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Code provisions for high strength concrete strength-temperature relationship at elevated temperatures

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ABSTRACT

This paper presents results of experiments, conducted at NIST and elsewhere, to measure compressive strength of concrete at elevated temperature. The paper compares the test data with existing design rules and recommendations to assess their applicability to HSC. Based on the compiled data, the paper proposes new strength-temperature relationship for HSC and discusses the need for standardizing the test procedure for testing concrete at high temperature and for a revision of the current design guides to include new data for properties of concrete at high temperature.

RÉSUMÉ

Cet article présente les résultats expérimentaux, recueillis au NIST et ailleurs, pour mesurer la résistance à la compression du béton soumis à des températures élevées. Cet exposé compare les données disponibles avec les règles et recommandations existantes pour la conception d'un béton afin de déterminer leur applicabilité pour le béton à haute résistance (HSC). Basé sur les données compilées, cet article propose une nouvelle relation entre la résistance et la température pour le béton à haute résistance. On discute de la nécessité de standardiser la procédure de mesure de la résistance du béton à haute température. On discute aussi de la nécessité de revoir les guides actuels pour y inclure les données récemment disponibles concernant les propriétés du béton à haute température.

1. INTRODUCTION

Degradation of concrete strength due to short-term exposure to elevated temperature has been studied as early as the 1950s. Among the early studies were those of Abrams [1], Malhotra [18], and Schneider [23-25]. Results of these studies constituted the technical basis for the provisions and recommendations for determining concrete strength at elevated temperature in many existing codes and authoritative design guides. While these studies provided valuable information on the variation of concrete strength as a function of temperatures, almost all used specimens made with normal strength concrete (NSC, according to the current ACI definition [2]). Thus, in light of the results of recent studies, which have shown that high-strength concrete (HSC) behavior at elevated temperature may be significantly different from that of NSC (Phan [20]; Phan and Carino [21, 22, 26, 27]), question may be raised as to whether existing design rules and recommendations are applicable to HSC.

The behavioral differences between HSC and NSC are found in two main areas: (1) *strength loss*: HSC has been found to have higher strength loss in the intermediate temperature range than NSC when exposed to the same heating condition, and (2) *explosive spalling*: HSC specimens are prone to explosive spalling, even when heated at a relatively slow heating rate (≤ 5°C/min).

This paper presents available test data on strength of concrete at elevated temperature, including data recently obtained in a NIST experimental program. The paper compares the compiled test data with existing design rules and recommendations to assess their applicability to HSC, and based on the compiled test data, proposes new strength-temperature relationship for HSC. The paper

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Table 1 – Summary of information on elevated temperature tests in various studies

	Test Methods and Programs	Specimen	$f_{23\,^\circ C}$ (MPa)	*w/cm*	Silica Fume (% by mass)	Preload (% of $f_{23\,^\circ C}$)	Heating Rate (°C/min)
Stressed	NIST Mixture I	100 x 200	98	0.22	10	40	5
	NIST Mixture II	100 x 200	88	0.33	10	40	5
	NIST Mixture III	100 x 200	75	0.33	0	40	5
	NIST Mixture IV	100 x 200	50	0.57	0	40	5
	Castillo and Durani	51 x 102	89	0.33	0	40	7 to 8
	Khoury and Algar	60 x 180	85	0.32	0	20	2
	Abrams	75 x 150	45	unknown	0	40	unknown
Unstressed	NIST Mixture I	100 x 200	98	0.22	10	0	5
	NIST Mixture II	100 x 200	88	0.33	10	0	5
	NIST Mixture III	100 x 200	75	0.33	0	0	5
	NIST Mixture IV	100 x 200	50	0.57	0	0	5
	Castillo and Durani	51 x 102	63, 31	0.33, 0.68	0	0	7 to 8
	Hammer	100 x 310	68 to 118	0.27 to 0.50	5	0	2
	Diederichs *et al.*	100 x 100 x 100 and 80 x 300	33 to 114	0.26 to 0.45	10	0	2, 32
	Furumura *et al.*	150 x 300	55, 79	0.41, 0.32	0	0	1
	Khoury and Algar	60 x 180	85	0.32	0	0	2
	Abrams	75 x 150	23	unknown	0	0	unknown
Unstressed Residual Property	NIST Mixture I	100 x 200	98	0.22	10	0	5
	NIST Mixture II	100 x 200	88	0.33	10	0	5
	NIST Mixture III	100 x 200	75	0.33	0	0	5
	NIST Mixture IV	100 x 200	50	0.57	0	0	5
	Hertz	100 x 200 57 x 100 28 x 52	150		1, 5, 10, 15, 20	0	1
	Morita *et al.*	100 x 200	20 to 74		0	0	1
	Felicetti *et al.*	100 x 300	72, 95	0.43, 0.30	9.4, 6.7	0	0.2
	Khoury and Algar	60 x 180	85	0.32	0	0	2
	Abrams	75 x 150	23, 45	unknown	0	0	unknown

also discusses the need for standardizing the test procedure for testing concrete at elevated temperature, and for a revision of the current U.S. authoritative guide to include newly available data for properties of concrete at high temperature.

2. NIST STUDY ON FIRE PERFORMANCE OF HSC

The NIST study includes an experimental program to measure (1) loss of mechanical properties of HSC due to elevated temperature exposure and (2) heat-induced pore pressure buildup in HSC with and without polypropylene fibers. Only the measurements for mechanical properties will be reported in this paper. This program to measure mechanical properties comprises of three series of tests on cylinders under steady-state temperature condition. The three test series differed by the test methods, namely *stressed, unstressed*, and *unstressed residual property* test methods. The *stressed* and *unstressed* test methods were designed to provide measurements of property data at elevated temperatures and required simultaneous application of loading and heating. In the stressed test, specimens were restrained by a preload equal to 40 percent of their room-temperature compressive strength ($0.4f_{23^\circ C}$) prior to and throughout the heating process. In the *unstressed* test, the specimens were heated without restraint. Both *stressed* and *unstressed* specimens were loaded to failure under uniaxial compression when the steady-state temperature is reached (5h: 15min ± 15min of heating at 5°C/min and holding at a target temperature) at the target temperature. The *unstressed residual property* test method was designed to provide property data of concrete at room temperature after exposure to elevated temperatures.

Specimens were made from four HSC mixtures, named mixture I to IV, using ASTM type I portland

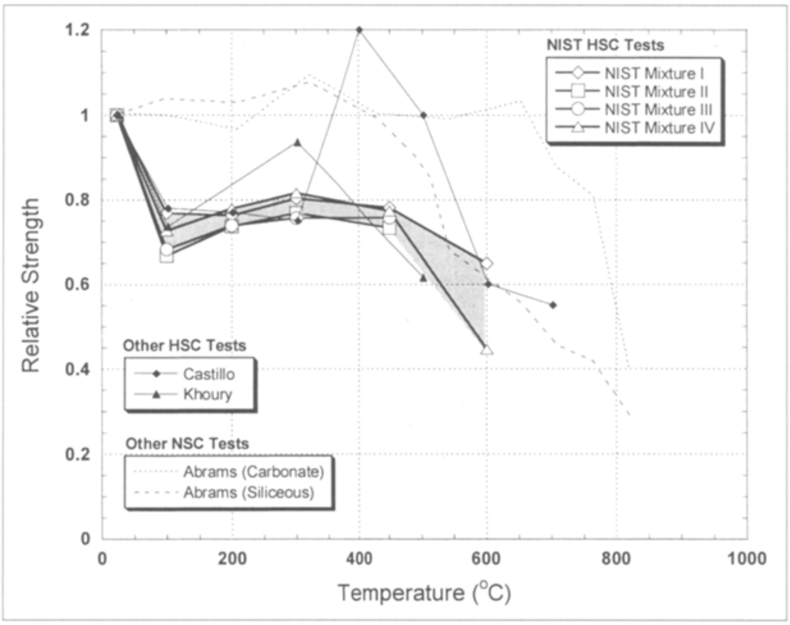

Fig. 1 – Stressed test results.

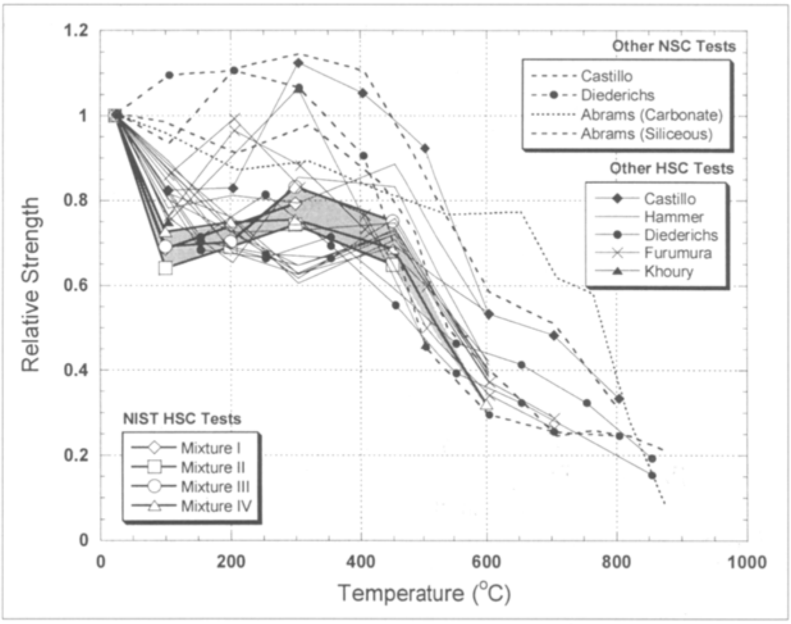

Fig. 2 – Unstressed test results.

cement, crushed limestone and natural river sand. Table 1 lists key information concerning the NIST test program as well as those from other test programs whose results are reviewed in this paper. More detailed information about the NIST study may be found in Phan and Carino [22]. Also, more detailed summaries of other studies whose data are shown in this paper may be found in Phan [20].

3. TEST DATA ON CONCRETE STRENGTH AT ELEVATED TEMPERATURES

Data obtained from NIST and other studies are compiled and shown in this section according to the test methods used. The ranges of NIST test results are shaded for convenience. While it is recognized that differences in the heating conditions (*i.e.*, exposure time, heating rate), type of aggregate, specimen shape and size, specimen curing condition and so forth, used in different test programs could result in measurements that are not directly compatible, it is necessary to compare the NIST results with those of others based only on the test methods since there are insufficient data to be normalized with respect to all the applicable variables.

3.1 Stressed test data

Fig. 1 shows the relative strength - temperature relationships of HSC (solid lines) and NSC (dashed lines) obtained under the stressed test method. As is shown in this figure, there is only a limited amount of test data available for this test condition prior to the NIST test series. This is probably due to the difficulty in applying and maintaining the constant preload on the test specimen while it is being heated simultaneously. In Fig. 1, NIST data are shown in thick solid lines with symbols. The symbols represent the mean measured strengths of at least three specimens at a particular temperature. The range of NIST test results was shaded for convenience.

In general, the NIST test results showed that HSC sustained an average strength loss of about 25% at 100°C. NIST results are consistent with data by Castillo and Durrani [4] at up to 200°C and with data by Khoury and Algar [17] at 100°C. Data for NSC by Abrams [1], however, indicated a slight strength gain for siliceous NSC and no effect on strength for calcareous NSC in this temperature range.

Strength data at 600°C for NIST mixtures II and III are not available due to explosive spalling of the specimens while being heated to this temperature. Castillo and Durrani [4] reported explosive spalling in about one third of the specimens being heated to 700°C while Khoury and Algar [17] did not mention explosive spalling. Detailed discussion concerning the effects of temperature, *w/cm*, preload level, and silica fume on concrete strength examined in the NIST study, as well as summaries of findings from other studies, may be found in Phan and Carino [22, 26].

3.2 Unstressed test data

More data are available for the unstressed tests than for the stressed tests, as shown in Table 1 and Fig. 2. The strength-temperature relationships observed in the NIST's unstressed test data are similar in trend with

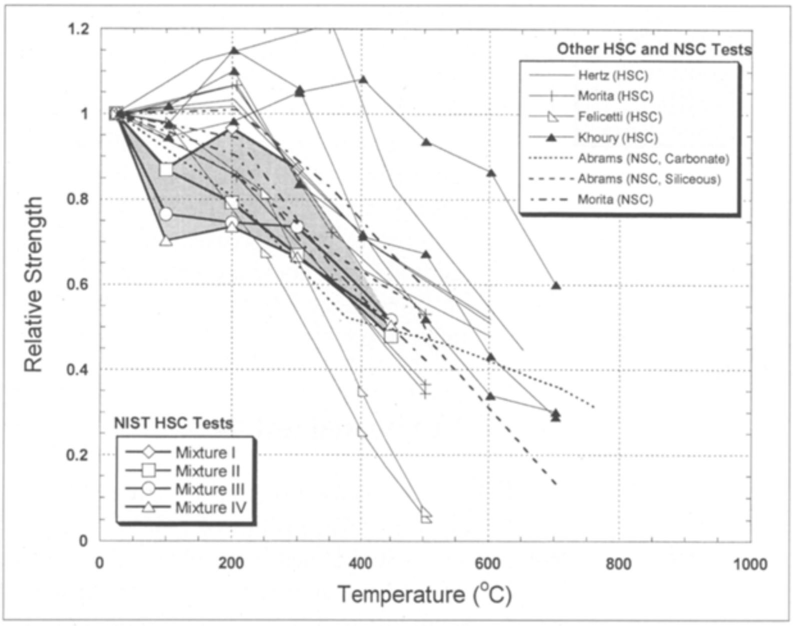

Fig. 3 – Unstressed residual strength test results.

those of the NIST's stressed test data, except that the strength losses in the unstressed tests are slightly larger at each target temperature. The NIST strength-temperature relationships also followed the general trend of unstressed HSC tests reported by Hammer [4] and Diederichs *et al.* [9-11], which constituted the majority of the unstressed test data for HSC. In general, within the intermediate temperature range of 100°C to 450°C, most studies reported higher strength loss for HSC compared to NSC.

More incidences of explosive spalling were observed in the NIST study under this test condition. As a result, NIST mixture I has no strength data above 300°C, and mixtures II and III have no strength data above 450°C. Explosive spalling did not occur in any of the mixture IV specimens.

Diederichs *et al.* [9-11], Hammer [14], and Furumura *et al.* [13] also reported explosive spalling failure of their unstressed HSC specimens, even though some of these studies used very low heating rates (1°C/min for Furumura and 2°C/min for Hammer). Study by Castillo and Durrani [4], however, indicated that explosive spalling occurred only in their stressed test specimens and none occurred under unstressed test condition.

3.3 Unstressed residual property test data

Fig. 3 shows the strength-temperature relationships for the unstressed residual property test. NIST test data showed a wider range of strength loss between the four mixtures under this test method than in the stressed or unstressed test methods. The NIST test results at under 200°C also differed from data for both HSC and NSC in other studies. The largest difference is at 100°C, at which the NIST results showed a strength loss ranging between 10% to 30% while data for HSC from other studies showed either a strength gain or loss of a little more than 5%. At above 300°C, the average difference in relative strengths between test programs appeared to be insignificant. The temperature rates of strength reduction between test programs are also similar.

Explosive spalling occurred in one (out of five) NIST mixture I and one (out of four) mixture II specimens while they were being heated to 300°C. Explosive spalling also occurred in all mixture I specimens while they were being heated to 450°C. Again, explosive spalling did not occur in any of the NIST mixture IV specimen. Of the referenced studies, only that of Hertz [15, 16], which used ultra high strength concrete, reported explosive spalling in the unstressed residual property test.

4. COMPARISONS OF TEST RESULTS WITH CODES

The compiled test data are compared with the provisions for computing concrete strength at elevated temperature prescribed by existing codes and authoritative design guides. Among the codes and design guides which specify design rules for computing concrete strength at elevated temperature are the Comité Européen de Normalisation (CEN ENV [6, 7], Eurocode 2 and Eurocode 4), the Comité Euro-International du Béton (CEB) model code [5], and the National Building Code of Finland's RakMK B4 [8]. ACI 216 R [3] provides strength test data obtained by Abrams but did not prescribe a strength-temperature relationship for concrete. Abrams test results are also referenced in the CEB model code.

The CEN ENV [6, 7] and CEB model code [5] make no distinction between HSC and NSC in their fire design provisions. Thus, their design rules are compared to both HSC and NSC data. Furthermore, while the CEN ENV [6, 7] and the CEB model code [5] did not explicitly prescribe whether their design rules were specified for concrete in service (*i.e.* concrete under service load), it is assumed that this is the case since both codes are for the design of structural concrete. Thus, the design rules prescribed by CEN ENV [6, 7] and CEB [5] will be compared with the data of the stressed tests. It should be noted that, at the time of this writing, it is believed that the provisions for concrete strength at elevated temperature of the CEN ENV [6, 7] are being revised by CEN Technical Committee 250. The revisions take into account the difference in concrete strength grades and also provide measures for mitigating explosive spalling problem in HSC.

The Concrete Association of Finland's *RakMK B4* [8] prescribes different design rules for HSC and NSC. HSC is concrete with designated strength grades of K70 to K100 (concretes with 70 MPa to 100 MPa compressive strength if 150 mm cubes are used, or 62 to 90 MPa if 150 x 300 mm cylinders are used). NSC is concrete with designated

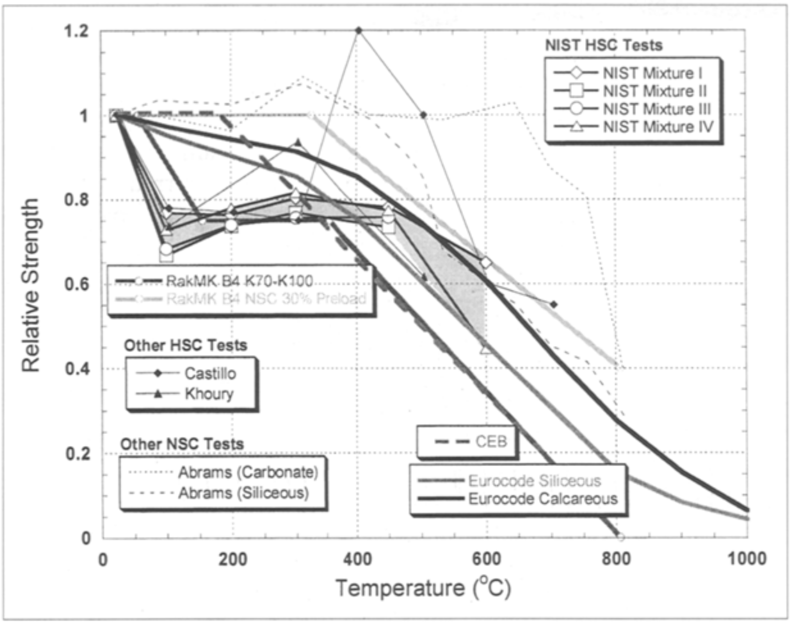

Fig. 4 – Comparison of stressed test data with codes.

strength grades of K10 to K70 (concretes with 10 MPa to 70 MPa compressive strength if 150 mm cubes are used, or 7 MPa to 62 MPa if 150 x 300 mm cylinders are used). The RakMK B4 also prescribes different design rules for concrete in service (stressed, $0.3f_{23°C}$) and for concrete which is not (unstressed). Thus, the applicability of RakMK B4 will be assessed by comparing with both the stressed and unstressed test data.

Also, comparisons with unstressed residual strength tests will not be made here since the code provisions were prescribed for concrete strength "at" elevated temperature, and not for concrete strength at room temperature after exposure to elevated temperature.

4.1 Comparisons of stressed test data with codes

Fig. 4 shows the compressive strength-temperature relationships obtained under the stressed test method for four HSC mixtures in this test program and in studies by Castillo and Durrani [4], Khoury and Algar [17] and Abrams [1]. The design rules for calculating concrete compressive strength at elevated temperatures, prescribed by the Eurocodes for calcareous aggregate concrete and siliceous aggregate concretes, and by the CEB, are superposed over the measured compressive strength-temperature relationships to provide an assessment of their applicability to HSC. It should be noted that since carbonate crushed limestones were used as coarse aggregate in the four concrete mixtures tested in this test program, the Eurocode's precription for calcareous aggregate concrete is to be used in the comparison with the NIST test results.

As shown in Fig. 4, the Eurocode's strength-temperature relationship for calcareous aggregate concrete is unconservative when used for estimating compressive strength of HSC at temperatures less than 450°C. The largest overestimation by the Eurocode was by about 20 percent. Above 450°C, the strength loss prescibed by the Eurocode becomes more consistent with both HSC and NSC data. The unconservative estimation of HSC's compressive strength by the Eurocode at temperatures less than 450°C is more significant when explosive spalling, which is not addressed by the current Eurocode but observed in this test program in the intermediate temperature range is considered.

Similarly, the provisions of CEB model code [5] were also based on NSC test data and are found to be unconservative when used for estimating HSC compressive strength at temperatures less than 350°C. The largest overestimation by the CEB model code is by about 25% at temperatures less than 200°C. The CEB's rate of strength loss at temperature above 350°C is consistent with data for both HSC and NSC. Also similar to the Eurocode, the unconservative estimation of HSC compressive strength by the CEB model code at temperatures less than 350°C is more significant since the CEB does not address the explosive spalling problem observed for HSC in this temperature range.

The RakMK B4's provision for NSC's strength at elevated temperature with 30 percent preload is shown as the thick brown dashed line in Fig. 4. This provision for NSC is also applicable to light weight aggregate concrete with preload of up to 30 percent the room temperature compressive strength of concrete. The RakMK B4's provision for HSC's strength at elevated temperature with 0 to 30 percent preload is shown as the thick dot-and-dash line in Fig. 4. The RakMK B4 provision for in-service concrete (stressed) of K10 to K70 strength grades (NSC) is consistent with the stressed test data for NSC up to 800°C. The RakMK B4 provision for concrete with K70 to K100 strength grades appears to be slightly unconservative at temperatures below 150°C. However, this is to a much lesser degree compared with the Eurocode CEN ENV [6, 7] and the CEB model code [5]. In the intermediate temperature range (150°C and 350°C), the RakMK B4 provision for in-service HSC are consistent with the NIST test data. From 350°C to 800°C, the RakMK B4 provision appears to be conservative compared with all test data, and is similar to the strength estimation prescribed by the CEB model code.

4.2 Comparisons of unstressed test data with codes

The RakMK B4's prescription for strength-temperature relationship for HSC under unstressed test is similar to that of the stressed test. This prescribed relationship is superposed over the unstressed test data on Fig. 5 as the thick dot-and-dash line. The prescription for NSC under unstressed test differs from the prescription for NSC under stressed test shown previously in Fig. 4.

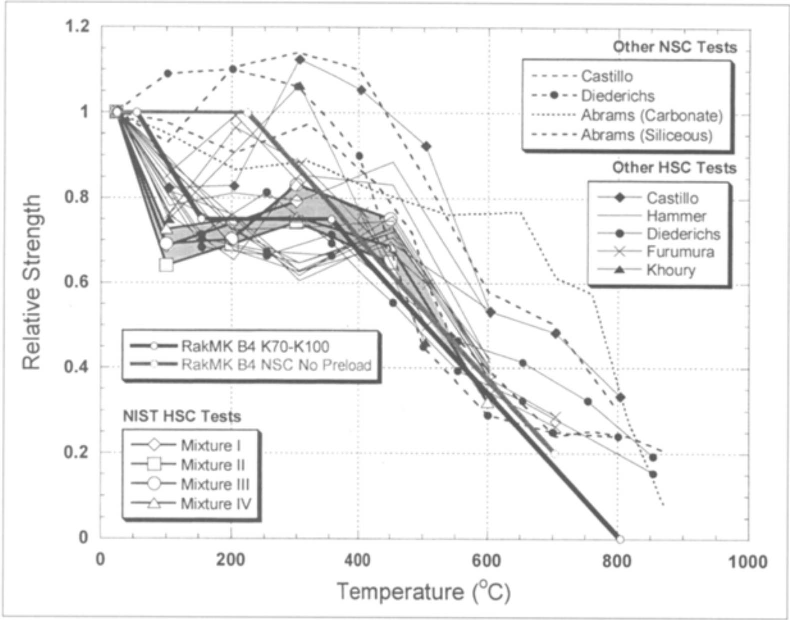

Fig. 5 – Comparison of unstressed test results with codes.

This is superposed on Fig. 5 as the thick dashed line.

Similar to the stressed test, the RakMK B4's strength provision for HSC appears to be slightly unconservative at temperatures below 150°C with respect to the NIST's test data. However, the RakMK B4's prescription for HSC appears to be consistent with the average of all test measurements when results of other studies are combined with the NIST test results. Between 150°C and 350°C, the RakMK B4's strength predictions are consistent with the NIST test data and the average of all existing unstressed test results for HSC. At temperatures above 350°C, the RakMK B4 prescribes a period of progressive strength loss that is consistent with the strength losses observed in NIST and other studies. The RakMK B4's strength prediction for unstressed NSC prescribes a range of no strength loss between room temperature and 220°C. This is consistent with the average results of tests by Castillo and Durrani [4], Abrams [1], and Diederichs *et al.* [9-11]. Above 220°C, RakMK B4 prescribes a strength loss period that has a similar rate of strength reduction as in the case for HSC. The prescribed strength loss is on the conservative side of the test data.

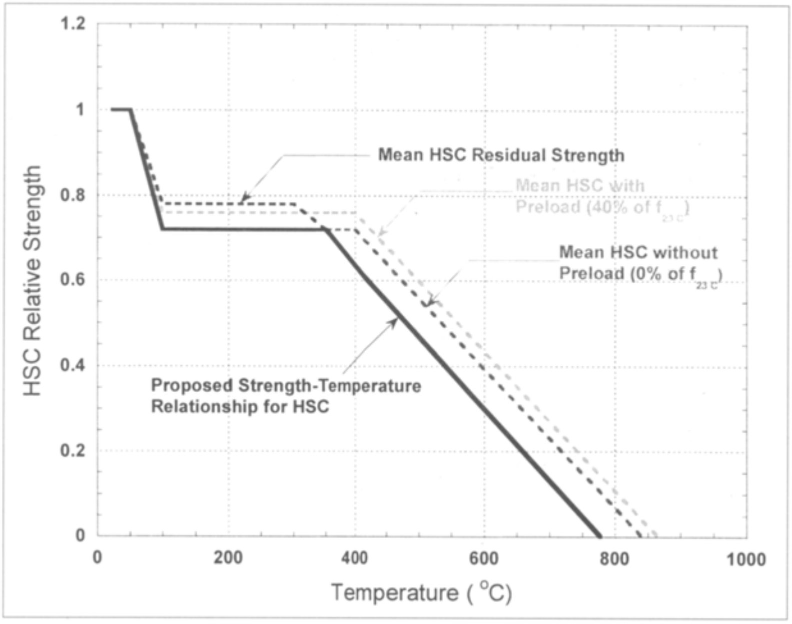

Fig. 6 – Proposed relative strength-temperature relationships for HSC.

5. RECOMMENDATIONS

- Except for the National Building Code of Finland, the provisions for concrete strength at elevated temperature in current major codes and authoritative guides, such as the Eurocode and the CEB model code, are unconservative when applied to HSC. In fact, these provisions were developed based on NSC test data and did not make the distinction between HSC and NSC. The National Building Code of Finland considered the difference between HSC and NSC in its provisions for concrete strength at elevated temperature. In the case of NSC, it made further distinction between concrete in- and not-in-service (stressed and unstressed). However, it is also found slightly unconservative for HSC in the intermediate temperature range (100°C and 350°C) and conservative at temperatures above this range. Thus, given the availability of new test data on HSC developed in this study, combined with existing test data as reviewed in this paper, a strength-temperature relationship is proposed for HSC. This proposed strength-temperature relationship is applicable to HSC made of limestone aggregate, with strength grades of between 50 MPa to 100 MPa (based on cylinder tests). The proposed strength-temperature relationship, which represents the lower bound of the means of test data for HSC in-service (stressed), HSC not-in-service (unstressed), HSC not-in-service after high temperature exposure (residual strength), is shown in Fig. 6. Table 2 shows the tabulated values for the proposed HSC strength-temperature relationship as well as the means of NIST and others' HSC test data (Phan and Carino [22, 26]).
- As discussed earlier, the test data reviewed in this paper and listed in Table 1 were obtained from different test programs and were normalized with respect to the test methods used. These test programs used different test protocols, materials and specimen sizes, and curing conditions which might affect the test results. One example is the results of residual strength tests by Felicetti *et al.* [12] (see Fig. 3), which used slow heating rate (0.2°C/min) and longer exposure time (30 h to 50 h of heating compared with 5 h of heating in the NIST test program). This prolonged heating exposure and slow heating rate is

Table 2 - Tabulated values for propsed HSC strength-temperature relationships

Temperature (°C)	HSC mean relative strength based on test data			Proposed HSC relative strength
	With 0.4 $f_{23°C}$ preload	Without preload	Residual	
23.0	1	1	1	1
50.0	1	1	1	1
100.0	0.76	0.72	0.78	0.72
300.0	0.76	0.72	0.78	0.72
350.0	0.76	0.72	0.72	0.72
400.0	0.76	0.72		
778.0			0	0
842.0		0		
866.0	0			

believed to be the reason for the larger strength loss shown in Fig. 3. Thus, there is a need for a standardized test protocol, similar to the recommended test method being proposed by RILEM Technical Committee 129-MHT, to be developed so that differences between test results can be minimized.

• In the U.S., the ACI 216R [3] is the only standard-related document that contains information on properties of concrete at high temperature. However, while the information in the present ACI 216R [3] was useful, they are not up-to-date when HSC is concerned and thus a revision to include new information on HSC is recommended.

The proposed HSC strength-temperature relationship, which consists of four temperature ranges: 23°C to 50°C; 50°C to 100°C; 100°C to 350°C (intermediate temperature range); and above 350°C, is superposed over the compiled test data and shown in Fig. 7 (a), (b), and (c) (see next page). These relationships differ from the existing provisions of the National Building Code of Finland's RakMK B4 in two areas: (1) the proposed relationships consider the differences caused by preload and the effect on concrete strength "at" elevated temperatures or at room temperature "after" elevated temperature exposure, whereas the RakMK B4 only considers the effect of preload for NSC; (2) the proposed relationship extends the intermediate temperature range for HSC with and without preload to between 100°C to 350°C, thereby eliminating the unconservativeness of the RakMK B4 in this intermediate temperature range.

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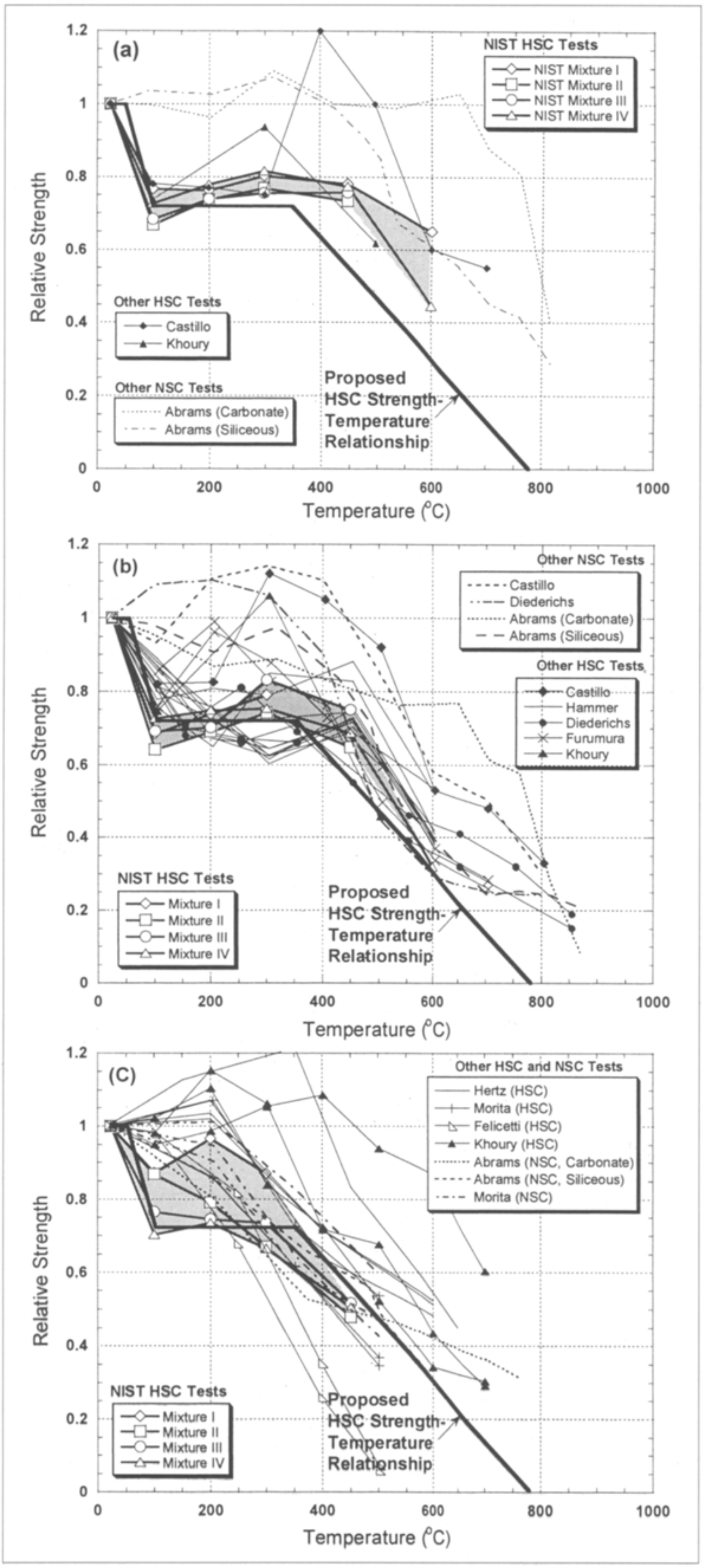

Fig. 7 – Comparisons of proposed strength-temperature relationship with data of (a) HSC with preload; (b) HSC without preload; (c) HSC residual strength.

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