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Full Length Research Paper

Numerical experiment on hygro-thermal deformation of concrete with different material or structural parameters

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Temperature and moisture are responsible for the deterioration processes of concrete structures, and the extensive failures in concrete elements often result from both thermal and moisture simultaneously. The influences of hygro-thermal physical parameters and structural parameters on the deformation of concrete were investigated numerically using a specially developed software, which is named Coupling Temperature and Moisture Simulation System for concrete (CTMSoft). The results of numerical experiment imply that evaluating the influence regularity of only a single parameter on the concrete deformation is unscientific and the coupling effect should be considered in the fact that there is not a definite relationship between concrete deformation and a single parameter. The efficiency of thermal-moisture isolation clapboard and coatings is inconspicuous according to the numerical analysis by imaginary equivalent thickness (EIT) method. The numerical calculation also validated that the neglect of lateral confinement will not result in obvious deviation in tunnel concrete deformation.

Key words: Hygro-thermal deformation, numerical experiment, concrete, imaginary equivalent thickness (EIT).

INTRODUCTION

Concrete deformation due to temperature and moisture condition will always develop simultaneously and interacttively (Nascimento et al., 2004; Suwito et al., 2006; Norris et al., 2008). The numerical simulation of hygro-thermal deformation of concrete is necessary to be investigated for better serviceability, durability estimation and life prediction (Isgor and Razaqpur, 2004; Andrade et al., 1999; Aquino et al., 2004). According to the heat and moisture transfer in concrete and its effect on concrete, the hygro-thermal deformation of concrete is decided by the thermal and moisture parameters such as specific heat, thermal conductivity, coefficient of thermal expansion (CTE) and moisture diffusivity etc (de Barros et al.,1995). In construction practice, some moisture and heat insulation materials are usually used to protect the concrete surface of the structure from the environmental heat and moisture. The insulation clapboard and coatings will prevent or weaken the heat and moisture exchange between structure and environment; they will also influence the hygro-thermal deformation performance of structural concrete. Besides previous conditions, the stress conditions must be considered when investigate the performance of concrete in structure.

This paper will investigate the effect of variation of basic thermal or moisture physical parameters, some structural measures on the hygro-thermal deformation of concrete by numerical experiment.

COMPUTATIONAL MODEL AND SOFTWARE

Coupling heat and moisture transfer equations

Material properties are considered to be uniform throughout concrete body. The heat and moisture transfer equations resulting from mass and energy conservation during the transfer process can be expressed as Equations. (1) and (2).

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \rho r h_{lv} \frac{\partial M}{\partial t} \quad (1)$$

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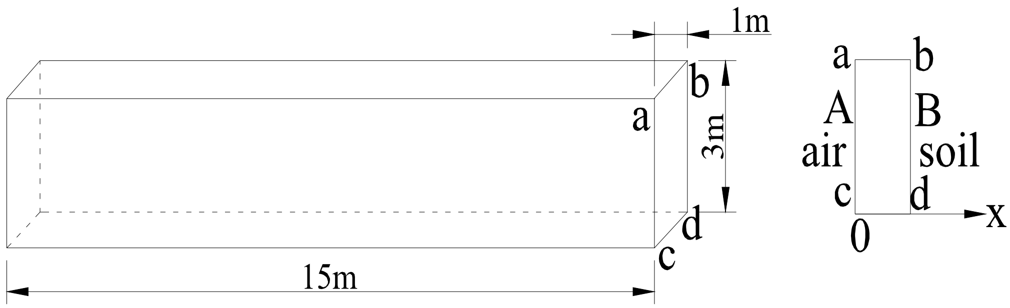

Figure 1. Schematic of the size of concrete wall element.

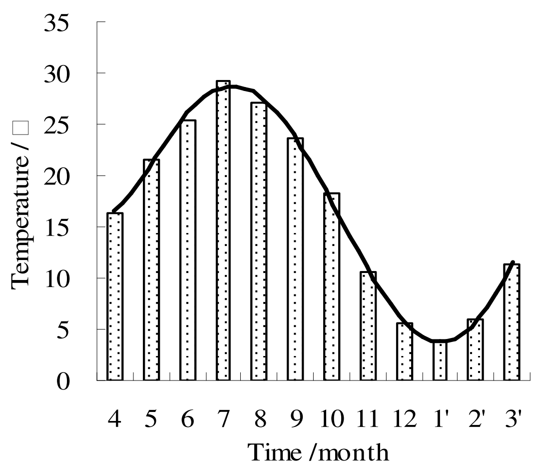

Figure 2. Measured ambient temperature (Side A).

$$\frac{\partial M}{\partial t} = D_{mk}\frac{\partial^2 M}{\partial x^2} + D_m\delta\frac{\partial^2 T}{\partial x^2} \tag{2}$$

where ρ is the density of the material, c_p is the specific heat of constituent, T is the temperature, λ is the thermal conductivity, r is the phase change factor, M is the moisture content, h_{lv} is the heat of phase change, D_{mk} is the moisture diffusion coefficient considering the effect of Knudsen diffusion, x is location variable, t is time variable and δ is the thermal gradient coefficient.

Boundary conditions

The object investigated was a concrete block sized 15 × 1 × 3 m cut from an under-lake tunnel wall (Figure 1). The temperature and moisture at one side (Side A) of the concrete block changing in ambient in one year was considered in the study. The other side (Side B) of the concrete was considered as moisture insulation and the temperature condition was considered as adiabatic of heat and moisture.

In numerical simulation process, the environmental tem-

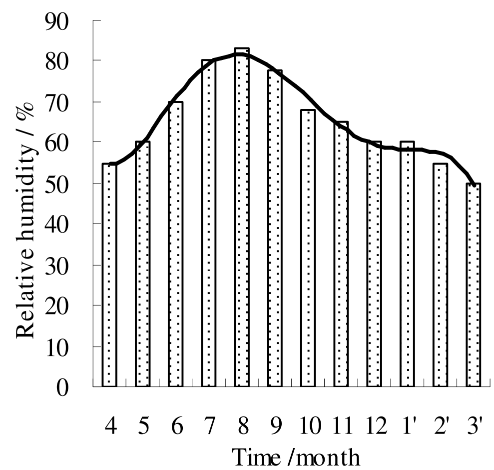

Figure 3. Measured ambient moisture (Side A).

perature and moisture for the lake tunnel were measured on site and used as the boundary conditions of Side A (Figures 2 - 3). Considering the measured data as the known temperature and moisture functions, the heat and moisture transfer boundary conditions could be expressed as Equations.(3) and (4).

$$\lambda\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = T(0,t) \tag{3}$$

$$D_{mk}\frac{\partial M(x,t)}{\partial x}\bigg|_{x=0} + D_{mk}\delta\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = M(0,t) \tag{4}$$

It is noteworthy that the measured temperature and moisture levels are interpolated when used in the numerical simulation. This leads to better correlation and more reasonable numerical results as compared to applying high-order curve fitting.

At Side B of the concrete wall element for the tunnel, when consider the boundary as moisture and thermal

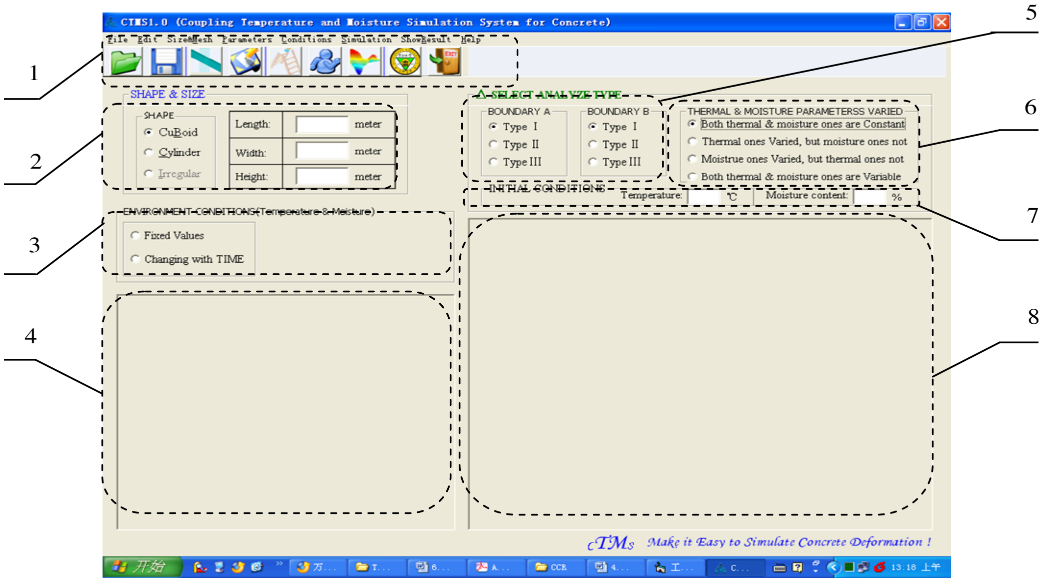

Figure 4. Main User Interface of CTMSoft.
1-Menu and command buttons; 2-Type and size determination and inputting; 3-Temperature and moisture definition; 4-Showing meshing result; 5-Boundary conditions definition; 6-Defining thermal and moisture parameters; 7-Defining initial conditions; 8-Displaying numerical results graphically.

insulation, which can be expressed in Eq. (5) and Equation (6).

$$\lambda \frac{\partial T(x,t)}{\partial x}\bigg|_{x=1} = 0 \qquad (5)$$

$$D_{mk} \frac{\partial M(x,t)}{\partial x}\bigg|_{x=1} + D_{mk}\,\delta \frac{\partial T(x,t)}{\partial x}\bigg|_{x=1} = 0 \qquad (6)$$

At the start, a temperature of 12℃ and a moisture (liquid and vapour) content of 12%, which is equivalent to 95% RH (relative humidity), are assumed uniformly distributed in the wall panel. This is in agreement with actual construction conditions where the concrete wall element selected.

$$T(x,0) = T_a \ , \ M(x,0) = M_a \qquad (7)$$

In the computing process, the time dependent ambient temperature and moisture levels were considered, as well as their on site variations over a year. The effects of temperature on thermo-physical properties and of RH on moisture diffusivity of concrete are also included according to the relationship between them based on experimental test.

CTMSoft

CTMSoft comprised analytical process and finite element analysis, seeing details in reference (Qian and Chen, 2008). An analytical procedure based on the mechanism of heat and moisture transfer in porous medium as an original methodology for predicting and estimating the heat and moisture transfer in porous media, was defined as a stand-alone and comprehensive frame for a real simultaneous solution connected to the heat and moisture transfer inside the materials and environmental temperature and moisture. In developing CTMSoft, FEM (Finite Element Method) was also necessary to calculate the hygro-thermal deformation of concrete, and before applying load on nodes of FEM, the moisture distribution should be transformed to moisture induced stress. However, we have not found any satisfying FEM software capable for transforming moisture load to deformation directly. The CTMSoft program considered the calculation of moisture induced stress according to the formula deduced from Kelvin-Laplace Equation and Mackenzie's Formula, find the detailed deducing process in reference (Chen, 2007).

The CTMSoft was developed as an advanced Windows application by using the powerful features of Visual Basic (VB) programming to offer to the user a graphical interface including the menu bar, commands buttons and figure viewer, etc. The GUI (Graphic User Interface) provided a simple and more intuitive interface for data inputting, program running and results displaying. The parameters inputting, boundary condition definition and environmental temperature and moisture settings were all active in GUI. The core of performing the numerical simulation, which was written in and complied with Matlab or APDL of ANSYS, executed the virtual calculation process when triggered by clicking the related menu or command buttons. The displaying and saving of figures of numerical results were performed at the main user interface. The main

Table 1. Thermal and moisture parameters.

Parameters	Reference values	Numerical simulation input
Specific heat, J/(g·K)	0.6 ~ 1.2	0.6, 0.8, 1.0, 1.2
Thermal conductivity, W/(m·K)	1.8 ~ 3.5	1.8, 2.4, 3.0, 3.6
CTE, $\times10^{-6}$/ K	7.4 ~ 13.1	7, 10, 13
Moisture diffusivity, $\times10^{-6}m^2/h$	0.017 ~ 38.5	0.36, 7.35, 15.7, 36

Table 2. Parameters for simulation.

Parameters	Symbol	Value
Latent heat, kJ/kg	h_{lv}	2443.6
Thermo gradient coefficient, 1/K	δ	0.001
Phase change factor	r	0.09
Density of concrete, kg/m^3	ρ	2450
Poisson ration	p_r	0.2
Bulk modulus, GPa	K_0	26.5
Elastic modulus, GPa	G_0	23.5
Molar volume of water, m^3/mol	V_m	1.8×10^{-5}
Volume percentage of paste in concrete, %	V_p/V_c	27

interface of CTMSoft is shown in Figure 4.

NUMERICAL EXPERIMENT

To investigate the effect of basic parameters of concrete on the hygro-thermal deformation, some numerical experiments were carried out using CTMSoft with the boundary conditions described as Equations (3) - (6). The involved parameters studied in this paper are specific heat, thermal conductivity, coefficient of thermal expansion and moisture diffusivity respectively. The effect of structural condition and potential structural measures for improving the deformation performance of concrete, which involved lateral confinement and thermal-moisture clapboard or coatings, were also studied.

The effect of materials parameters on concrete deformation

Basic parameters in simulation: The values of all kinds of investigated parameters used in the numerical experiment are listed in Table 1, which were selected according to the corresponding references (Uysal et al., 2004; Gilliland, 2000; Neville, 1995; Kodur and Sultan, 2003; Pan et al., 2006; Sellevoly and Bjøntegaard, 2006; Huo et al., 2006; Cano-Barrita et al., 2004; Hansen M and Hansen E, 2002).

The other necessary parameters in simulation are listed in Table 2.

Numerical simulation results and discussion: The numerically simulated hygro-thermal deformation with different parameters and values are shown in Figures 5 - 8. As shown in Figures 5 - 8, the effect of the parameters variation shows difference in the previous period (in which the temperature and moisture are increasing) comparing to the later period (when temperature and moisture is mainly decreasing), see Figures 2 - 3. The increase of specific heat or thermal conductivity decreases the shrinkage early and increases that later, while the effect of CTE or moisture diffusivity is contrary to that. Generally speak-ing, the increase of specific heat will reduce the shrinkage while CTE and thermal conductivity improve them assuming that the other condition is changeless. The increase of moisture diffusivity accelerates the moisture transfer in concrete, which benefits the increase of concrete deformation depends on the combined effect of inner relative humidity (moisture content) level and environmental moisture variation. In a few words, proposing the relationship between some or other parameter and the deformation of concrete is unscientific in itself, and there isn't a simple plus-minus law that can be used to express the influence of different parameters rationally. The coupling effect of different parameters on the deformation of concrete must be recognized and analyzed based on the coupling transfer of moisture and temperature in concrete, especially for the complex conditions.

The effect of some structural parameters

Equivalent imaginary thickness (EIT): Only the effect of thermal-moisture clapboard and coatings on concrete surface in tunnel was investigated in this paper. The equivalent imaginary thickness (EIT) was adopted to simplify the

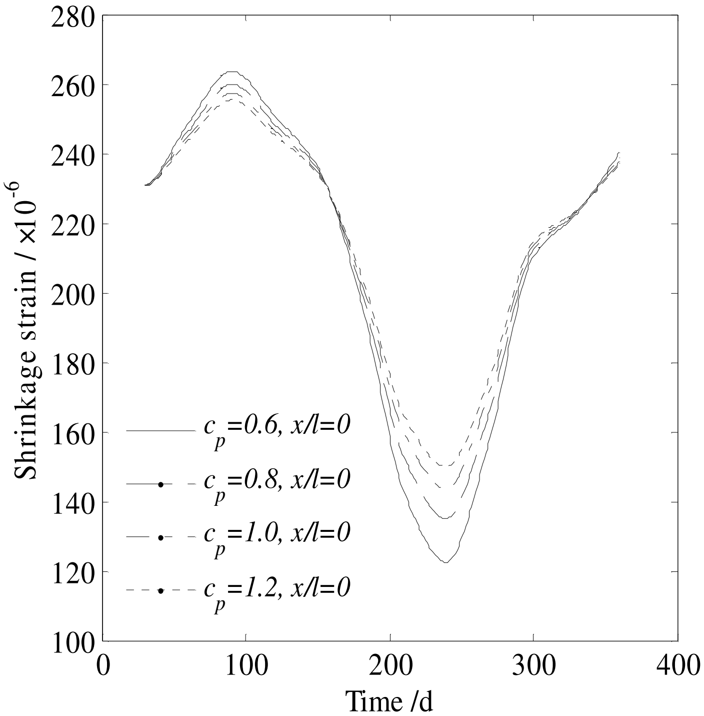

Figure 5. Numerical simulation of concrete deformation with different specific heat.

Note: “x/l=0” represent the relative depth from inner side is 0, the inside of block in fact.

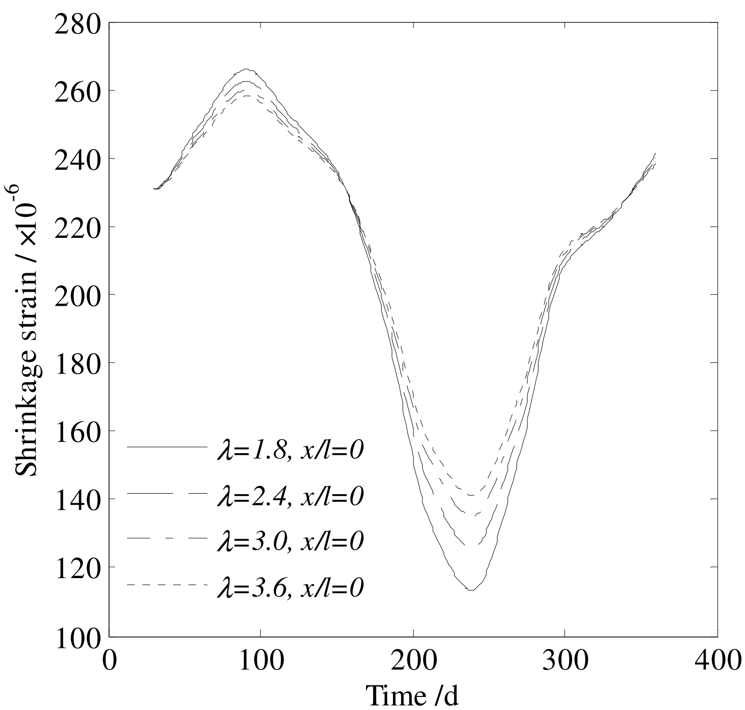

Figure 6. Numerical simulation of concrete deformation with different thermal conductivity.

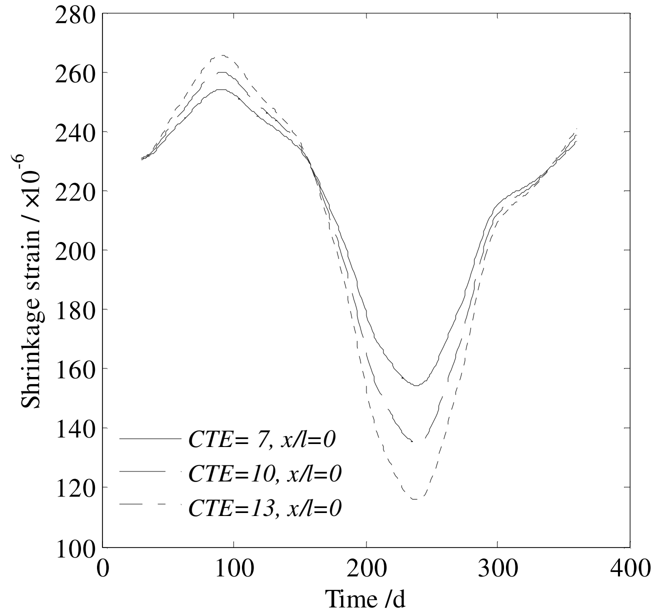

Figure 7. Numerical simulation of concrete deformation with different CTE.

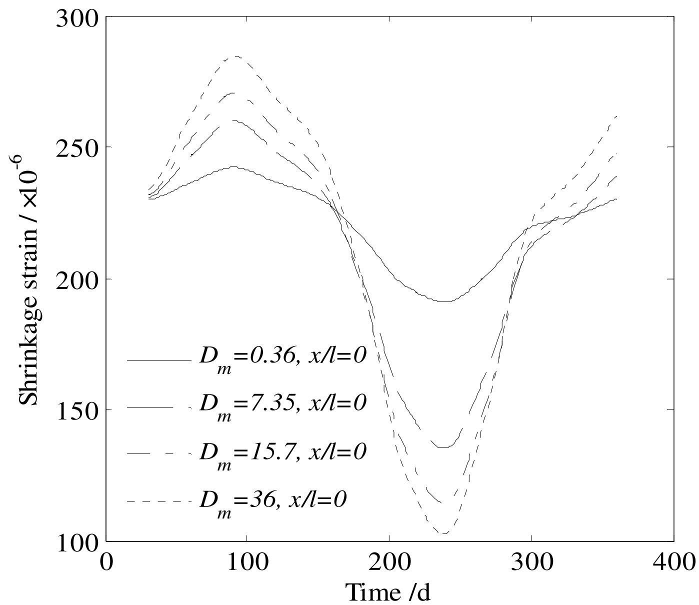

Figure 8. Numerical simulation of concrete deformation with different moisture diffusivity.

the boundary condition in analyzing the influence of adiabatic board and surface coating, which may be classified as thermal EIT and moisture EIT expressed by Equation (8) and (9) respectively (Chen, 2007). Coatings or clapboard on concrete can be uniformed by EIT, and consequently the effect of EIT was investigated for predicting the efficiency of the potential improvement on concrete deformation.

$$\delta_H = \lambda\left(\frac{\delta_B}{\lambda_B} + \frac{1}{\alpha}\right) \tag{8}$$

Where δ_H is thermal equivalent imaginary thickness, λ is thermal conductivity of concrete, δ_B is the thickness

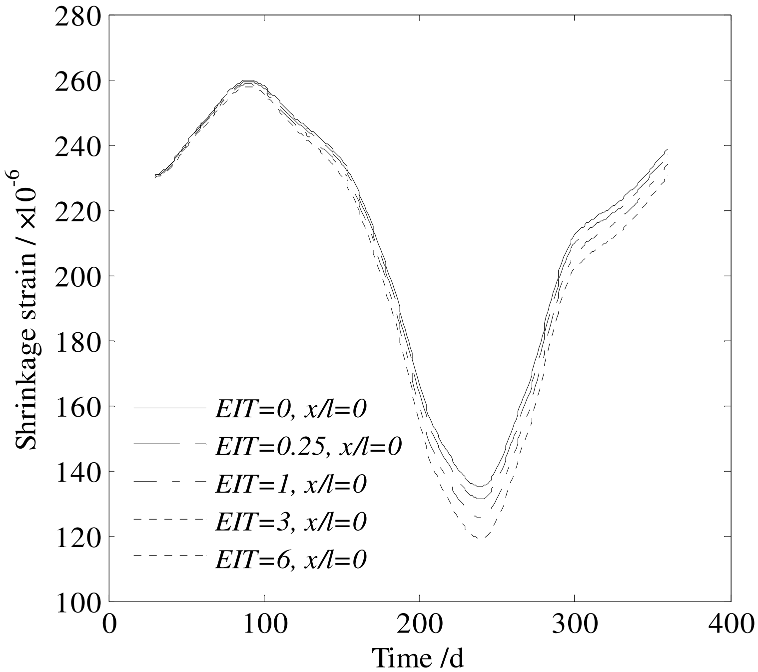

Figure 9. Numerical simulation of concrete deformation with different EIT.

adiabatic layer, and α is convective heat transfer coefficient;

$$\delta_M = D_m\left(\frac{\delta_B}{D_B} + \frac{1}{\beta}\right) \tag{9}$$

Where δ_M is moisture equivalent imaginary thickness, D_m is moisture diffusivity of concrete, δ_B is the thickness of adiabatic layer, D_B is the moisture diffusivity of adiabatic layer, and β is convective moisture transfer coefficient.

The effect of structural measures: EIT can be easily calculated according to the Equation (8) or (9) when knowing the values of the other involved parameters. For example, if λ = 3.03 W/(m·K), α = 23.26 W/(m^2·K) and the adiabatic board like polyurethane foam provided with the thickness of 0.02 m and thermal conductivity of 0.02 W/(m·K), the thermal EIT can be calculated as 3.16 m. When comes to the moisture EIT, if D_m=7.35×10^{-6} m^2/h, D_B = 0.05 × 10^{-6} m^2/h, β = 2.5 × 10^{-6} m/s, the moisture EIT δ_M = 7.35 × (0.02/0.05+1/2.5) = 5.88m. The thermal and moisture EITs were selected uniform as 0.25, 1, 3 and 6 separately for the convenience of numerical simulation. The numerical simulated concrete shrinkage with different EIT was given in Figure 9.

Figure 9 show that the increase of EIT will slightly reduce the concrete shrinkage. Thus the deformation of concrete may not be improved by adiabatic clipboard or coatings. The adiabatic clipboard and coatings will benefit the other performance of concrete especially when the interface suffers water penetration or contacts with the aggressive gas or liquid.

The effect of lateral confinement: The effect of lateral confinement on the underside of concrete block was considered in the analysis of the deformation of tunnel concrete by CTMSoft, which was also compared with that of unconfinement (as zero fricition) deformation. The result t is given in Figure 10.

As shown in Figure 10, the lateral confinement will slightly reduce the deformation of concrete. Without considering the lateral confinement in numerical calculating concrete deformation may not result in obvious deviation of concrete deformation.

Conclusions

The results of numerical analysis of the effect of basic parameters imply that the varying of thermal and physical parameters would not obviously change the concrete deformation. It is not always a simple plus-minus law can be used to express the influence of different parameters rationally along with time. It is unscientific to evaluate the influence regularity of single parameter on the concrete deformation.

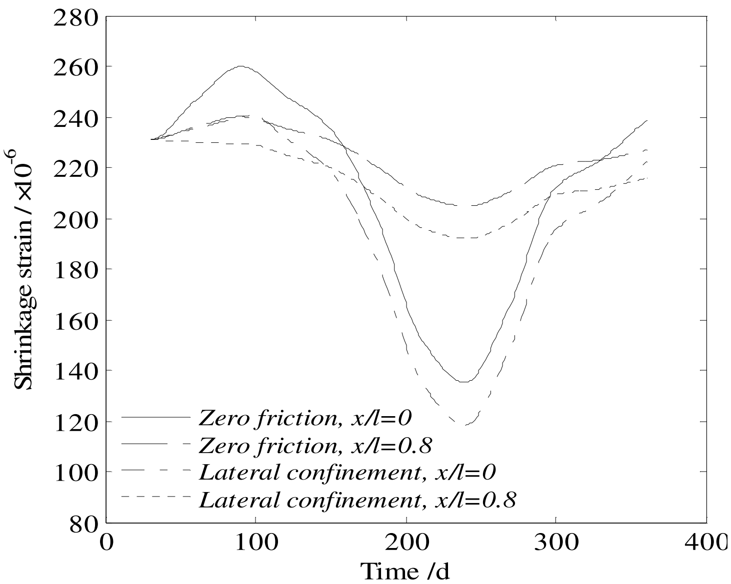

Figure 10. Numerical simulation of concrete deformation with lateral confinement or not.

The efficiency of thermal-moisture clapboard and coatings is inconspicuous and even less than that of thermal-

moisture physical parameters from the numerical results. There is no remarkable difference of lateral confinement on concrete deformation comparing with that of zero friction condition, which also implies that neglecting the lateral confinement will not result in obvious deviation.

It is more effective to change the material parameters than structural ones in improving the deformation performance of concrete. The coupling effect of different parameters on the deformation of concrete must be recognized and analyzed based on the coupling transfer of moisture and temperature in concrete, especially for the complex conditions.

REFERENCES

Andrade C, Sarria J, Alonso C (1999). Relative humidity in the interior of concrete exposed to natural and artificial weathering. Cement Concrete Res. 29: 1249-1259.

Aquino W, Hawkins N, Lange D (2004). Moisture distribution in partially enclosed concrete. ACI Mater. J. 101: 259-265.

Cano-Barrita P, Balcom B, Bremner T, MacMillan M, Langley W (2004). Moisture distribution in drying ordinary and high performance concrete cured in a simulated hot dry climate. Mater. Struct. 37: 522-531.

Chen D (2007). Study on Numerical simulation of hygro-thermal deformation of concrete based on heat and moisture transfer in porous medium and its application[D]. Nanjing: Southeast University, 2007.

dDe Barros T, Santos R, Fernandes A , da Piedade M (1995). Accuracy and precision of heat capacity measurements using a heat flux differrential scanning calorimeter. Thermochimica Acta. 269/270: 51-60.

Gilliland JA (2000). Thermal and shrinkage effects in high performance concrete structures during construction[D]. Calgary: The University of Calgary, 2000.

Hansen MH, Hansen EJ dP (2002). Determination of liquid diffusivity using single point moisture content measurements and boltzmann's transformation. Building Physics 2002-6th Nordic Symposium pp. 389-396.

Huo K, Shui Z, Li Y (2006). Determination of the thermal expansion coefficient of concrete at early ages by using temperature-stress testing machine. J. Wuhan University of Technol. Mater. Sci. Edition 21: 146-149.

Isgor O, Razaqpur A (2004). Finite element modeling of coupled heat transfer, moisture transport and carbonation processes in concrete structures. Cement and Concrete Composites.26: 57-73.

Kodur VKR, Sultan MA (2003). Effect of temperature on thermal properties of high-strength concrete. J. Mater. in Civ. Eng. 15: 101-107.

Nascimento J, Neves G, Belo F, Antonio G (2004). Simultaneous heat and moisture transfer and shringkage during drying of ceramic materials. Drying 2004-Proceeding of the 14th International Drying Symposium, Sao Paulo pp. 501-509.

Neville AM (1995). Properties of Concrete. London, Longman Group Ltd.

Norris A, Saafi M, Romine P (2008). Temperature and moisture monitoring in concrete structures using embedded nanotechnology/microelectromechanical systems (MEMS) sensors. Construction and Building Materials 22: 111-120.

Pan Z, Nakamura H, Wee T (2006). Shrinkage behavior of high performance concrete at different elevated temperatures under different sealing conditions. J. Wuhan University of Technol. Mater. Sci. Edition 21: 138-141.

Qian C, Chen D (2008). Simultaneous Heat and Moisture Transfer in Concrete with Time-dependent Boundary Conditions. Magazine of Concrete Research 60: 725-733.

Sellevold E, Bjøntegaard Ø (2006). Coefficient of thermal expansion of cement paste and concrete: Mechanisms of moisture interaction. Mater. Struct. 39: 809-815.

Suwito A, Ababneh A, Xi Y, Willam K (2006). The coupling effect of drying shrinkage and moisture diffusion in concrete. Computers and Concrete 3: 103-122.

Uysal H, Demirboga R, Sahin R, Gul R (2004). The effects of different cement dosages, slumps, and pumice aggregate ratios on the thermal conductivity and density of concrete. Cement and Concrete Research. 34: 845-848.