions as it would be subjected to in the mass of the actual structure. This approach has been attempted by researchers and practicing engineers with various successes. The usual drawbacks are represented by too expensive and complicated equipment on one side and excessive inaccuracy in the curing conditions on the other.

In this study it was attempted to develop a heating system for curing specimens under prescribed temperature history which overcomes the mentioned drawbacks in the systems of this sort. For the sake of generality in application, it was decided to employ a decision-making mechanism based on the fuzzy logic, as the fuzzy theory proved effective in cases when little or scarce knowledge is at hand, [1]. This approach proved to be effective in treating the uncertainties related to heat losses, the rate of heat supply and the actual temperature measurement while providing very acceptable accuracy. Another advantage of this approach is the zero requirement to know any exact characteristics related to the performance of heaters, heat losses and the thermal properties of the materials used in the system. Instead, the parameters required for fuzzy decision making are obtained from few preliminary tests of the system which address its overall performance. In this paper, the basic features of the heating system are described and the performance of the system is discussed. This tool can be used in direct combination with the method proposed in [2] for investigation of mechanical behavior of solidifying concrete.

2. STRATEGY FOR EXPERIMENTAL ANALYSIS OF MASSIVE CONCRETE STRUCTURES

Since the retrieval of testing specimens directly from actual massive concrete structures is very difficult, the strategy of curing specimens outside the structure under conditions corresponding to those in the actual structure seems worth pursuing. This strategy allows experimental investigation of the response of solidifying concrete to the thermal and loading conditions inside mass structure. Such

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experiments can be conducted in the real time during the construction process based on real temperature measurements or at the design stage when the temperature history is obtained from a thermal analysis of the structure, which is a useful means for prevention of the detrimental effects related to the hydration process. The imaginary position of a specimen in a thick concrete wall is shown in Fig. 1.

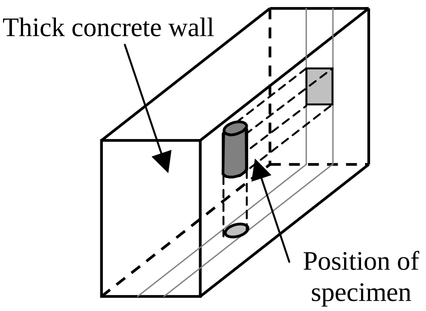

Fig. 1. Imaginary position of specimen inside thick concrete wall

2. ACQUISITION OF TEMPERATURE HISTORY

The temperature history can be obtained from real measurements or from a thermal analysis where the function of heat generation is the influencing factor. The adiabatic test conducted with the actual concrete to be used is the most convenient source of the heat generation function. In the cases where the adiabatic test is not possible a recommended form of the heat generation function, e.g., that given by JSCE Standard Specification [3] can be used. The thermal parameters of typical concrete are available, e.g., in [4] where the thermal analysis of concrete is also explained. The thermal parameters of solidifying concrete are also available.

The general form of the heat balance condition is given by

$$\sum_{i=1}^{3} b\frac{\partial^2 T}{\partial x_i^2} + \rho_c \dot{H}(t) = \rho C \frac{\partial T}{\partial t}. \tag{1}$$

where T is temperature, t is time, x_i is a coordinate, b is thermal conductivity, C is specific heat, ρ is mass density of concrete, ρ_c is cement mass per unit volume of concrete and H is a function of heat generation per unit mass of cement.

For our purposes, 700 mm thick wall made of concrete with the mix proportions shown in Table 1 using rapid hardening portland cement was considered for the relatively rapid increase of temperature which was used for testing the heating system. Because in the analysis of thermal fields in a wall the direction normal to the wall plane is the influencing direction, the analysis can be considered as a uniaxial problem. The finite element model of the wall is shown in Fig. 2.

The thermal parameters and the heat generation function used for this analysis were those for typical concrete which are provided by JSCE. The thermal properties used in Eq. 1 are listed in Table 2. The temperature history in the center of the wall is plotted in Fig. 3.

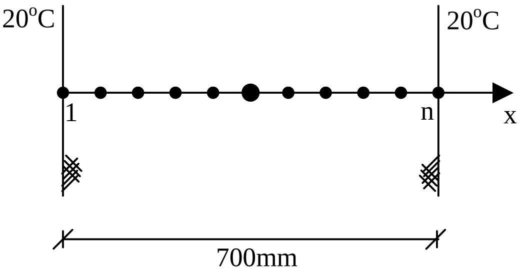

Fig. 2. Uniaxial model of thick wall

Table 1. Mix proportions of concrete

Type	Weight per unit volume (kg/m^3)			
	W	C	S	A
60 MPa	181	490	599	1093

Table 2. Material parameters of concrete for thermal analysis

b (J/m/h/°C)	C (J/°C/kg)	ρ (kg/m^3)	ρ_c (kg/m^3)	H (kJ/kg)
0.00075	1150	2300	490	407.3

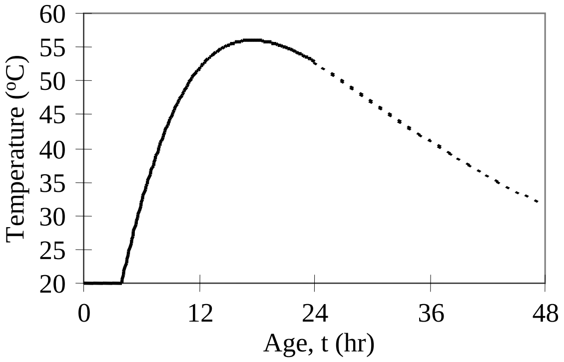

Fig. 3. Temperature history in center of thick concrete wall

The part of the function (0 to 24 hrs) which was taken as the target temperature history for the heating system is distinguished by a thick solid curve. Because the heat generation function proposed by JSCE does not take into account the onset of the hydration, based on the observations from preceding experiments the beginning of the heat generation function was delayed till the initial setting time, which was 4 hours after mixing. The ambient temperature, set as the boundary conditions, was kept constant at 20 °C.

3. FUZZY APPROACH IN HEAT SUPPLY CONTROL

The controlling units of heating systems in general have to overcome the difficulties with a delay in response to heating which is due to the thermal conduction, convection and radiation characteristics of materials. For the conventional convection-conduction systems an efficient stirring is essential to reduce this effect. The controlling units can be divided into two classes, first, those with simple on/off switches controlling a constant rate of heat supply and, second, those capable of changing the rate of heat supply. Obviously, the second class has a greater potential to ensure a good accuracy. However, the final accuracy and stability of a heating system depend on the decisions when or how much heat should be supplied.

The traditional mechanical thermostats using bimetallic strips, which engage and disengage the heat supply source upon reaching a certain temperature value, are replaced with electronic units based on a similar principle, which is a change in properties or shape of a material with varying temperature. Mathematically, the controlling units acting at a certain temperature value are based on the classical set theory with the classical logic decisions giving the true or false ruling. Such controlling units are suitable for heating systems whose parameters are known and which do not change significantly within the range of their application, therefore those heating systems are usually closed systems which were previously well calibrated. For systems whose parameters may vary, such as the heat losses, the amount of supplied heat or the volume of heated medium, those controlling units in their simple form do not work well, and for ensuring a good accuracy the decision making based on true/false rulings becomes too robust to be applied at all.

The ruling based on the fuzzy set theory a priori assumes occurrence of not precise input data and so the decision making is formulated in a very general form, mainly derived from observed tendencies, with the rulings based on the maximum of minima principle [5]. Of course, such a controlling unit cannot maintain the desired value precisely, but, if a small reasonable inaccuracy is allowed deliberately, the controlling unit gives stable rulings which ensure a good accuracy even for systems with varying parameters.

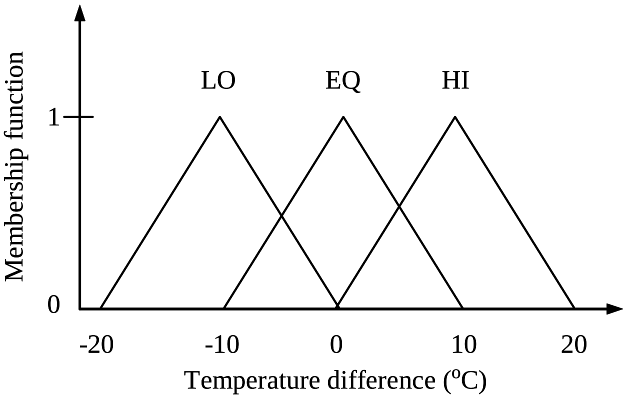

Fig. 4. Temperature difference interpreted by fuzzy sets

The objective in development of the heat controlling system is a general controlling unit which can be applied to an arbitrary set of a heat source with a constant rate of heat supply, stirring device, thermocouples, a container and a heated medium. This was achieved by choosing the target temperature history, the temperature of a concrete specimen and the temperature of the medium surrounding the concrete specimens (water in our case) as the ruling quantities and the duration of heating and the duration of waiting for the recognition of an action as the acting quantities. Based on the inaccuracy among the target history temperature, the temperature of concrete and water, and their rates of change, the decision on heating duration and corresponding waiting time are made. The calibration of the above fuzzy quantities is made on three tests where the first is focused on the performance of the heater and the response of the system, the second on the heat losses and the third on the interval after which an action can be recognized. It should be noted that no exact information on the parts of the system is necessary, that means the volume of the medium and its thermal properties do not have to be measured, the type and nominal performance of a heat source does not have to be known and the dimensions and material properties of a container also do not have to be considered.

An example of temperature difference described by the fuzzy sets is shown in Fig. 4, where the temperature difference is granulated into three granules denoted by “LO”, “EQ” and “HI”, which can be defined linguistically as, e.g. “lower than”, “about the same” and “higher than”, respectively. The other quantities are described similarly. Then, it is relatively easy to define the rulings in the decision making mechanism, which will call upon appropriate actions. An example of a ruling can be: IF “temperature of water is lower than that of concrete specimen” and “temperature of concrete specimen is lower than target temperature“ THEN “keep the heater on for long time”. The construction of a fuzzy controller is explained very comprehensively in, e.g. [6, 7].

4. EXPERIMENTAL SETUP

The heating system is schematically described in Fig. 5. The system consists of a metallic container lined with two surface heaters. The water in the container was stirred by a screw propeller. The temperature was measured by CC thermocouples, where two thermocouples were placed in the monitored specimen. The temperature readings were transferred through a data logger to a PC where the decisions were made upon the temperature information and the target history temperature. The PC then turned on the surface heaters for a decided heating time duration, or it rested while monitoring the temperature development.

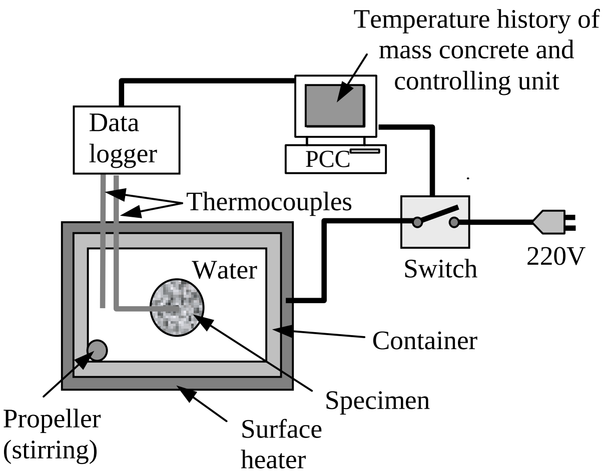

Fig. 5. Experimental setup

5. COMPARISON OF RESULTS

The result of the simulation is shown in Fig. 6. The difference between the actual temperature inside a specimen and the prescribed temperature history is shown in Fig. 7.

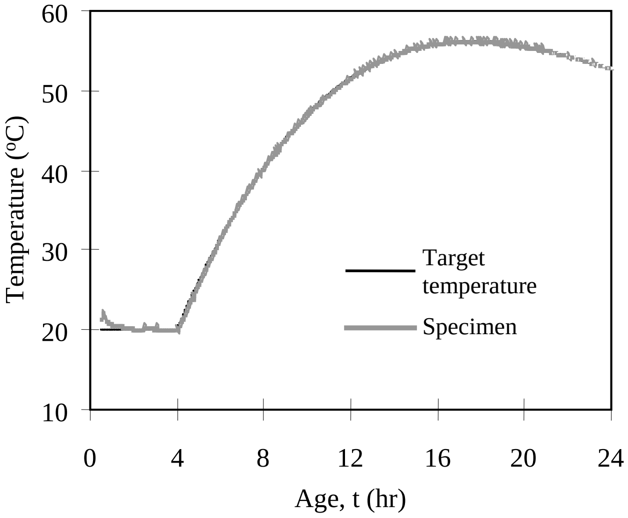

Fig. 6. Comparison between target and specimen temperature

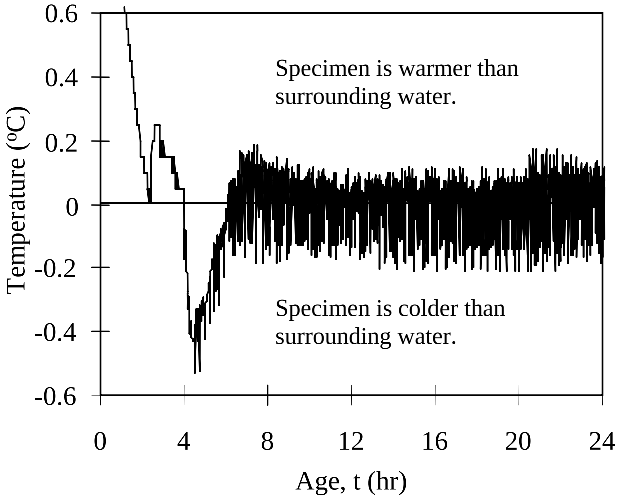

Fig. 7. Difference between target and specimen temperature

The initial discrepancy in the temperatures, which is noticeable between time zero (water mixed with cement) and 3 hrs, was caused by the initial temperature of a specimen which was 21.5 °C. This inaccuracy is followed by a slight overshooting in heat supply disappearing by 4 hrs. Because the cooling of this system is provided by mere evaporation and other natural heat losses, and since the room temperature was kept constant at 20 °C, any overshooting in heat supply had to be prevented. However, in this case the overshooting incurred an error of only 1 %. The lagging of the temperature inside the specimen behind the prescribed temperature history in the period from 4 to 6 hrs is due to the unrealistic transition from the constant temperature to the greatest rate of the hydration reaction. Because the hydration reaction depends on temperature this sudden change in the prescribed temperature gradient, or the hydration reaction rate, results in the increase of inaccuracy. This can be avoided by inserting a smooth transition into the troubled region, in our case between 2.5 to 5 hrs which is more realistic and which corresponds with the semi-adiabatic tests performed on the same concrete where the temperature rose continuously from time zero and the steepest region occurred at about 5 hours. After the hydration reaction fully developed the temperature of the specimen oscillated about the prescribed temperature history with an amplitude of 0.2 °C, which represents an error of 0.35 % to 0.5 % depending on the related temperature.

CONCLUSIONS

A heating system was developed for curing specimens under prescribed temperature history. This tool can help to simulate similar temperature conditions in laboratory for investigation of mechanical behavior of concrete at extremely early ages. The range of application of this tool covers both the verification of the actual concrete characteristics after construction has been completed and also the laboratory investigation of concrete behavior before the actual construction, which facilitates the decision making about accelerated execution or earliest possible loading of the concrete structure, while the possible consequences will be known. For those two cases the temperature history can be obtained either from the actual records or from a thermal analysis.

The controlling unit of the heating system was based on the fuzzy logic, which allows assembling a system of components of unknown thermal properties while ensuring a reasonable accuracy. The fuzzy parameters are obtained from three preliminary tests on the overall performance of the heating system. The controlling system was able to simulate prescribed temperature history in a concrete specimen with sufficient accuracy.

Acknowledgments

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