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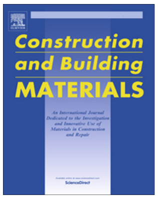

Self-restraint thermal stress in early-age concrete samples and its evaluation

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HIGHLIGHTS

- Mesoscopic thermo-mechanical model for concrete sample is proposed.
- Detailed parameters identification of concrete constituents is carried out.
- Self-restraint thermal stress in early-age concrete sample is numerically evaluated.
- Main driving factors of self-restraint thermal stress are studied.

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ABSTRACT

The self-restraint thermal stress caused by mismatch in thermal and mechanical behaviors of cementitious material and coarse aggregates could be a factor associated with early-age cracking in massive concrete structures, which might be even complicated when considering the mesostructure of concrete. This paper presents the application of mesoscopic model based numerical approach to trace the progression of thermo-mechanical mismatch and consequent self-restraint thermal stress development during early-age hydration in concrete. The mesostructure of concrete sample which contains aggregates, mortar and ITZ is modeled, with the material properties for each phase rationally incorporated. Thermo-mechanical behaviors of both homogeneous mortar and heterogeneous concrete samples under standard curing condition are simulated, focusing on the production mechanism of self-restraint stress. Numerical results show that the spatial-time distribution of temperature and expansion coefficient fields in concrete samples is the main origin of the self-restraint stress. The magnitude of this stress is non-negligible, which may become an influential factor to the load-bearing capacity of concrete.

1. Introduction

In recent years, a number of super-high (around 300 m) concrete dams have been built or are under construction in southwest China. Within these massive concrete structures, a larger release of hydration heat results in significant temperature variations at early ages [1–3]. Such temperature variations can cause thermal deformation (i.e., expansion or contraction), produce thermal stresses and induce cracking that adversely affects the mechanical properties and durability of concrete. Therefore, safety assessment of potential early-age thermal cracking in concrete structures has received substantial attention [4–6].

Over the past few decades, the theory and practice for thermal analysis and thermal stress control of concrete have been extensively developed [5,7–9], based on the hypothesis that concrete is a homogeneous material, and that thermal stress in concrete is associated with either external restraint or internal restraint. When the thermal volume deformation is confined externally by rock foundation or lift surfaces, thermal stress generates. On the other hand, thermal stress also may emerge if the temperature history is varied significantly between two cast lifts [10]. In addition, with more rapid artificial cooling conditions, the surface temperature of a concrete lift might be lower comparing with its interior portion during the hydration process. Due to the differential deformations between the center and the edges, the thermal stress manifests in such a lift even in the absence of external constraints or loads, usually termed as the self-restraint stress [11–13].

However, apart from the aforementioned two most commonly recognized forms of restraint, there is also other self-restraint thermal stress originating from the multi-phase heterogeneous nature

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of concrete, which should attract sufficient attention, particularly for dam concrete. As known, concrete possesses a complex mesostructure with multi phases, i.e., mortar matrix, coarse aggregates, interfaces and pores. Such heterogeneity is more apparent for massive dam concrete. Normally, concrete for dam construction uses a three-graded or four-graded mixture ratio, where the largest aggregate size is 80 mm or 150 mm and the volume fraction of coarse aggregate is relatively high [14]. When temperature gradient exists, the differential thermal expansion between constituents of concrete, primarily in mortar and coarse aggregates [15,16], may create additional internal restraint, which in turn brings about thermal stress. The production mechanism of such stress involves a complex coupling process between heat transfer and stress-strain response in the multi-phase mesostructure, and is difficult to be captured by experimental or analytical approaches. At present, mesoscopic numerical modeling might be an effective and suitable way to look into this issue [17].

Some useful models have been developed to numerically investigate the thermal deformation mismatch between aggregates and the matrix in concrete materials exposed to high temperatures or fires. For example, with a 2D mesoscopic thermal-elastic damage model, Fu et al. [18] studied the thermal deformation mismatch between aggregates and the cement paste matrix in cement-based composites under thermal loads and the cracks induced by the temperature gradient. With the help of a 3D fully coupled thermo-hygro-mechanical model, Xotta et al. [19] numerically examined the magnitude of the induced stress caused by mismatches of the thermal and hydraulic transport properties of two components in concrete specimens and the resulting damage evolution at high temperatures. Considering thermal incompatibility of the aggregates – mortar composite and the degradation of bonds, Sinaie et al. [20] investigated the strength degradation of concrete due to temperature exposure with the two-phase discrete element model.

Less attention has been paid to the thermal mismatch in early-age concrete materials of dam during the hydration process. Due to the heat release from the ongoing cement hydration, the thermally induced stress may appear in interfaces between aggregates and mortar matrix, which are more vulnerable to cracking at early ages. Recently, Zunino et al. [21] established an analytical elastic model with one aggregate particle for concrete to predict the self-restraint thermal stress and estimate the thermal cracking damage. They concluded that the mismatch between strains in concrete phases is the major cause of early-age thermal cracking. However, their analytical model may be too simplified for describing the highly heterogeneous mesostructure of real concrete, or incorporating the time-dependent behavior of cementitious matrix, such as the elastic modulus growth and creep, which are crucial factors affecting the thermal stress in young concrete. There is still a lack of reliable models for tracing the rise of thermo-mechanical mismatch and assessing the self-restraint stress development in early-age concrete.

To improve this situation, a mesoscopic thermo-mechanical model based numerical approach is developed. The three-phase mesostructure which contains coarse aggregates, mortar matrix and the Interfacial Transition Zone (ITZ) is generated for modeling the laboratory-sized concrete samples. In order to make the model capable of representing what really happens inside concrete, the properties of different constituents during early stage of curing are suitably incorporated. With the proposed approach, thermo-mechanical behaviors of a homogeneous mortar sample and a three-phase concrete sample under standard curing condition are respectively simulated. The main driving factors and the magnitude of the self-restraint stress in concrete sample are quantitatively studied based on the numerical results.

2. Mesoscopic thermo-mechanical model

2.1. Mesostructure of concrete

In this work, the thermo-mechanical behavior of dam concrete during early-age curing stage is investigated in a laboratory scale. The Chinese code DL/T5150-2001 (Test code for hydraulic concrete) [22] states that the concrete sample should be cast with appropriate compaction and demoulded after 24 h–48 h of initial curing, and then cured in the standard curing condition, i.e., 20 ± 3 °C and more than 95% relative humidity (RH). A complicated thermo-mechanical process takes place during this stage, and may produce self-restraint thermal stress in the concrete sample.

In such a laboratory scale, cubic or cylindrical samples are mostly utilized for experimentally evaluating concrete's mechanical properties due to the availability of test set-ups and the convenience of the test procedure. Concrete, at this level, can be seen as a heterogeneous material system with exceedingly complex composite structure. Numerical simulation with mesostructure models has proven to be a practical and useful approach for studying the origin and nature of concrete's composite behaviors [23,24]. In this study, a 3D mesostructure model for concrete, comprising three phases of coarse aggregates, mortar matrix and ITZ, is randomly generated and imported into the finite element (FE) analysis.

Various geometry configuration parameters are considered in the three-phase mesostructure model, such as volume fractions, size distributions and spatial distributions of coarse aggregates. In general, these coarse aggregates (greater than 5 mm in size) occupy 30–80% of the concrete volume [14,23,25]. The aggregate size distribution is determined by the Fuller curve [23]. In order to resemble the real concrete, the spatial distribution of the aggregate particles should be as macroscopically homogeneous in space. The "occupation and removal method" [14,26] is therefore employed for the arrangement of particles in a cubic or cylindrical concrete sample. Though the aggregate shape may have considerable bearing on mechanical behaviors of concrete, it's not the main concern of the current work. For simplicity, aggregates are assumed to be spherical particles. As shown in Table 1, the maximum particle size for a cubic sample is determined according to the sample dimensions, see also [22].

The layout of the matrix material is then dependent on the spatial distribution of coarse aggregates. In this model, fine aggregates (smaller than 5 mm) together with the cement paste are regarded as mortar matrix with homogeneous and uniform properties. Note that aggregates hereinafter are referred to coarse ones. ITZ is another crucial phase in the mesostructure, as it is usually recognized as the weakest zone in concrete [19]. The thickness of ITZ is typically in the range of 15 μm–50 μm, according to some experimental observations [1,27]. In this study, the ITZ has been assumed to be homogeneous and with a constant thickness around the coarse aggregates. ITZ is characterized by a layered structure with similar behavior to that of the mortar matrix except a reduced stiffness.

The detailed procedure of generating the mesostructure model has been given in the previous study of the authors [28]. A typical cubic concrete sample (150 mm in side length) with aggregate

Table 1
The maximum particle size of aggregates for sample dimensions.[22]

Maximum particle size (mm)	Dimensions (mm)
⩽30	100 × 100 × 100
40	150 × 150 × 150
80	300 × 300 × 300
150 (120)	450 × 450 × 450