8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

SPALLING OF CONCRETE: HIGH TEMPERATURE EXPERIMENTS AND SIMULATIONS

*** Kaspar J. Willam[1], Keun Lee[2], Jaesung Lee[3] and Yunping Xi [4]**

[1] Uni. of Colorado Boulder
CEAE Department
428 UCB
Boulder, CO 80302-0428
USA
willam@colorado.edu

[2] Uni. of Colorado Boulder
CEAE Department
428 UCB
Boulder, CO 80302-0428
USA
leekk@colorado.edu

[3] Research Institute of
Industrial Science & Techn.
P.O. Box 135
Pohang 790-600
Korea
jaesung.lee@colorado.edu

[4] Uni. of Colorado Boulder
CEAE Department
428 UCB
Boulder, CO 80302-0428
USA
yunping.xi@colorado.edu

Key Words: *Multi-physics Problem, Thermo-hydraulic Spalling of Concrete, Thermo-hydro-mechanical Stress Analysis, Coupling of Energy and Mass Transport with Mechanical Response.*

ABSTRACT

This paper describes the findings of an experimental and computational campaign to investigate hygro-thermal spalling phenomena of concrete specimens. Whereas the overall effort of the NSF sponsored project is focused on the high temperature performance of concrete materials and reinforced concrete structures, RCS, this part of the project considers the response behavior of $4 \times 8\,in$ concrete cylinders which were subjected to a variety of heating scenarios at different relative humidity conditions.

The principal objective is to quantify the two origins for spalling and to assess their relative magnitude: (a) thermal spalling due to large temperature gradients which generate large compression at the heated surface and ablation in the form of local buckling; (b) hydraulic spalling due to evaporation of the pore humidity under high temperatures and the concomitant internal pore pressure build-up introducing tension in the concrete skeleton.

To this end two heating rates of the concrete cylinders were examined in a furnace, slow heating at $1^0 C/min$ and fast heating at $30^0 C/min$ which introduces large temperature gradients near the surface and hence large circumferential compression near the surface of the cylindrical concrete specimens. Whereas the temperature gradient is the main source for thermal spalling of oven-dried specimens, both thermal and hydraulic spalling effects are active in the case of saturated and partially saturated specimens. In the latter case evaporation and pore pressure build-up at temperature levels above $100^o\,C$ dramatically increases the effect of drying shrinkage at room temperature.

The results of the experimental campaign clearly indicate that spalling occurs only when both thermal and hydraulic effects are active. In fact, spalling occurred for rapid heating rates only when nearly saturated specimens were considered. In this case the internal pore pressure build-up introduces triaxial tension-compression near the heated surface introducing ablation and separation of the outside concrete layer.

For computational simulation an in-house FE program was developed to quantify the thermo-hygral transport of heat and pore pressure in addition to the mechanical response behavior in axisymmetric

structures. A good number of high temperature material experiments preceded the performance evaluation of the concrete cylinders at different levels of initial relative humidity. Concrete cylinder tests were carried out to verify and validate the underlying material models under simple hygro-thermo-mechanical loading scenarios.

The paper is focused on the underlying computational issues which come to the forefront when spalling of the concrete cylinder is of main interest. In this case the mechanical performance of concrete cylinder is the principal topic of our investigation aside from the hygro-thermal transport of energy and mass. The presentation highlights the fundamental spalling issues related to *'thermal spalling'* versus *'hydraulic spalling'* which are primarily responsible for the transport properties in the porous concrete material structure and the mechanical failure in triaxial tension-compression. The underlying loss of cohesion is of interest not only at the macro-scale of observation, it is of fundamental importance at the meso- and micro-scales of observation when the transport properties in the porous microstructure are of central interest in addition to strength and ductility of the material skeleton.

In principle, concrete may be characterized as a porous material subjected to hygro-thermal transport processes which are tightly coupled with the cohesive-frictional behavior of the mechanical concrete response. In fact, degradation and spalling strongly depends on the level of triaxial confinement and the transport properties in the heterogeneous concrete composite. The relevant constitutive aspects are reviewed in terms of the thermodynamic concept of *'generalized standard materials'* within the format of micro-morphic continua. This raises a number of fundamental questions as to whether and how hardening and softening may be captured at multiple scales of observation. In other terms, the issue of multi-scale analysis requires special attention when brittle failure mechanisms need to be transported across different scales of observation.