FIRE PERFORMANCE OF HIGH STRENGTH CONCRETE: RESEARCH NEEDS

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ABSTRACT

A compilation of fire test data which shows distinct behavioral differences between high-strength concrete (HSC) and normal strength concrete (NSC) at elevated temperature is presented. The differences are most pronounced in the temperature range of 20 °C to 400 °C. What is more important is the observed explosive spalling of HSC specimens during fire tests.. A comparison of test results with current code provisions on the effects of elevated temperatures on concrete strength shows that the CEN Eurocodes and the CEB provisions are unconservative. Aspects of analytical modeling for predicting the buildup of internal pressure during heating are discussed. The paper concludes with recommended research needs, identified at a workshop on fire performance of HSC, convened at NIST in February 1997.

INTRODUCTION

HSC is a state-of-the-art material that can be manufactured by most concrete plants due to the availability of a variety of additives such as silica fume and water reducing admixtures. The definition of HSC has evolved with its gradual development and usage over the years. At present, ACI 363R-92 (1) defines HSC as concretes, made using conventional materials, admixtures, and techniques, having specified compressive strengths for design of at least 40 MPa (6000 psi). This definition is adopted in this paper to distinguish between HSC and NSC data.

It is well established that mechanical properties of concrete are adversely affected by thermal exposure (2,3,4,5,6,7). NSC typically loses between 10 to 20% of its original compressive strength when heated to 300 °C, and between 60 to 75% at 600 °C. Elastic modulus decreases in a similar fashion. For HSC, higher rates of strength loss, as much as 40% of the original strength, were observed at temperatures below 450 °C. However, what is more important about HSC is the occurrence of explosive spalling when it is subjected to rapid heating. It has been theorized that the higher susceptibility of HSC to explosive spalling is due, in part, to its lower permeability, which limits the ability of water vapor to escape from the pores. This results in a build-up of pore pressure within the cement paste. As heating increases, the pore pressure also increases. This increase in vapor pressure continues until the internal stresses become so large as to result in sudden, explosive spalling. Spalling, however, has been observed on an inconsistent basis. Often, explosive spalling has occurred to only a few HSC specimens from a larger group of specimens that were subjected to identical testing conditions. This erratic behavior makes it difficult to predict with certainty when HSC will fail by explosive spalling.

Given the potential benefits of HSC and its increased usage, questions about its fire performance need to be resolved. Also, the applicability of existing fire-design provisions, which were developed mostly from the results of fire tests on NSC, to HSC needs to be evaluated. To address these issues, a workshop, entitled *International Workshop on Fire Performance of HSC*, was convened by the Buidling and Fire Research Laboratory at NIST (Gaithersburg, Maryland, U.S.A.) in February, 1997 (8). The participants included international and U.S. experts who have been involved with experimental or analytical studies of fire-exposed concrete. The workshop reviewed the current state of knowledge and recommended research to fill knowledge gaps. The workshop participants were divided into four working groups: (1) *Material tests* group, to identify research needs concerning material properties of HSC at elevated temperature; (2) *Element tests* group, to identify research needs concerning fire testing of HSC structural elements; (3)

Analytical studies group, to identify research needs concerning modeling aspects of fire-exposed HSC; and (4) *Code and Standards* group, to identify research needs for making current code provisions, fire design procedure, and testing standards applicable to HSC.

In the sections to follow, results of high temperature tests of HSC are reviewed, the behavioral differences between HSC and NSC are discussed, and the applicability of existing code provisions to fire design of HSC structures is examined. Aspects of analytical modeling for predicting the development of heat-induced pore pressure in concretes are also discussed. The paper concludes with a summary of research needs as identified by participants of the NIST workshop.

ISSUES RELATED TO FIRE PERFORMANCE OF HSC

Mechanical Properties of HSC at Elevated Temperature

Mechanical properties of concrete at elevated temperature are determined by testing plain concrete specimens using one of three types of steady-state temperature tests: *stressed* tests, *unstressed* tests, and *unstressed residual property* tests. Briefly, in *stressed* tests, a preload (20 to 40% of the room temperature compressive strength) is applied to the specimen prior to heating and is sustained during heating. Heat is applied at a constant rate until a target temperature T is reached, and is maintained for a time t until a thermal steady state is achieved. Stress or strain is then increased at a prescribed rate until the specimen fails. In *unstressed* tests, the specimen is heated, without preload, at a constant rate to the target temperature, which is maintained until a thermal steady state is achieved. Stress or strain is then applied at a prescribed rate until failure occurs. In *unstressed residual property* tests, the specimen is heated without preload at a prescribed rate to the target temperature, which is maintained until a thermal steady state is achieved. The specimen is then allowed to cool, at a prescribed rate, to room temperature. The specimen is tested at room temperature. These three types of test are schematically shown in Figure 1 a, b, and c.

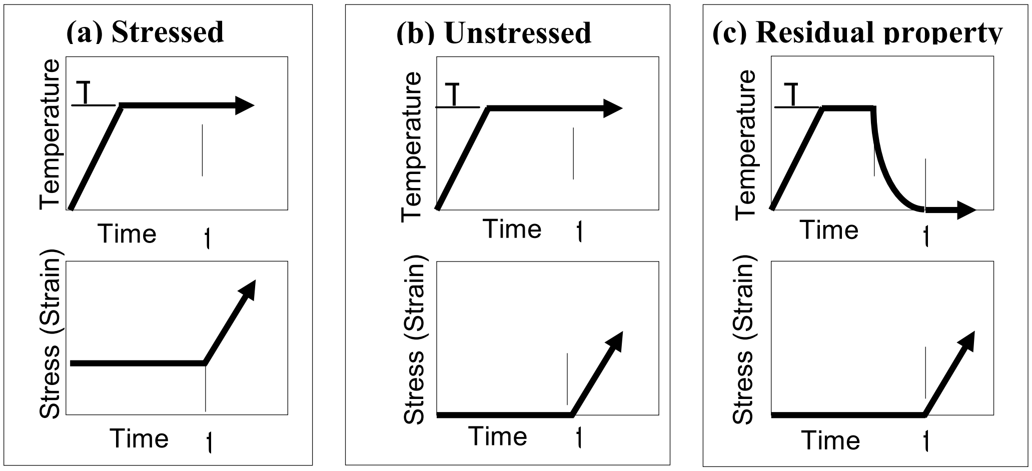

Figure 1. Schematic temperature and load histories for steady-state temperature tests

To date, only a limited number of studies which focused on the material behavior of HSC under high heating rate has been conducted (9,10,11,12,13,14,15,16,17,18). The specimens used in these studies had compressive strengths ranging from 20 MPa to 150 MPa, and consisted of both prisms and cylinders of various sizes (100x100x100 mm to 80x275x500 mm for prisms, and 28x52 mm to 160x320 mm for cylinders). The specimens were made using a variety of concrete mixtures. Some were made with conventional portland cement, others included additives such as silica fume, fly ash, and steel fibers. The type of coarse aggregate used included calcareous and siliceous NWA, and LWA. The heating rates varied from 0.2 to 32 °C/min, but the majority of studies used a heating rate of 1 °C/min.

For comparison purpose, the results of these studies are grouped according to the test method and the type of aggregate (NWA and LWA), and are shown as normalized compressive strength (Figures 2 to 4) and modulus of elasticity (Figure 5) versus temperature relationships. The solid lines in these figures are results of HSC tests, and the dashed lines are of NSC tests. These experimental results indicate the following key findings (19):

(1) *For stressed and unstressed tests, compressive strength of HSC vary differently and more unfavorably with temperature than that of NSC*. The differences are more pronounced in the temperature range between 25 °C to about 400 °C, where HSC sustains markedly higher strength loss than NSC. Differences become less significant at temperatures above 400 °C. The variations of compressive strength with temperature may be characterized by an initial stage of strength loss (25 °C to approximately 100 °C), followed by a stage of stabilized strength and recovery (100 °C to approximately 400 °C), and a stage above 400 °C characterized by a monotonic decrease in strength with increasing temperature. The strength recovery stage of HSC occurs at higher temperatures than NSC.

(2) *There is a serious lack of fire test data for LWA HSC under all three test conditions and for NWA HSC under the stressed test condition.*

(3) *The reduction in modulus of elasticity of HSC and NSC follow similar trends, but LWA HSC retains higher proportions of the original modulus of elasticity at high temperature than NWA HSC.* The difference is more pronounced for *unstressed residual properties* tests than for *unstressed* tests

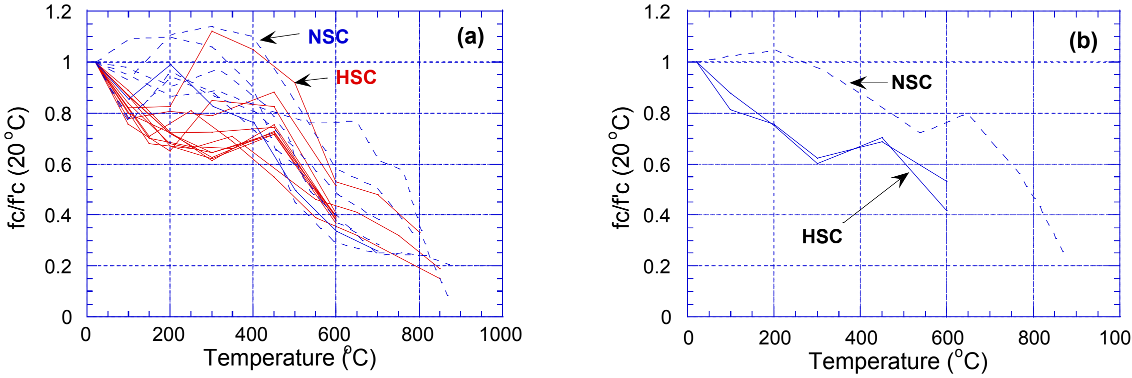

Figure 2. Compressive strength-temperature relationships for (a) NWA and (b) LWA concrete (unstressed tests)

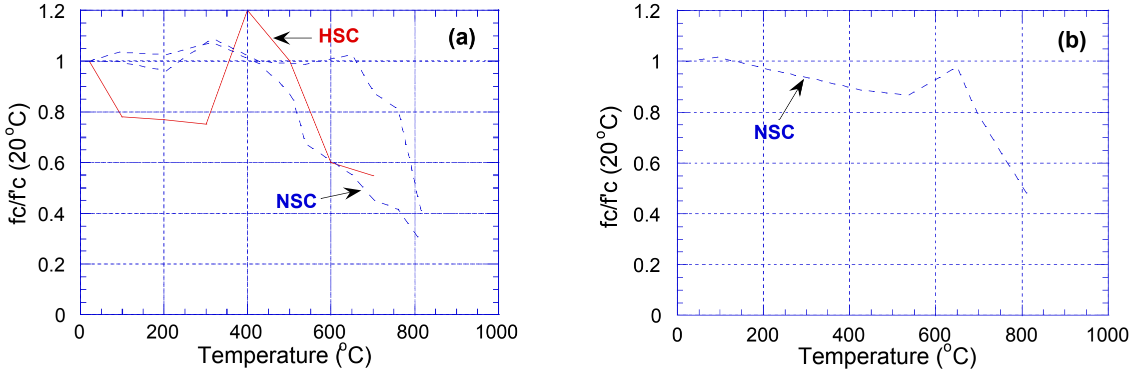

Figure 3. Compressive strength-temperature relationships for (a) NWA and (b) LWA concrete (stressed tests)

(4) *Explosive spalling occurred predominantly in HSC specimens at temperatures between 300 °C to 650 °C*. This failure mode was observed in all three types of tests. However, explosive spalling was not consistently observed in all these studies.

Code Provisions for Mechanical Properties of Fire-Exposed Concrete

For design purpose, mechanical properties of concrete at elevated temperature may be obtained using design curves prescribed by codes (5,6,3,20).

Except for the Finnish Code (20) which prescribes a design curve specifically for HSC, the current CEN Eurocodes (5,6) and CEB (3) provisions do not specify a strength limit for their prescribed compressive strength-temperature curves. Since these design curves were based on results of fire tests on concrete prior to the advent of HSC, the applicability of these provisions to HSC must be validated for fire design of HSC.

An indication of the applicability of these design curves may be obtained by superposing these curves onto the results of HSC tests (Figures 2 to 5). This superposition is shown in Figures 6 to 9. The following observations can be made:

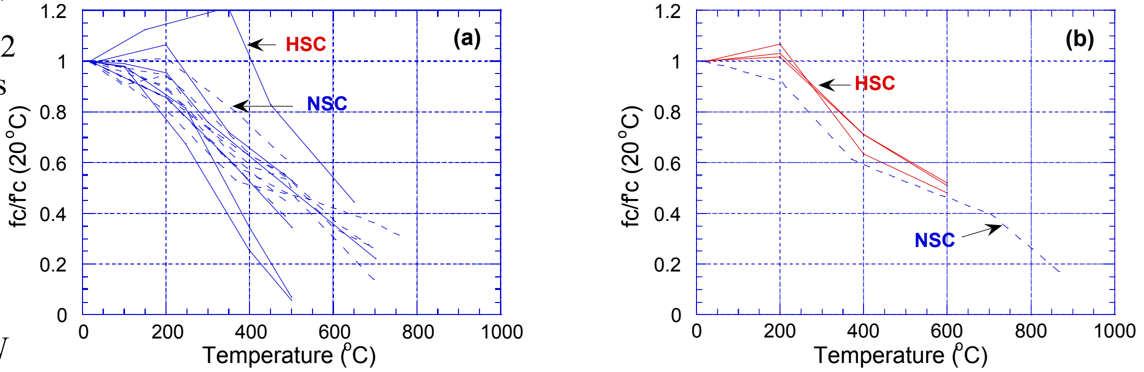

Figure 4. Compressive strength-temperature relationships for (a) NWA and (b) LWA concrete (unstressed residual property tests

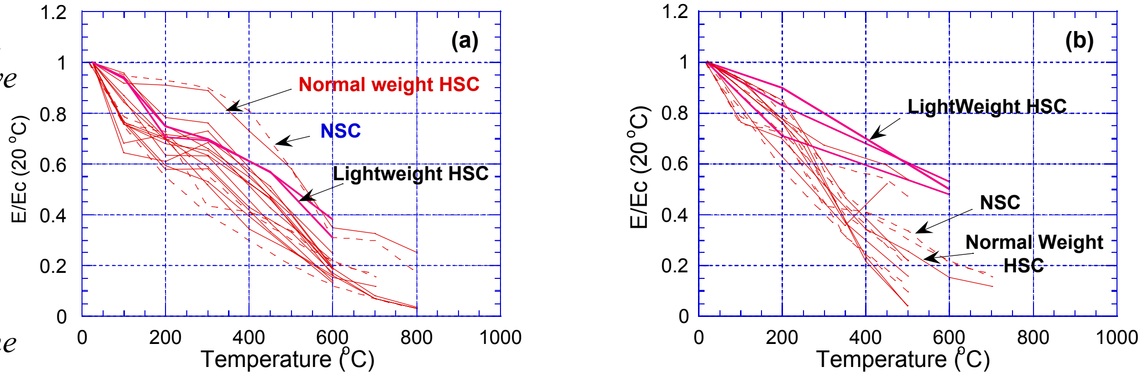

Figure 5. Elastic modulus-temperature relationships for NWA and LWA concrete obtained from (a) unstressed tests and (b) unstressed residual property tests

(1) *The CEN Eurocodes and CEB fire design provisions are applicable to NSC, but are unconservative for HSC. While the Finnish design curve is more applicable to HSC, it is slightly unconservative, especially in the temperature range of 200 °C to 400 °C.* For *stressed* and *unstressed* tests (Figures 6 and 7), the Eurocode and CEB design curves are unconservative for both NWA and LWA HSC in the temperature range between room temperature to about 350 °C. It should be noted that the majority of explosive spalling failures were reported to have occurred at approximately this temperature. Above 350 °C, the code design curves are more applicable to both HSC and NSC, which is consistent with experimental observations that the difference between HSC and NSC decreased at about this temperature. For *unstressed residual property* tests (Figure 8), the Eurocode and CEB design curves are in better agreement with HSC data at temperature between 25 °C and 400 °C than for *unstressed* tests. However, the design curves appear to be slightly unconservative for both NWA and LWA HSC and also for NSC at above 250 °C. For modulus of elasticity, only CEB explicitly recommends design curves for LWA and NWA concrete, which are unconservative compared with *unstressed* test data for both NWA and LWA HSC. For *unstressed residual property* tests, the design curve for LWA concrete appears to be in good agreement with data for LWA HSC (Figure 9a). However, the design curve for NWA concrete remains unconservative compared with data of NWA HSC (Figure 9b).

(2) *Higher susceptibility of HSC to explosive spalling is not explicitly addressed in current codes.* None of

the codes addresses in detail the potential for spalling of HSC due to fire exposure.

Modeling Aspects Concerning Fire-Exposed HSC

While heat-induced pore pressure and thermal stress effects are generally thought to be the possible causes of explosive spalling in HSC, a basic quantitative understanding of how high temperatures cause explosive spalling in HSC has not been completely developed. Adding to the difficulty in understanding this failure mechanism is the inconsistent occurrences with which it has been observed in various experimental programs. Inconsistent test procedures and measurement techniques used by different researchers also do not allow easy quantification of parameters that may influence explosive spalling of HSC. The limited number of analytical studies dealing with calculating the internal stresses due to pore vapor pressure in concrete is indicative of the complexity of this problem. While there are limited fire test data of *concrete* structural elements, *data on fire-exposed HSC structural elements are scarce.* This makes it difficult to validate analytical models.

There are a limited number of studies dealing with modeling the development of internal stresses caused by heat-induced water vapor pressure in concrete pores (21,22,23,18). These studies attempt to take into account the material properties of a concrete and how these properties affect fire performance. However, there is no consensus on what *are* the key material properties and how they affect fire performance of HSC, yet the accuracy of analytical predictions is highly dependent upon using the correct concrete properties, such as diffusivity, permeability, porosity, etc. While these modeling techniques are promising, a better theoretical understanding is needed in order for accurate models to be developed that can predict the fire performance of HSC, based on knowledge of readily-measured properties.

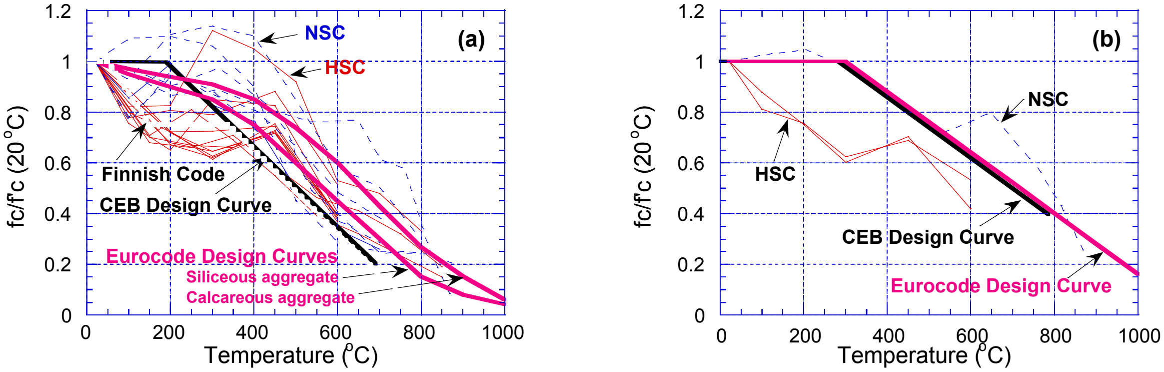

Figure 6. Comparison of design curves for compressive strength and results of unstressed tests for (a) NWA and (b) LWA concrete

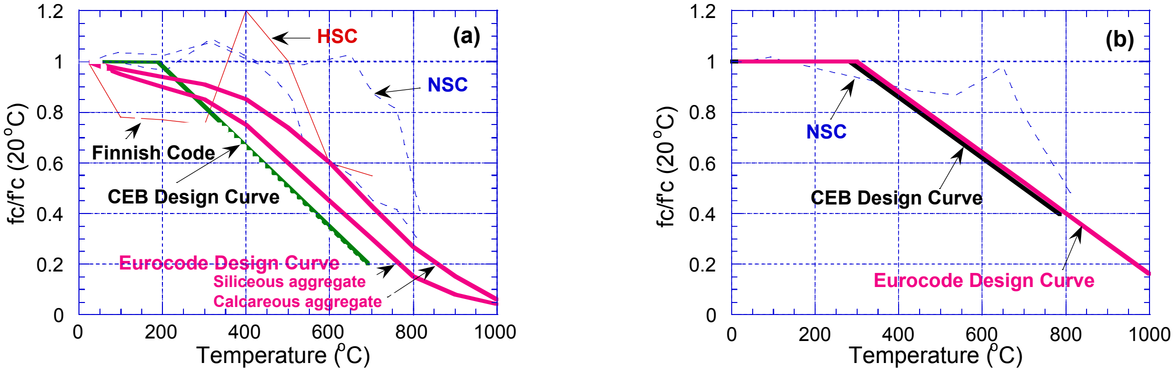

Figure 7. Comparison of design curves for compressive strength and results of unstressed tests of (a) NWA and (b) LWA concrete

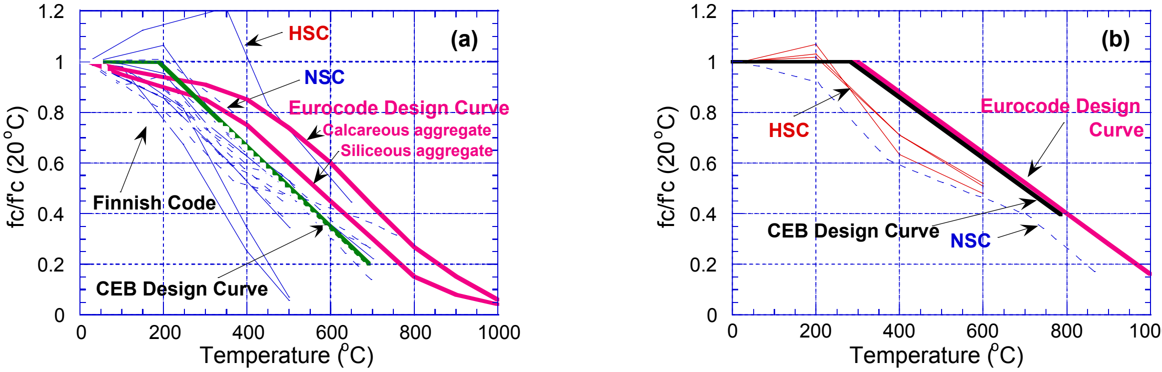

Figure 8. Comparison of design curves for compressive strength and results of unstressed residual property tests of (a) NWA and (b) LWA concrete

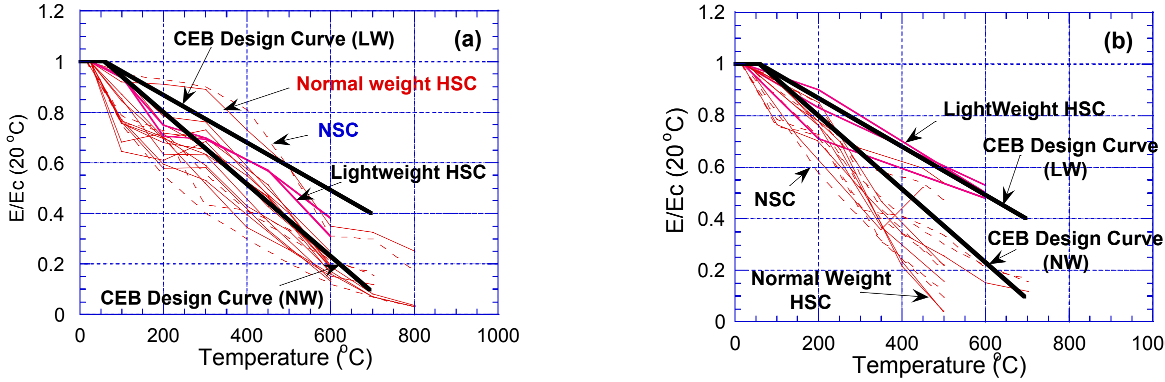

Figure 9. Comparison of design curves for modulus of elasticity and results of (a) unstressed tests and (b) unstressed residual property tests

SUMMARY AND RESEARCH NEEDS

This paper reviewed findings concerning the material behavior, code provisions, and analytical modeling aspects of HSC at elevated temperature. These findings are summarized as follows:

- HSC has a higher strength loss than NSC in the temperature range between 25 °C to 400 °C.
- HSC is more susceptible to explosive spalling when exposed to high temperature (above 300 °C).
- Data for LWA HSC under all three test conditions are scarce, as is data for NWA HSC under *stressed* test conditions.
- The modulus of elasticity of HSC and NSC vary similarly with temperature, but LWA HSC retains higher proportions of the original elastic modulus at high temperature than NWA HSC.
- Current fire design provisions of codes such as the CEN Eurocodes and the CEB are unconservative for estimating mechanical properties of HSC at elevated temperatures. The Finnish design curve is more applicable, but it is still slightly unconservative, especially in the temperature range of 200 °C to 400 °C.
- The basic understanding of how high temperatures cause explosive spalling in HSC has not been completely developed.
- Data on fire-exposed HSC structural elements, which may be used for validating analytical models, are scarce.

The followings research needs are identified by the NIST workshop to address the above issues:
(1) *Experimental studies to develop an understanding of the spalling mechanism(s) and establish a predictive parameter and standard method(s) for its measurement.* A combination of experimental and analytical studies will be needed to gain the understanding necessary to develop a parameter for use in predicting susceptibility to spalling, similar to a parameter in the field of refractory concrete that includes permeability, tensile strength, porosity, and moisture content. Experimental data which include measurement

of internal pore pressures and moisture distribution are also needed for validation of analytical predictions. Effects of compositional and processing factors (curing methods, maturity, self-desiccation) on spalling tendency should be assessed. Also, the effects of thermal exposure conditions (rate of temperature rise, maximum temperature, and uniformity of exposure conditions) should be examined. The results of this work should allow understanding for why spalling has not always been observed in tests of HSC.

(2) *Standard protocols for measurement of properties of HSC as a function of temperature*. Most current engineering property data were obtained by testing HSC specimens using different heating rates, specimen sizes and shapes, and loading combinations. These differences may result in incompatible test results, especially for HSC since the rate of pore pressure buildup and the moisture escape path have an important influence on the performance of the test specimen. In order to permit the comparison of data from different research programs, it will be necessary to establish a suite of standard test methods. Factors such as maturity and conditioning prior to testing need to be studied and standardized. Experimental studies should also include measurements of other mechanical properties such as tensile strength, time-dependent behavior, and fracture mechanics parameters. The effects of specimen shape and size and of previous load histories on measured properties should also be examined. In addition, other material characteristics, including transport properties, thermal properties, sorption isotherms, and water release during dehydration, need to be measured as functions of temperature to provide input data for numerical models.

(3) Methods for evaluating local and manufactured aggregates for optimizing fire resistance of concrete. Practical methods are needed to evaluate different aggregate sources so that those that can be expected to result in poor performance can be eliminated during the selection of materials for HSC mixtures to be used in critical structural elements.

(4) *Methods for evaluation of fire damage.* There should be investigations of the applicability of advanced techniques based on stress-wave propagation (e.g., acoustic tomography and spectral analysis of surface waves) and microwave radiation to evaluate the extent of damage after a fire. Other techniques based on the scanning electron microscope should be developed for analysis of microstructural damage or changes of samples taken from the affected structure.

(5) *Coupled heat and mass transfer leading to pore pressure prediction in HSC with and without polypropylene fibers, and investigation of the need for new numerical methods to handle the saturated-unsaturated interface zone.* High temperature exposures cause vaporization of pore water in concrete. The slow transport of water and water vapor then leads to elevated pore pressure levels. Since the elevated pore pressures may be a cause of damage in the concrete, accurate predictions of these pressures need to be developed. Because a sharp interface develops between the saturated and unsaturated parts of the concrete (liquid:vapor interface), it is possible that existing analytical and numerical tools may be inadequate. Therefore the development of new mathematical tools needs to be investigated. The role of polypropylene fibers, in terms of the mechanism by which they can give fire protection, needs to be understood.

(7) *Coupling of pore pressure and fracture consideration*. The elevated pore pressures must be quantitatively linked to spalling (fracture) of the concrete. Since it has been known for a long time that the fracture of concrete at room temperature is not controlled by a simple strength criterion, but is rather a fracture process, it is reasonable to assume that a similar situation applies at fire temperatures as well.

(8) *Creep and thermal shrinkage at fire temperatures*. Concrete is a viscoelastic material (creep), and has dimensional changes with changes in moisture levels (shrinkage). Fire temperatures induce large amounts of water removal from concrete, with correspondingly high amounts of induced shrinkage. Thermal stresses and pore pressure-caused stresses can be partially relieved by creep, although the amount of relief will be determined by the relative time scales of relaxation processes versus water loss, since the viscoelastic properties of concrete are dependent on water content.

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