Fracture Mechanics of Concrete Structures, de Borst et al (eds) © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 825 0

Numerical Investigations on Damage in Cementitious Composites under Combined Drying Shrinkage and Mechanical Load

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ABSTRACT: This contribution deals with a numerical study related to crack formation in cement-based materials as induced by endogenous and/or drying shrinkage. The analyses are performed on the structural mesolevel of concrete. This means that the material is considered to be a composite material consisting of two phases, i.e. coarse aggregates embedded in a porous hardened cement paste or mortar matrix. The model called Numerical Concrete has been applied. First of all, time-dependent moisture distributions in cement-based composite materials such as normal and high performance concrete subjected to external and endogenous drying have been simulated. The eigen-stresses induced by endogenous shrinkage and drying shrinkage are analyzed. Crack formation and crack growth are simulated in normal and high performance concrete. Special attention has been paid to the risk of crack formation due to endogenous shrinkage in the composite structure of high performance concrete. The influence of an applied load on the process, of crack formation, the crack pattern and on the apparent shrinkage strain has been studied. The numerical study showed that the induced damage leads to anisotropy of the composite material if an external sustained load is applied. Numerical predictions are compared with observed results obtained by appropriate experiments

1 INTRODUCTION

In order to understand the distinction which is made in this contribution between endogenous (or autogenous) shrinkage and drying shrinkage, it is necessary to recall the basis of both phenomena (Tazawa 1998).

(i) Endogenous shrinkage in a cement-based material, which starts at an early age of the material, is mainly the consequence of self-desiccation. Self-desiccation can occur in a sealed or non-sealed specimen of cement-based materials, as long as the hydration process proceeds. The amount of free water in hardening cement paste gradually decreases due to water consumption by the hydration process of the clinker minerals. The degree of self-desiccation is more pronounced in mortar or concrete mixes with low water-cement ratios and in high strength concrete (HSC). In this case, a high percentage of the relatively small amount of water used for mixing is rapidly consumed by early age hydration of cement. The gradual moisture loss in the rigid porous matrix then will induce a reduction in volume. This time-dependent phenomenon is known as endogenous shrinkage. Although endogenous shrinkage of concrete is known for many years, no attention has been paid to study its influence on the short and long term mechanical behavior and on the properties of the material. In concrete, the endogenous shrinkage of the hydrating binding matrix will be restrained by the embedded, generally dense and stiff aggregates. This restraint will inevitably induce eigen-stresses. One of the purposes of this contribution is to evaluate, by means of the 2-dimensional Numerical Concrete Model (Roelfstra et al. 1985), the tensile stresses in the matrix generated by restrained endogenous shrinkage and consequently to assess the risk of early microcracking of the composite material.

(ii) As for endogenous drying, drying of cement-based materials to the surrounding air is induced by a decrease of the moisture held in the pores of the matrix. Nevertheless, the mechanism of the moisture loss is moisture migration (diffusion) from the center of the specimen towards the outer dry environment. Compared with endogenous drying, great attention has been paid to drying shrinkage especially with respect to crack formation (Alvaredo 1994). Nevertheless, this phenomenon will also be treated in this contribution but at the mesostructural level of the composite material.

2 NUMERICAL CONCRETE

Concrete is a multiscale particle composite. In this contribution, the structural mesolevel of concrete will be modeled by the Numerical Concrete. Concrete is considered to be a composite material, composed of two majors phases, namely coarse aggregates (inclusions) embedded in a hydraulic cement matrix. The inclusions, randomly distributed in the porous binding matrix, are assumed to follow an adequate grain size distribution. The volume content of the aggregates and their shape in the computer-generated composite structures can be chosen according to predefined requirements. The generated composite structures are then subdivided into finite elements (FE), in order to perform a numerical simulation of processes, such as heat flow and moisture transfer or the mechanical behavior under load. Fig.1 shows a FE idealization of two different computer-generated composite structures.

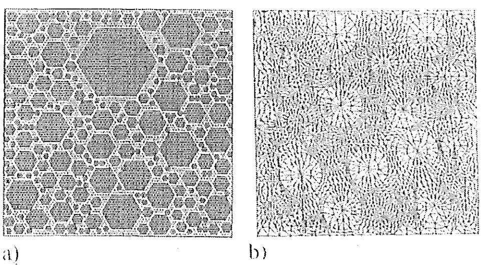


Fig.1: Computer-generated composite structures and their finite element idealization.

3 CRACK FORMATION INDUCED BY DRYING SHRINKAGE

Numerical analyses presented below are performed by means of the FE code DIANA (DIANA 1999). In the following, a composite structure representing a normal concrete specimen (see Fig.1) is subjected to external drying, namely initially the porous matrix is assumed to be moisture saturated and both lateral sides of the structure are exposed to 60% RH. The eigenstresses induced by the hygral differential shrinkage strains and the restraint of the non-porous stiff inclusions are analyzed with respect to crack formation and as function of drying time. Fig.2 shows the microcrack pattern after a drying time of 2.5 days. As the drying process continues, the front of the microcracks progresses to the centre of the specimen. As it can be seen in Fig.2, microcracks are mostly oriented normal to the circumference of the aggregates.

If a sustained compressive load is applied on the top of the drying composite structure (load direction normal to the drying process), the number of microcraks normal to the applied load is strongly reduced in comparison with the unloaded specimen. Fig.3 shows microcrack patterns of the unloaded

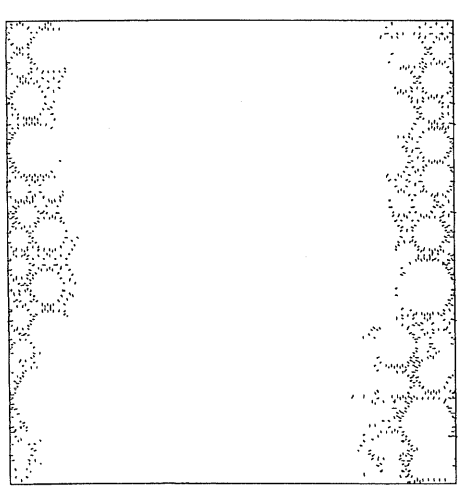


Fig.2: Microcrack patterns in the matrix of a normal concrete specimen subjected to drying shrinkage (drying time: 2.5 days)

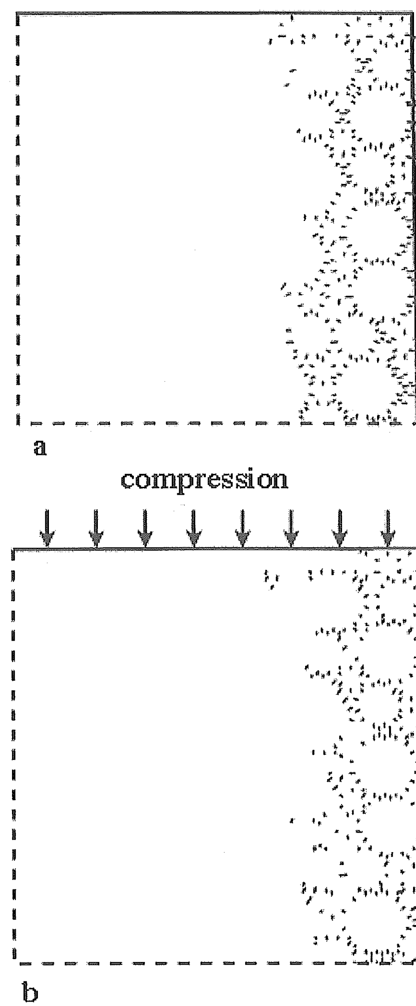


Fig.3: Comparison of microcrack patterns in a drying concrete specimen, (a) without external load (b) with external load.

is more pronounced at higher compressive load levels.

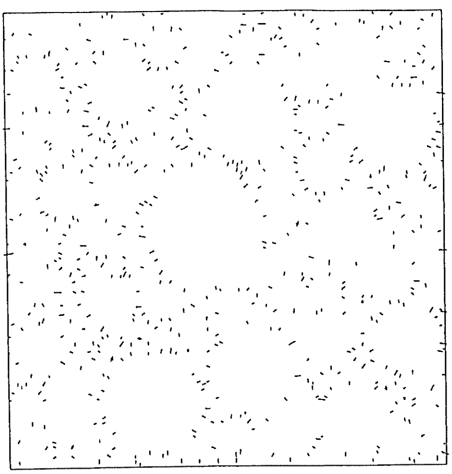
4 CRACK FORMATION INDUCED BY ENDOGENOUS SHRINKAGE

In this analysis a sealed high strength concrete (HSC) specimen is considered. This means that the specimen is subjected to self-desiccation only. The specimen is represented by as composite structure (see Fig.1a). The cement matrix is characterized by a very low water-cement ratio. In this case, the pore humidity decreases rapidely during the hydration process (Baroghel-Bouny 1994). The decrease of the humidity induces shrinkage of the porous matrix.

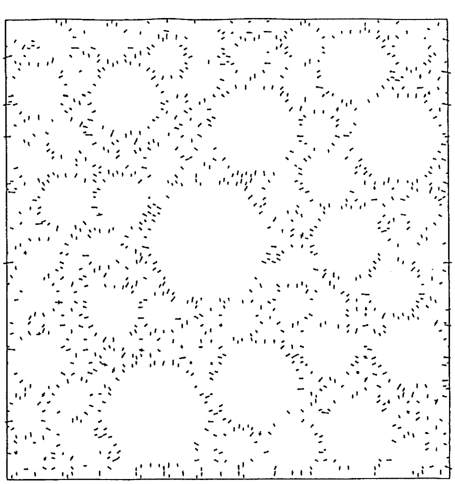
The hygral deformations of the matrix are restrained by the presence of the stiff inclusions. Consequently, tensile eigenstresses will be generated in the matrix leading eventually to crack formation.

Fig.4 shows microcrack patterns obtained by the model for two different ages of the specimen i.e. 2 and 4 days. These figues show that the microcracks are mainly oriented normal to the circumference of the aggregates. In other words, the microcracking in the matrix is isotropic.

The following numerical experiment will show how an applied sustained compressive load influences the orientation of the microcracks induced by

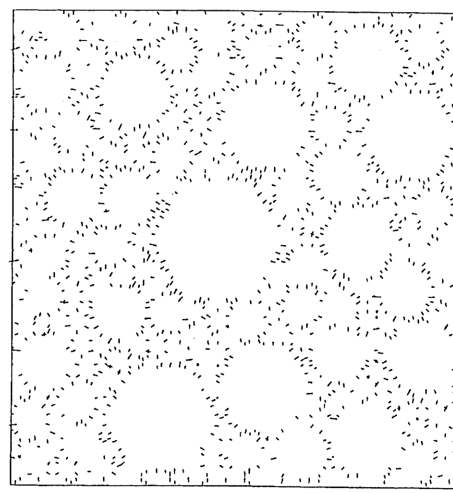


b) τ = 2 days

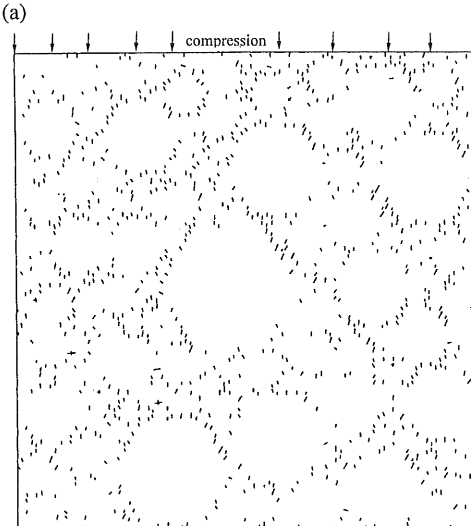


b) τ = 4days

Fig.4 Microcrack patterns in composite structure of HSC subjected to endogenous drying at two different ages, (a) 2 and (b) 4 days.



(a)



(b)

Fig.5 Microcrack patterns of the composite structure of HSC subjected to endogenous drying at an age of 4 days. (a) unloaded specimen, (b) loaded specimen.

endogenous shrinkage and thus imposes anisotropy to the composite material. The same composite structure as in the previous analysis (see Fig.4) has sand loaded specimen for the same drying time. This figure shows clearly that microcraks are strongly oriented parallel to the load direction if the load is applied. This preferential orientation of microcracks been used to idealize the composite structure of HSC. The system is subjected to self-desiccation only (sealed). A sustained compressive load is applied acting on the upper and lower surface of the specimen during the self-desiccation process. Fig.5 (a) and (b) show the resulting microcrack patterns at an age of 4 days in unloaded and loaded specimens, respectively. Numerous numerical experiments performed lead to the following results:

(i) an applied compressive load favors formation of microcracks running parallel to the direction of the load. The number of horizontal cracks (normal to the load) is reduced. This phenomenon of selective orientation becomes more pronounced as the load increases.

(ii) a high compressive load increases the risk of damage by parallel to the load.

(iii) because of the preferential crack orientation, the damaged material degenerates to an anisotropic material.

5 OUTLOOK AND CONCLUSIONS

The heterogenous structure of the composite cement-based materials can be represented by a numerical model called Numerical Concrete.

Microcracking in the porous matrix induced by either drying shrinkage or endogenous shrinkage can be simulated.

In the case of HSC, microcracking induced by endogenous shrinkage in the matrix is statistically isotropic.

If HSC is subjected to a sustained compressive load in addition, the resulting microcracks are prefenrentially oriented parallel to the applied load. Damage induced by simultaneously acting endogenous shrinkage and uniaxial external load leads to an anisotropic material.

In the next step, creep and relaxation phenomena will be taken into account in order to be more realistic. Further more, adequate experiments must be carried out in order to validate and to improve the model.

REFERENCES

Alvaredo, A.M. 1994. Drying shrinkage and crack formation, PhD Thesis, Swiss Federal Institute of Technology, also published in *Building Materials Reports,* No.5, Aedificatio Publishers.

Baroghel-Bouny, V. 1994. Caractérisations des pâtes de ciment et des bétons, thèse de doctorat de l'Ecole Nationale des Ponts et Chaussées.

DIANA, 1996. Users Manuals, Diana Analysis BV, Delft, The Netherlands.

Tazawa, E. 1998. Autogenous shrinkage of concrete, Proc. of the Int. Worshop organized by the Japan Concrete Institute, Hiroshima, Japan E. Tazawa ed.