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Experimental Plan for Testing the Mechanical Properties of High-Strength Concrete at Elevated Temperatures

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United States Department of Commerce
gy Administration
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Abstract

This report outlines an experimental plan designed to quantify the effect of elevated temperature on the mechanical properties of high-strength concrete. The experimental program will examine the influences of the following factors: (1) different steady-state test methods, (2) rates of heating, (3) water-to-cementitious materials (w/c) ratios (and implicitly compressive strengths), (4) inclusion or absence of silica fume (and implicitly paste density). These effects will be studied through 148 test combinations developed using a full factorial experimental design. The highest strength concrete to be tested is 95 MPa, and the lowest strength is 28 MPa.

Keywords: building technology; compressive strength; concrete; design of experiment, elastic modulus; explosive spalling; fire; high-strength concrete; steady-state test methods; temperature.

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1. INTRODUCTION

1.1 Background

A recent review of the state-of-the-art (*Phan*, 1996; *Phan and Carino,* 1998) on the effects of elevated temperature exposure on mechanical properties (compressive strength and elastic modulus) of high-strength concrete (HSC) has shown that there are significant differences in the reductions of HSC's mechanical properties at elevated temperatures compared with the reductions observed in ordinary concrete. These differences are most pronounced in the temperature range between 100 °C and 400 °C, where HSC's mechanical properties could be reduced by close to 40 % of the original values - a reduction of approximately 20 % to 30 % lower than in ordinary concrete when exposed to the same temperature range. More importantly, HSC - which is achieved typically by using a low water-to-cementitious materials (w/c) ratio and silica fume, and thus possesses higher cementitious material content and lower permeability than ordinary concrete - has been experimentally observed, albeit inconsistently, to have a significantly higher potential for sudden, explosive spalling failure when heated at a rate similar to that generated by a fire. These findings have raised questions about the applicability to HSC structures of current design provisions for fire-exposed concrete such as those described by the Eurocodes (*CEN*, 1993; 1994) and the Comités Euro-International Du Beton (*CEB*, 1991), which were developed based on results of studies that used ordinary concrete specimens. Given the beneficial attributes of HSC, its availability from most concrete plants, and its increased usage in structural applications, fundamental understanding of the effects of elevated temperature exposure to engineering properties of HSC need to be developed and/or validated. This report outlines an experimental plan that aims to develop data to facilitate such fundamental understanding.

Based on the limited amount of experimental data available to date, it has been found that the effects of elevated temperature exposures on HSC's mechanical properties vary with a number of factors, some of which are external and some internal. External factors include the **test methods**, i.e., the loading and heating regimes (*stressed* test, *unstressed* test, and *unstressed residual property* test) and the **heating rates** used. In the next chapter these test methods will be explained in more detail. Internal factors include original, room temperature **compressive strength**, porosity or permeability which can vary with the use of **silica fume**, the **types of aggregate** used (normal weight calcareous and siliceous, or lightweight), and **moisture content** at start of testing.

With regard to the effect of the **test methods**, an early study by *Abrams* (1971), which involved normal strength concrete with strength up to 45 MPa using the above three test methods (i.e. *stressed* test, *unstressed* test, and *unstressed residual property* test), and a more recent study by *Castillo and Durani* (1990), which tested HSC with strength up to 83 MPa, have shown that - while a quantitative comparison is statistically unreliable due to the limited amount of data available relative to the numbers of variables in these two studies - the differences in compressive strength of fire-exposed concrete due to different test methods could be as large as 30 %, and strength obtained from the *stressed* test method are generally higher than those obtained from the *unstressed* and *unstressed residual property* test methods. Moreover, HSC specimens tested using the *stressed* test method displayed higher incidences of explosive spalling in the temperature range of 320 °C to 360 °C, and none of these specimens were able to sustain load beyond 700 °C. Similar findings which showed discernible differences in concrete's mechanical properties obtained using two test methods, *unstressed* and *unstressed residual property* tests, were also reported by *Sullivan and Shanshar* (1992) and *Furumura et al.* (1995).

For the effect of the second external factor - **heating rates** - there was only one study, conducted by *Diederichs et al.* (1988, 1989, 1995), which examined this effect. The study used heating rates of 2 °C/min and 32 °C/min to simulate the *steady-state* and *transient* temperature exposure conditions and revealed that specimens heated with the higher heating rate were more prone to explosive spalling than those heated with the lower heating rate. Similar to the effect of test methods, a quantitative conclusion concerning the effect of heating rate is not possible due to the limited amount of data currently available.

For internal factors, original **compressive strength** - and implicitly the **w/c ratio**, the presence or absence of **silica fume**, and initial **moisture content-** has been shown to have a significant effect on the mechanical properties and the failure mechanism of HSC at elevated temperature in studies by *Castillo and Durani* (1990), *Diederichs et al.* (1988, 1989, 1995), *Hammer* (1989, 1995), *Furumura et al.* (1995) which involved the *unstressed* test method, and studies by *Hertz* (1984, 1991), *Morita et al.* (1992), and *Furumura et al.* (1995) which involved the *unstressed residual property* test method. Briefly, the results of these studies can be combined to show that concrete with higher original compressive strength undergoes higher rates of strength loss at high temperature than ordinary concrete. Moreover, high strength HSC with silica fume sustained higher strength loss when heated than similar strength HSC but without silica fume. Finally, high strength HSC and/or HSC with silica fume were observed to have higher incidences of explosive spalling.

Similar to the effect of other variables on the mechanical properties of HSC, there is only a limited amount of experimental data for assessing the effects of different **types of aggregates**. These include studies by *Hammer* (1995), *Abrams* (1971), and *Sullivan and Shanshar* (1992). In general, concretes with siliceous, calcareous, or lightweight aggregates have been found to undergo similar strength loss at temperatures below 480 °C. Above this temperature, siliceous aggregate concrete sustained higher strength loss than calcareous and lightweight aggregate concretes. Finally, albeit with limited data available, HSC made with lightweight aggregate appears to be more prone to explosive spalling than HSC made of normal weight aggregate.

The above findings were summarized in *Phan* (1996) and *Phan and Carino* (1998) which normalized and compared the various experimental results from different experimental programs. Comparisons of the normalized strength and modulus of elasticity versus temperature relationships with current fire design provisions, prescribed by the Eurocode (*CEN* (1993, 1994)); *CEB* (1991); and the *Finnish Code* (1991), was also presented in those two papers. It was concluded that - due to the many differences in experimental procedures, materials, and variables among research programs, and also the inconsistent results observed in these programs - the existing data can only be viewed as trends and are not statistically sufficient to constitute a fire design guideline. This point can be further illustrated by the fact that the present fire design provisions do not make distinctions for fire exposed HSC under different stress conditions even though experimental observations clearly indicated that the presence or absence of stress prior to heating, i.e., the different test methods, would have a significant influence on mechanical properties of HSC. The experimental program described in this report aims to provide a comprehensive set of empirical data that addresses the effects on the mechanical properties of fire-exposed HSC which can form the basis for developing fire design provisions applicable to HSC.

1.2 Purpose

Understanding performance characteristics of HSC when exposed to high temperature is an important first step in reducing the likelihood of structural collapse in the event of fire, which is the long term goal of this project. To achieve this long-term goal, it is the purpose of this experimental program, which is described in the next chapter, to develop experimental data necessary for accurate characterization of behavior of HSC when subjected to fire, including the explosive spalling failure mechanism. These data can also be used for the validation of predictive models, which can account for the developed pore vapor pressure and the moisture transport in HSC, and the sudden spalling failure mechanism of HSC when subjected to fire.

2. EXPERIMENTAL PROGRAM

2.1 Design of Experiment

External and internal factors that could affect mechanical properties of HSC at elevated temperatures have been discussed in the previous chapter. In this section, a detailed experimental plan, designed to quantify the effects of these factors, is presented. The factors to be studied include:

- *Heating rates:* Two heating rates, 5 °C/min and 30 °C/min, will be used for heating the specimens to *steady-state* temperature condition.

  Briefly, in the *steady-state* test condition, the specimen is heated to a target temperature following one of the two selected heating rates. The ambient temperature is then held constant to allow the internal specimen temperature to reach a uniform value, and concrete mechanical properties are measured after a uniform internal temperature is reached. Thus, *steady-state* test condition provides property data associated with a controlled temperature exposure and allows the material properties for different concretes to be studied. It is noted that the heating rate prescribed for an ASTM E 119 standard fire exposure is approximately 28 °C/min for temperatures up to about 850 °C.

- *Test methods*: Three *steady-state* test methods will be performed to study the effects of different combinations of loading and heating to HSC properties. These test methods, which will be explained in more detail in the sections to follow, include:

  1. Stressed test method (preload of 40 % of room temperature compressive strength)
  2. Unstressed test method (no preload)
  3. Unstressed residual strength test method

- *w/c ratios (compressive strength)*: three w/c ratios - 0.22, 0.3, and 0.57 - will be examined.

- *Silica fume*: two levels - 0 and 10 % cement replacement - will be used.

- *Temperatures* : room temperature and six target elevated temperature levels (23 °C, 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, and 850 °C) are planned. A smaller/larger increment of temperature below/above 450 °C is selected based on the review of the state-of-the-art (*Phan*, 1996; *Phan* and *Carino*, 1998) which shows the differences between engineering properties of HSC and ordinary concrete are more pronounced in the temperature range of 23 °C and 450 °C, and become less significant at temperatures above 450 °C.

The effects of w/c ratio, compressive strength, and silica fume are interdependent and will be addressed using four concrete mixtures to be described in the next section. For the purpose of this experimental design, the four concrete mixtures, hereafter coded as I, II, III, and IV, are as follow:

Table 1. Concrete Mixtures

	I	II	III	IV
w/c ratio	0.2	0.3	0.3	0.57
silica fume (% cement replacement)	10	10	----	----
28-day compressive strength (MPa)	95	70	65	28

Table 2 shows 24 test combinations for a target temperature level T, derived using the full factorial experimental design procedure, that will facilitate examination of the effects of 4 concrete mixtures (which entails 3 w/c ratios, 4 compressive strength levels, and 2 levels of silica fume), 2 heating rates, and 3 *steady-state* test methods on mechanical properties of HSC as a function of T. For convenience, the test methods will be coded as (+) for *stressed* test, (-) for *unstressed* test, and (0) for *unstressed residual properties* test.

Table 2. Test Combinations at a Target Temperature T

Test Number	Mix-ture	Test Method	Heating Rate (°C/min)
-	I	+	5
2	II	+	5
4	III	+	5
4	IV	+	5
5	I	-	5
8	II	-	5
-	III	-	5
8	IV	-	5
9	I	0	5
10	II	0	5
11	III	0	5
12	IV	0	5
13	I	+	30
14	II	+	30
15	III	+	30

Test Number	Mix-ture	Test Method	Heating Rate (°C/min)
16	IV	+	30
17	I	-	30
18	II	-	30
19	III	-	30
20	IV	-	30
21	I	0	30
22	II	0	30
23	III	0	30
24	IV	0	30

For each test combination shown in Table 2, three specimens will be tested at the target temperature level T and one replication will be tested at room temperature. These 24 test combinations will facilitate examinations of the effects of the selected variables in this experimental program by the following comparisons:

- For the effect of *silica fume*:

  Test number: 2 vs. 3
  14 vs. 15
  2 comparisons under *stressed* test method

  Test number: 6 vs. 7
  18 vs. 19
  2 comparisons under *unstressed* test method

  Test number: 10 vs. 11
  22 vs. 23
  2 comparisons under *unstressed residual properties* test method

- For the effect of *w/c ratio*:

  Test number: 1 vs. 2
  5 vs. 6
  9 vs.10
  3 comparisons under the 5 °C/min heating rate and with silica fume

  Test number: 13 vs. 14
  17 vs. 18
  21 vs. 22
  3 comparisons under the 30 °C/min heating rate and with silica fume

  Test number: 3 vs. 4
  7 vs. 8
  11 vs. 12
  3 comparisons under the 5 °C/min heating rate and without silica fume

  Test number: 15 vs. 16
  19 vs. 20
  23 vs. 24
  3 comparisons under the 30 °C/min heating rate and without silica fume

- For the effect of *test methods*:

  Test number: 1 vs. 5 vs. 9 4 comparisons under the 5 °C/min heating rate
  2 vs. 6 vs. 10
  3 vs. 7 vs. 11
  4 vs. 8 vs. 12

  Test number: 13 vs. 17 vs. 21 4 comparisons under the 30 °C/min heating rate
  14 vs. 18 vs. 22
  15 vs. 19 vs. 23
  16 vs. 20 vs. 24

- For the effect of *compressive strength*:

  Test number: 1 vs. Avg (2,3) vs. 4 6 comparisons under the 5 °C/min heating rate
  5 vs. Avg (6,7) vs. 8
  9 vs. Avg (10,11) vs. 12

  Test number: 13 vs. Avg (14,15) vs.16 6 comparisons under the 30 °C/min heating rate
  17 vs. Avg (18,19) vs. 20
  21 vs. Avg (22,23) vs. 24

- For the effect of *heating rate (steady-state* vs. *transient* test condition):

  Test number: 1 vs. 13 4 comparisons under *stressed* test method
  2 vs. 14
  3 vs. 15
  4 vs. 16

  Test number: 5 vs. 17 4 comparisons under *unstressed* test method
  6 vs. 18
  7 vs. 19
  8 vs. 20

  Test number: 9 vs. 21 4 comparisons under *unstressed residual properties* test method
  10 vs. 22
  11 vs. 23
  12 vs. 24

Table 2 shows 24 test combinations for each of the six target temperature levels. For all six target temperature levels (100 °C, 200 °C, 300 °C, 450 °C, 650 °C, and 850 °C), there will be 144 test combinations. In addition, 4 test combinations will be needed as control tests at room temperature. Comparing data of different temperature levels will provide relationships for mechanical properties of HSC versus temperature. Table 3 shows the 4 control test combinations (shaded) plus the 144 test combinations planned for this test program. For convenience, the test methods will be designated as TM, heating rates as HR, and temperatures as T in Table 3.

Table 3. Test Combinations

Test #	Mix- ture	TM[1]	HR (°C/min)	T (°C)
1	I			23
2	II			23
3	III			23
4	IV			23
5	I	+	5	100
6	II	+	5	100
7	III	+	5	100
8	IV	+	5	100
9	I	-	5	100
10	II	-	5	100
11	III	-	5	100
12	IV	-	5	100
13	I	0	5	100
14	II	0	5	100
15	III	0	5	100
16	IV	0	5	100
17	I	+	30	100
18	II	+	30	100
19	III	+	30	100
20	IV	+	30	100
21	I	-	30	100
22	II	-	30	100
23	III	-	30	100
24	IV	-	30	100
25	I	0	30	100
26	II	0	30	100
27	III	0	30	100
28	IV	0	30	100
29	I	+	5	200
30	II	+	5	200
31	III	+	5	200
32	IV	+	5	200
33	I	-	5	200
34	II	-	5	200
35	III	-	5	200
36	IV	-	5	200
37	I	0	5	200
38	II	0	5	200
39	III	0	5	200
40	IV	0	5	200
41	I	+	30	200
42	II	+	30	200
43	III	+	30	200
44	IV	+	30	200
45	I	-	30	200
46	II	-	30	200
47	III	-	30	200
48	IV	-	30	200
49	I	0	30	200
50	II	0	30	200
51	III	0	30	200
52	IV	0	30	200
53	I	+	5	300
54	II	+	5	300
55	III	+	5	300
56	IV	+	5	300
57	I	-	5	300
58	II	-	5	300
59	III	-	5	300
60	IV	-	5	300
61	I	0	5	300
62	II	0	5	300
63	III	0	5	300
64	IV	0	5	300
65	I	+	30	300
66	II	+	30	300
67	III	+	30	300
68	IV	+	30	300
69	I	-	30	300
70	II	-	30	300
71	III	-	30	300
72	IV	-	30	300
73	I	0	30	300
74	II	0	30	300

Test #	Mix-ture	TM[1]	HR (°C/min)	T (°C)
75	III	0	30	300
76	IV	0	30	300
77	I	+	5	450
78	II	+	5	450
79	III	+	5	450
80	IV	-	5	450
81	I	-	5	450
82	II	-	5	450
83	III	-	5	450
84	IV	-	5	450
85	I	0	5	450
86	II	0	5	450
87	III	0	5	450
88	IV	0	5	450
89	I	+	30	450
90	II	+	30	450
91	III	+	30	450
92	IV	+	30	450
93	I	-	30	450
94	II	-	30	450
95	III	-	30	450
96	IV	-	30	450
97	I	0	30	450
98	II	0	30	450
99	III	0	30	450
100	IV	0	30	450
101	I	+	5	650
102	II	+	5	650
103	III	+	5	650
104	IV	+	5	650
105	I	-	5	650
106	II	-	5	650
107	III	-	5	650
108	IV	-	5	650
109	I	0	5	650
110	II	0	5	650
111	III	0	5	650
112	IV	0	5	650
113	I	+	30	650
114	II	+	30	650
115	III	+	30	650
116	IV	-	30	650
117	I	-	30	650
118	II	-	30	650
119	III	-	30	650
120	IV	-	30	650
121	I	0	30	650
122	II	0	30	650
123	III	0	30	650
124	IV	0	30	650
125	I	-	5	850
126	II	-	5	850
127	III	-	5	850
128	IV	-	5	850
129	I	-	5	850
130	II	-	5	850
131	III	-	5	850
132	IV	-	5	850
133	I	0	5	850
134	II	0	5	850
135	III	0	5	850
136	IV	0	5	850
137	I	+	30	850
138	II	+	30	850
139	III	+	30	850
140	IV	+	30	850
141	I	-	30	850
142	II	-	30	850
143	III	-	30	850
144	IV	-	30	850
145	I	0	30	850
146	II	0	30	850
147	III	0	30	850
148	IV	0	30	850

TM[1]:

(+) Stressed test method.

(-) Unstressed test method.

(0) Unstressed residual properties test method.

2.2 Concrete Mixture Proportions

As mentioned in the previous section, four concrete mixtures will be used. All mixtures use Type I portland cement, a crushed limestones coarse aggregate of 13 mm (½-in.) nominal maximum size, and a natural sand fine aggregate with a finess modulus (FM) of 2.85. Mixture I is a HSC mixture, has a low water-to-cementitious materials (w/c) ratio of 0.22, contains 10 % of silica fume as replacement for cement, and is designed to produce a 28-day compressive strength of 95 MPa (13,800 psi). Mixtures II and III are also HSC mixtures and are designed to have similar strength but differ by the inclusion of silica fume to facilitate the examination of the effect of silica fume. Mixture II has a w/c ratio of 0.30, contains 10 % of silica fume, and has a 28-day compressive strength of 70 MPa (10,100 psi). Mixture III also has a w/c ratio of 0.30, contains no silica fume, and has a 28-day compressive strength of 65 MPa (9,400 psi). Mixture IV is a NSC mixture, has a w/c ratio of 0.57, contains no silica fume, and has a 28-day compressive strength of 28 MPa (4,060 psi). The mixture proportions are shown in Table 4. The silica fume is added to the concrete mixtures in the form of a slurry with a density of 1.42 g/cc and a 54% silica fume concentration. A commercially available sulfonated naphthalene high range water-reducing admixture (HRWR) is used in mixtures I to III to improve the workability of the concretes. Some properties of the aggregates used are summarized in Table 5, and properties of fresh and hardened concretes are shown in Table 6.

Table 4 . Concrete Mixture Proportions

Parameter	**Mixture I** (w/c = 0.22)	**Mixture II** (w/c = 0.3)	**Mixture III** (w/c = 0.3)	**Mixture IV** (w/c=.57)
Cement (kg/m^3) (lb/ft^3)	595.9 37.2	595.9 37.2	661.6 41.3	376.4 23.5
Water (kg/m^3) (lb/ft^3)	133.0 8.3	198.6 12.4	198.6 12.4	213.0 13.3
Crushed Limestone coarse aggregate, 13-mm (½-in) maximum size, SSD: (kg/m^3) (lb/ft^3)	845.8 52.8	845.8 52.8	845.8 52.8	853.8 53.3
Fine Aggregate, SSD (kg/m^3) (lb/ft^3)	733.6 45.8	733.6 45.8	733.6 45.8	868.2 54.2
Silica Fume (kg/m^3) (lb/ft^3)	65.7 4.1	65.7 4.1	—	***
HRWR (ml) (oz)	400 13.5	354 12.0	154 5.2	***

Table 5. Properties of Aggregates

Properties	**Coarse Aggregate** 13-mm (1/2-in.) crushed limestone	**Fine Aggregate** natural sand
Dry rodded unit weight (kg/m^3) (lb/ft^3)	1520 94.9	1456 90.9
Finess Modulus		2.85
Absorption (%)		0.59
Specific Gravity Saturated Surface Dry	2.6	2.63

Table 6. Properties of Fresh and Hardened Concretes

Properties	**Mixture I** (w/c = 0.22)	**Mixture II** (w/c = 0.3)	**Mixture III** (w/c =0.3)	**Mixture IV** (w/c = 0.57)
Fresh Concrete				
Slump (cm) (in)	23.6 9.3	23.1 9.1	3.3 1.3	7.6 3.0
Air Content (%)	3.2	2.75	2.0	2.5
Hardened Concrete at 28 days				
Compressive Strength (MPa) (ksi)	91 13.2	71 10.3	64 9.3	28 4.1
Young's Modulus E (MPa) (ksi)	40,825 5,921	42,330 6139	42450 6157	****
Torsional Rigidity, G (MPa) (ksi)	16,785 2,434	15,150 2,197	*****	****

2.3 Test Specimens, Test Setup, and Instrumentation

All test specimens will be 102 mm diameter by 204 mm long (4 x 8 in.) cylinders. Compressive load will be provided by a servo-controlled 1.34 MN (300 kip) compression test machine and heat will be provided by a computer-controlled electric split-tube furnace. The 102 mm x 204 mm (4 in x 8 in specimen will be placed at the center of the furnace where it will be exposed to direct heating. The interior of the furnace is cylindrical with dimensions of 260 mm (10 ¼ in.) in diameter and 380 mm (15 in.) in height. The furnace has two 165 mm (6 ½ in.) diameter openings, one at the top and one at the bottom, to allow high-temperature alloy steel loading rams to transmit compressive load from the test machine to the concrete specimen being heated at the center of the furnace. A high-temperature compressometer with water cooled furnace mounting bracket and inconel rods will be mounted on the outside of the furnace at mid-height. The inconel rods will be placed in contact with the specimen through cut-out slots on the side of the furnace to measure strain development in the specimen at elevated temperatures.

A small group of specimens, each will be instrumented with two type K thermocouples (nickel-chrome, nickel) with Nextel Ceramic insulation, one at the center and one at 25 mm (1 in.) from the center of the specimen. These specimens will be heated in accordance with the two selected heating rates prior to testing the main group of specimens. The aim is to develop the internal temperature profiles on the cross section of the specimen. These temperature profiles will be used for controlling the exposure time required for the specimen to attain the steady-state temperature condition, i.e., when (1) the rate of temperature rise at the center of the specimen is less than 5 °C/hr, or (2) the center of the specimen reaches a level that is within ± 10 °C of the target temperature, whichever comes first. The specimen dimensions and instrumentation scheme are shown in Figure 1. The test setup for *stressed* and *unstressed* tests, which requires simultaneous applications of heat and load, is as shown in Figure 2.

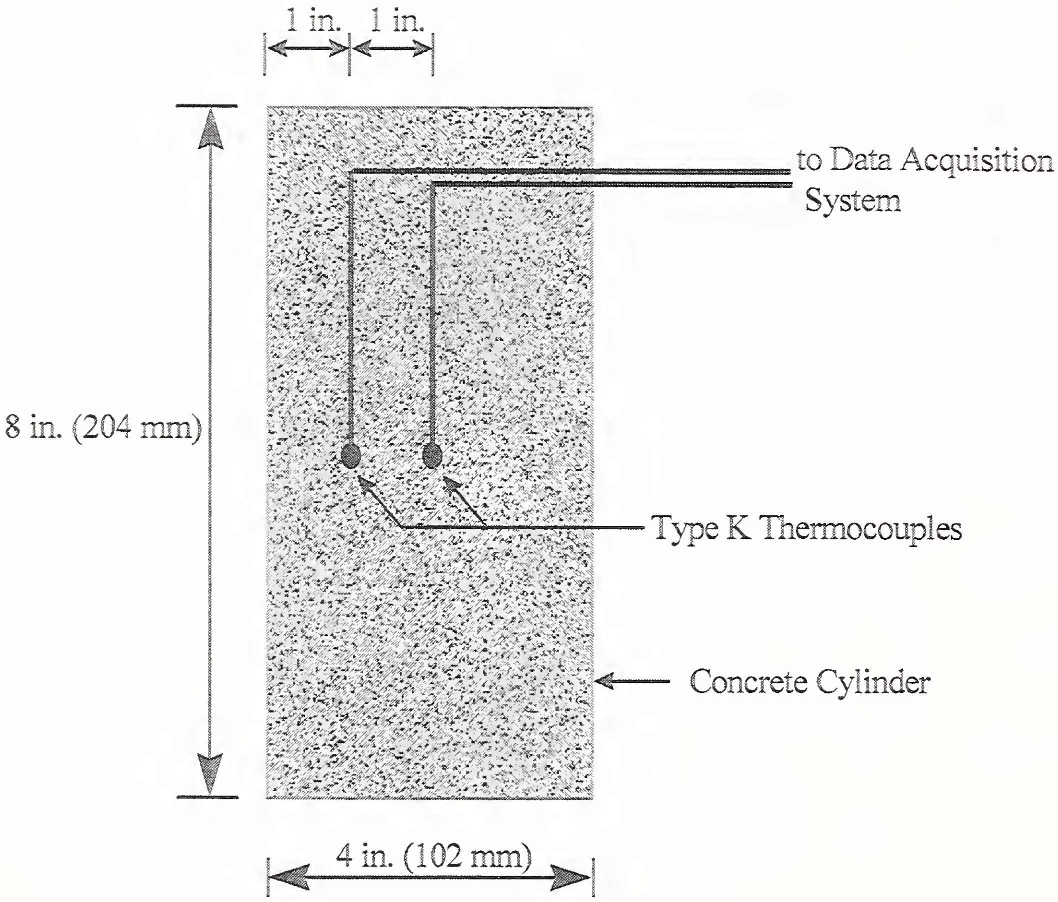

Figure 1. Specimen Dimensions and Instrumentation Scheme

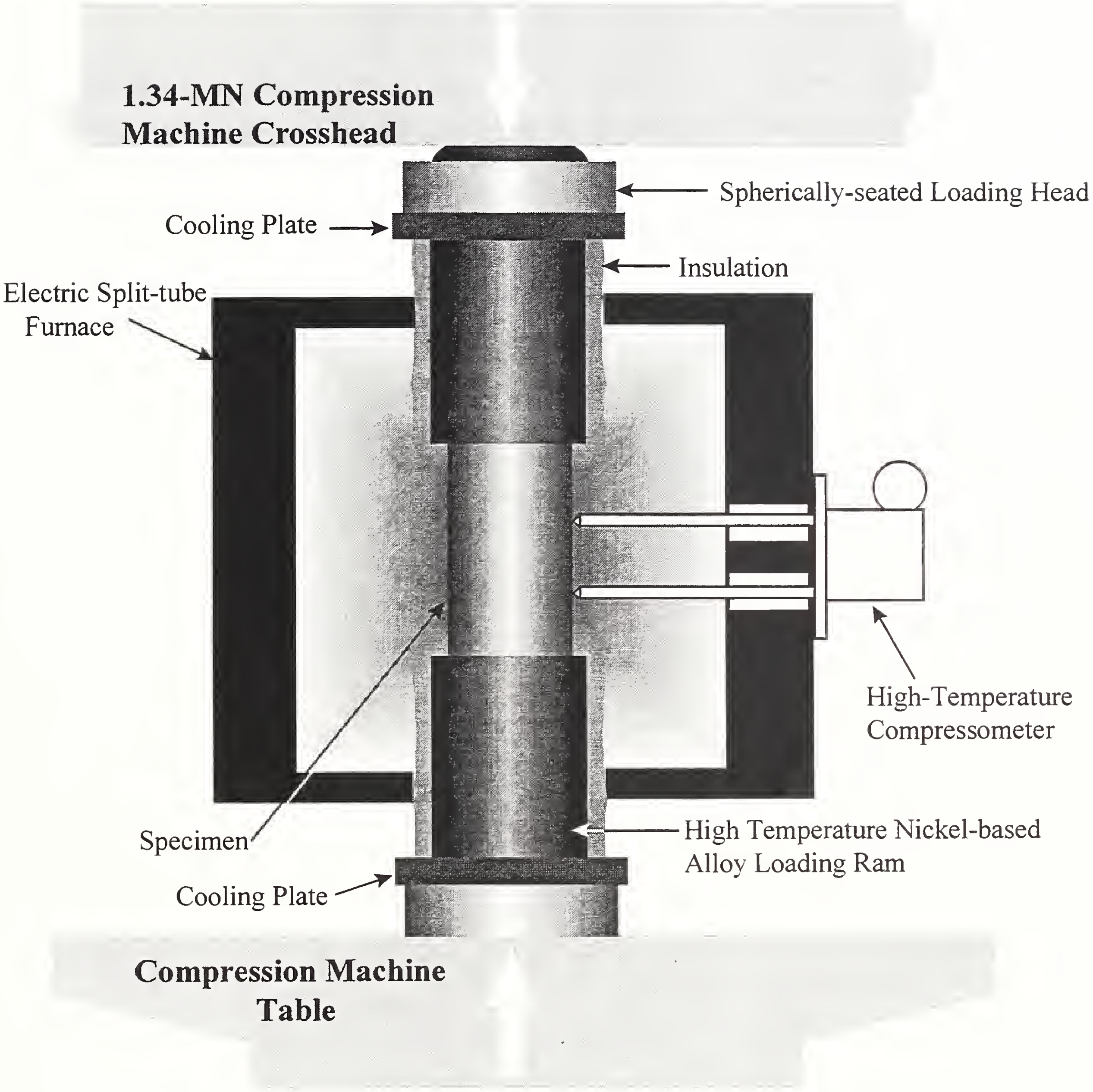

Figure 2. Test setup for *stressed* and *unstressed* test methods

2.4 Test Conditions, Test Methods, and Temperature Control

As stated in section 2.1, the *steady-state* test condition provides properties data associated with a controlled temperature exposure and allows the material properties of different concretes to be studied. In this test condition, the ambient temperature will be increased to a target temperature following one of the two selected heating rates (5 °C/min or 30 °C/min). The ambient temperature is then held constant until (1) the rate of temperature rise at the center of the specimen, as measured by the two type K thermocouples shown in Fig. 1, is less than 5 °C/hr, or (2) the temperature at the center of the specimen reaches a uniform value that is within ±10 °C of the target temperature, whichever comes first. These conditions are defined as the *steady-state* conditions in this test program.

Three **test methods**, representing three variations of the *steady-state* test condition, will be used to facilitate examination of the effects of existing compressive load prior to heating (preload, as in the case of HSC columns) and of elevated temperature exposure to residual properties of HSC. The test methods include:

1. *Unstressed test* - In this method, specimen will be heated to a target temperature in the absence of stress, and the specimen is loaded to failure when the target temperature is reached.

2. *Stressed test* - In this method, the specimen is loaded at room temperature to 40 % of its room temperature compressive strength; this preload is sustained while the specimen is heated to a target temperature and, after the steady-state condition is reached, the specimen is further loaded to failure.

3. *Unstressed Residual Properties test* - In this method, the specimen is heated to a target temperature, then it is cooled to room temperature using the same rate as the heating rate. The specimen is then loaded to failure at room temperature.

In these test methods, the loading of the specimen will follow the deformation control technique with a constant deformation rate of about 0.25 mm/min (0.01 inch/min). Strain reading will be recorded by a high temperature compressometer that will be mounted on the side of the split-tube furnace (see Fig. 2). The compressomoter has a 102 mm (4 in.) gage length, a travel length of ±20 mm (±0.8 in.), and a maximum temperature range of 1200 °C. The compressometer's inconel rods will be placed in contact with the specimen through a slot on the side of the furnace.

To estimate the thermal response of the concrete specimens at different target temperatures and heating rates, a finite-element model, FIRES-T3 (Iding, et. al., 1996), designed to predict the thermal response of materials subjected to fire conditions was used. Figure 3(a) shows the grid of 142 nodes and 107 elements used to model a symmetric one fourth of the furnace, specimen, and supporting loading rams. Element temperatures at the center of the concrete specimen, near the surface of the loading ram in contact with the testing machine and a profile of temperature from the surface to the center of the concrete sample provide appropriate estimates of specimen response at elevated temperature.

Figures 3(b) and 3(c) show the predicted concrete temperature and testing machine surface temperature for a range of target temperatures and three heating rates (30 °C/min: dotted lines, 5 °C/min: dashed lines, 1 °C/min: solid lines). As expected, the heating rate does not effect the final steady-state temperature, but rather the time to steady-state conditions. Steady-state temperatures at the center of the concrete specimen are, as expected, lower than the furnace temperature due to heat losses from the furnace and from the ends of the concrete specimen to the alloy loading rams. For high target temperatures, the testing machine surface, Figure 3(c), can reach significantly elevated temperatures, making appropriate cooling necessary to protect the machine from damage.

Figure 4 shows the predicted temperature on the surface and at the center of the concrete sample for a range of ambient furnace temperatures. Not surprisingly, the interior temperature of the concrete sample is considerably less than the ambient furnace temperature at the end of the heating period. Thus, as indicated in section 2.3, thermocouples will be placed in a small number of specimens to monitor the temperature during heating using Figure 4 for initial estimates of the necessary furnace temperature to obtain the chosen heating profile for the tests. At steady state, the temperature gradient in the concrete sample ranges from less than 6 °C at a furnace target temperature of 100 °C to more than 65 °C at a furnace target temperature of 1000 °C.

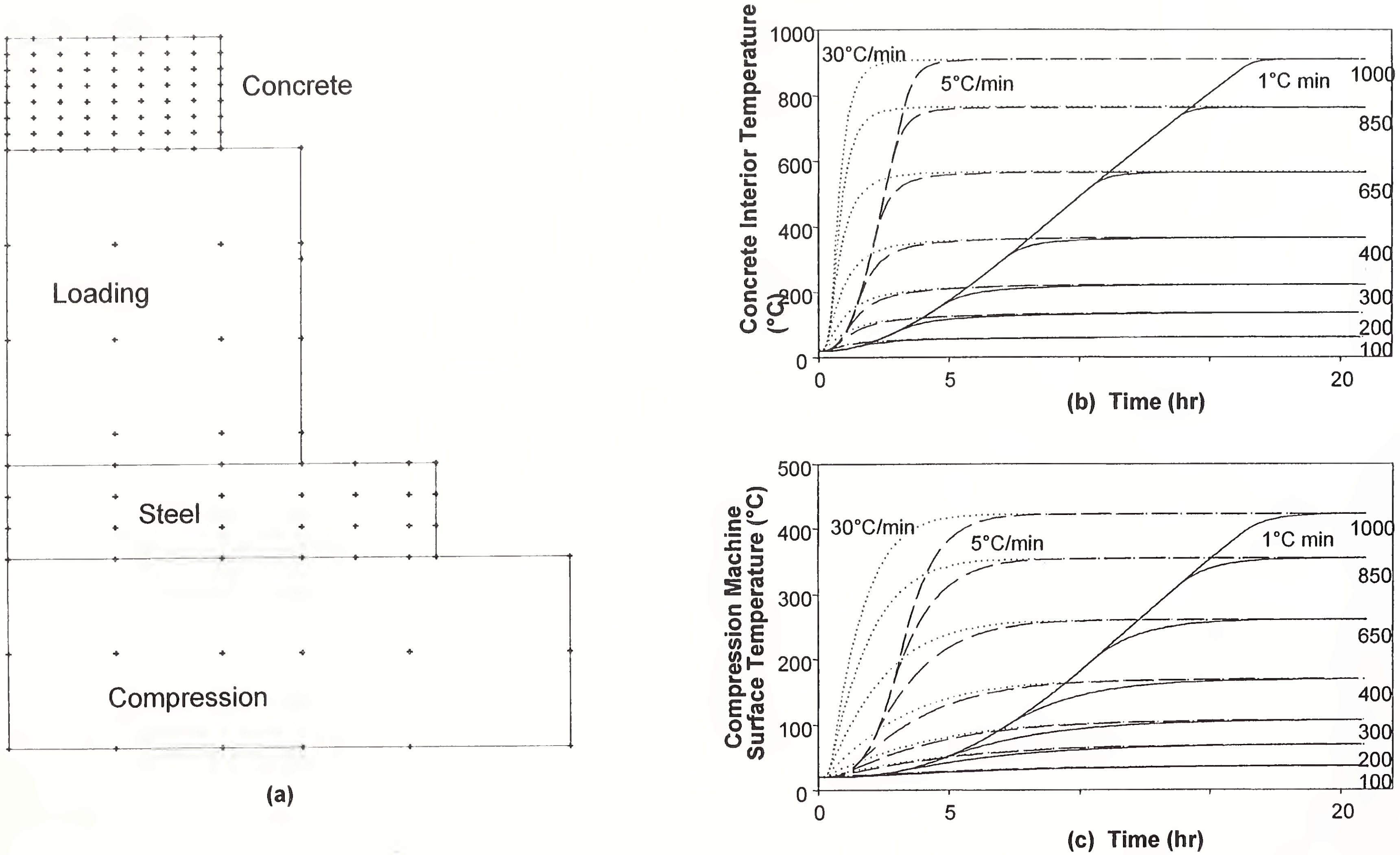

Figure 3. Finite-element modeling estimation of concrete sample heating

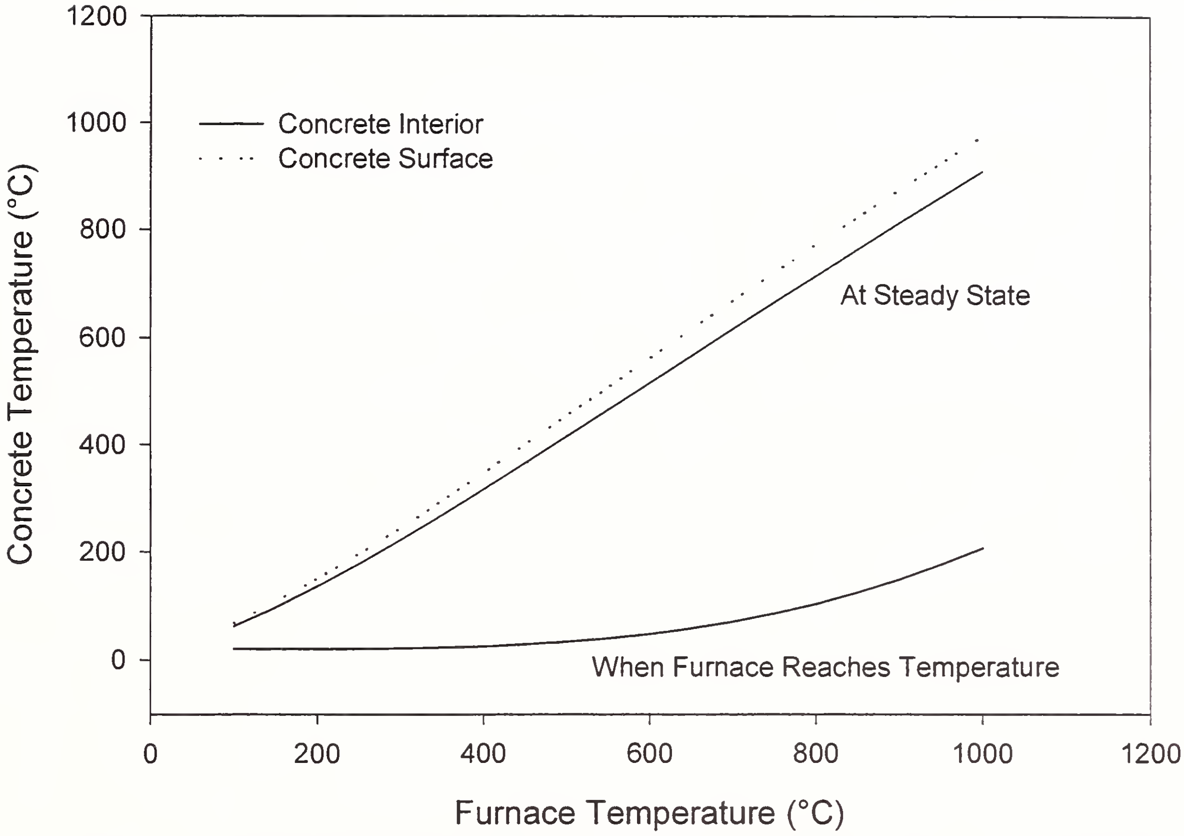

Figure 4. Estimated Rate of Temperature Rise at Center of Concrete Sample

a c

2.5 Test Procedure and Measurement

All specimens will be stripped from molds one day after casting and cured under water until testing. The specimens that will be tested at elevated temperatures will be removed from the water for grinding to provide smooth ends at least one week before testing. After grinding, the specimens will again be stored under water until test time.

The three *steady-state* test methods described in section 2.4 are schematically shown in Figures 5 a to c. For *stressed* tests, each specimen will be subjected to a preload equal to 40 % of the room temperature maximum load prior to heating. This preload will be applied at a 1 MPa/s ramp rate and maintained while the specimen internal temperature is heated to a target temperature (either 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, or 850 °C). The rates of temperature rise, controllable by the programmable electric split-tube furnace used in this test program, will be either 5 °C/min or 30 °C/min. Schematic showing *stressed* test method under *steady-state* test condition is shown in Figure 5(b).

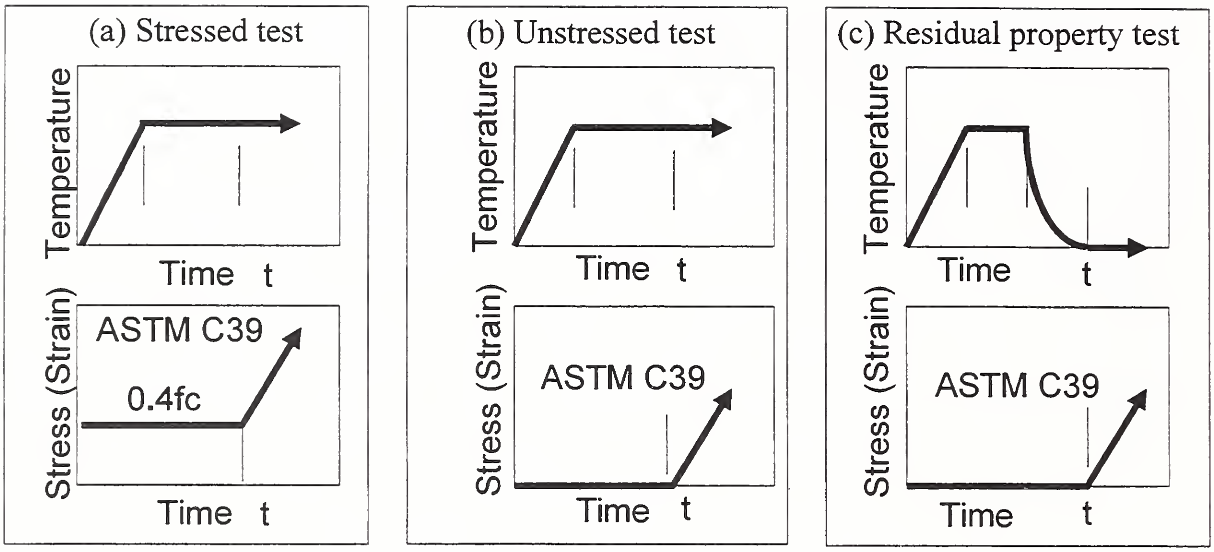

Figure 5. Schematic temperature and load histories for *steady-state* elevated temperature tests

Schematic showing *steady-state unstressed* test method is shown in Figure 5(a). Each specimen will be heated, without any external load, to a target temperature of either 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, or 850 °C, using a heating rate of either 5 °C/min or 30 °C/min. The temperature is maintained at this target level until the steady-state temperature condition is achieved. The specimen is then loaded to failure at a constant deformation rate of 0.25 mm/min (0.01 inch/min).

Schematic showing *steady-state residual property* test method is shown in Figure 5(c). Each specimen will be heated without loading to a target temperature of either 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, or 850 °C. The target temperature is maintained until a steady-state temperature is achieved. Once that is attained, the specimen is allowed to cool to room temperature. The specimen is then loaded to failure at room temperature. The heating and cooling rates will be either +5 °C/min and -5 °C/min or +30 °C/min and -30 °C/min.

The mechanical properties that will be measured include compressive strength and elastic modulus of the concrete after being exposed to the target temperatures. Strain readings will be obtained using a high temperature electronic compressometer. Load and deformation information will be obtained from the programmable compression test machine. Where applicable, the test procedure and measurements will follow appropriate ASTM standards.

3. SUMMARY OF EXPERIMENTAL PLAN

An experimental plan has been outlined for quantifying the effects of four variables, including the *test method*, *heating rate*, *w/c ratio*, and *inclusion of silica fume*, on the relationships between the maximum exposure temperature and the mechanical properties of HSC.

Three steady state temperature test methods, namely *stressed*, *unstressed*, and *unstressed residual strength*, will be used. The *stressed* and *unstressed* test methods are designed to provide property data at elevated temperature, i.e. during a fire, and require simultaneous application of loading and heating. In the *stressed* test, a pre-load equal to 40% of the room temperature compressive strength will be applied to the specimen prior to heating. The *unstressed residual strength* test method is designed to provide property data when the specimen has cooled down to room temperature after being exposed to elevated temperatures.

Two heating rates, 5 °C/min and 30 °C/min, will be used. The higher heating rate of 30 °C/min is equivalent to the heating rate prescribed for the first 850 °C of ASTM E 119 standard fire exposure (approximately 28°C/min, or 30 minutes to reach temperature of about 850 °C).

Three water-cementitious materials ratios of 0.22, 0.3, and 0.57 will be used in four concrete mixtures. Mixture I has a w/c ratio of 0.22 (28-day compressive strength of 95 MPa), Mixtures II and III have w/c ratios of 0.3 (and 28-day compressive strengths of 70 MPa and 65 MPa, respectively), and Mixture IV has w/c ratio of 0.57 (28-day compressive strength of 28 MPa). Mixture IV is intended to represent a normal-strength concrete.

Two amounts of silica fume addition, 0 % and 10 % replacement of cement, will be used. Mixtures I and II will have 10 % silica fume by mass. Mixtures III and IV will have no silica fume.

The specimens will be heated to six target elevated temperatures, 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, and 850 °C. For each target elevated temperature, a set of three specimens will be tested at room temperature as reference specimens for comparison.

To quantify the effects of the above variables on mechanical properties of HSC, a total of 148 test combinations is planned based on a full factorial experimental design procedure. Each test combination consists of three 102 mm x 204 mm (4 in x 8 in) cylinders to be tested at high temperature and one 102 mm x 204 mm (4 x 8-in) cylinders to be tested at room temperature for comparison. All specimens will be water cured until testing. At least a week prior to testing, the specimen will be removed from the water and ground to provide smooth ends. Loading will be applied following the deformation control procedure with a constant deformation rate of 0.25 mm/min (0.01 inch/min). Strain measurements will be obtained using a high temperature compressometer (temperature range up to 1200 °C) mounted on the outside of the split-tube furnace. The compressometer has a 102 mm (4 in.) gage length and a ±20.3 mm (±0.8 in) travel length. A limited number of specimens will be instrumented with type K thermocouples to monitor temperature distribution inside the specimen. Two thermocouples, one placed at the center and one at mid-depth (between the surface and the center) of the specimen, will be used. The internal temperature profiles recorded will be used to control the heating of all other specimens to ensure that the temperature at center of the specimen reaches within ± 10 °C of the target temperature, i.e. the *steady-state* thermal condition is achieved prior to loading the specimen to failure.

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