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Effects of Test Conditions and Mixture Proportions on Behavior of High-Strength Concrete Exposed to High Temperatures

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Mechanical properties of high-strength concrete exposed to elevated temperatures were measured by heating 100 x 200 mm cylinders at 5 C/min to temperatures of up to 600 C. Heating was carried out with and without a sustained stress, and properties were measured at elevated temperatures as well as after cooling to room temperature. Four mixtures with water-cementitious materials ratios (w/cms) ranging from 0.22 to 0.57 and room-temperature strengths ranging from 51 to 98 MPa were used. Two of the mixtures contained silica fume. Measured compressive strengths and elastic moduli were normalized with respect to room temperature values, and analysis of variance was used to determine whether the test condition, the value of w/cm, or the presence of silica fume affected the results. The influence of these variables on the tendency for explosive spalling was also examined. Results indicate that losses in relative strength due to high-temperature exposure were affected by the test condition and w/cm, but there were significant interactions among the main factors that resulted in complex behaviors. The presence of silica fume does not appear to have a significant effect. Measurements of temperature histories in the cylinders revealed complex behaviors that are believed to be linked to heat-induced transformations and transport of free and chemically combined water.

Keywords: compressive strength; high-strength concrete; modulus of elasticity; silica fume; spalling; temperature.

INTRODUCTION

Based on studies of the effects of elevated temperatures on engineering properties of concrete,[1-21] it has been concluded that the behavior of high-strength concrete (HSC) differs from that of normal-strength concrete (NSC) under the same temperature exposure. A recent review of the fire performance of HSC[22,23] identified two main differences between HSC and NSC: 1) the relative strength loss in the intermediate temperature range (100 to 400 C); and (2) the occurrence of explosive spalling in HSC specimens at similar intermediate temperatures (200 to 400 C).

In terms of strength loss, studies[22,23] have shown that, for intermediate temperatures between 100 and 400 C, the compressive strength of HSC could be reduced by close to 40% of the room-temperature strength—a reduction of approximately 20 to 30 percentage points more than in NSC exposed to the same temperatures.

In terms of explosive spalling, which refers to a sudden and violent breaking away of a surface layer of heated concrete, it has been observed in laboratory tests that HSC has a significantly higher potential for explosive spalling than NSC, even at heating rates less than 5 C/min, which is lower than that would occur during real fires.[4-7,10-14,19] The phenomenon, however, has been observed inconsistently, and there is not a complete understanding of the factors that control explosive spalling in HSC. The general feeling is that its occurrence is related to the inability of HSC, due to its low permeability, to mitigate the buildup of internal pressure as free water and chemically-combined water are vaporized with increasing concrete temperature.

In some countries, the performance of a concrete structure during a fire is considered explicitly in the design, and provisions have been developed that provide relationships between concrete temperature and mechanical properties. The behavioral differences between HSC and NSC at elevated temperatures raise questions about the applicability of current fire design provisions to HSC structures, since most existing provisions are based on experience with NSC.[22,23] Specifically, the larger strength loss incurred by HSC in the intermediate temperature range compared with NSC means that these design provisions are not conservative when applied to HSC. Further, the tendency for explosive spalling of HSC means that HSC structural elements may be more susceptible than NSC to losing the concrete cover that provides thermal protection for the steel reinforcement. None of the current codes addresses the tendency for explosive spalling of HSC.

Given the many benefits of HSC and its increased use in structural applications, it is essential that the fundamental behavior of HSC at elevated temperatures be understood to ensure that structural fire design involving HSC will be safe. This paper, which focuses on the mechanical properties and potential for explosive spalling of HSC, is part of an overall research program at NIST that aims to provide the technical basis for fire design provisions applicable to HSC structures and to develop methods to mitigate explosive spalling. An important issue in developing this understanding is the role of the test conditions. There are no consensus standards on measuring the properties of concrete at elevated temperatures, and different researchers have used different methods. It is necessary to understand whether test conditions have significant effects on the measured relationships between temperature and HSC properties. Also, it is important to be able to quantify the effects of other key variables such as the mixture proportions and silica fume on HSC properties at high temperatures.

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RESEARCH SIGNIFICANCE

The results presented in this paper provide new information on the heating behavior of HSC when exposed to elevated temperatures. Also provided are data on the compressive strength of HSC at elevated temperatures under a restrained condition (data for restrained tests on HSC are rare). This study provides a comprehensive examination of the effects of major variables on mechanical properties of HSC at elevated temperatures and on the tendency for explosive spalling.

EXPERIMENTAL PROGRAM

Test variables and test conditions

The effects of the following variables on the behavior of HSC at elevated temperature were studied:

- Test conditions (stressed, unstressed, and unstressed residual property tests);
- Water-cementitious materials ratio (*w/cm*) (0.22, 0.33, and 0.57); and
- Silica fume content (0 and 10% cement replacement by mass).

Figure 1(a), (b), and (c) show the heating and loading histories for the three test conditions that were used. For the stressed and unstressed tests, the specimens are loaded at elevated temperatures after a steady-state temperature condition is attained. Steady state is defined as when the temperature at the center of the specimen is within 10 C of the target temperature *T*, and the difference between the surface and center temperatures is less than 10 C. In the stressed test, the specimen is restrained by a preload equal to 40% of the room temperature compressive strength that was applied before heating and maintained during heating. For all test conditions, the specimen is heated to the target temperature *T* at a furnace heating rate of 5 C/min to the target temperature 7, which is maintained until time t (or t_1 for residual property test) when the steady-state temperature condition is achieved. The specimen is then loaded to failure while hot (at time t for stressed and unstressed tests) or at room temperature after natural cooling (at time t_2 for residual property test). For this study. the target temperatures were 100, 200. 300, 450, and 600 C, the time t (or t_1) was 5 h: 15 min ± 15 min, and the time t_2 was 24 h ± 60 min.

Concrete mixture proportions, materials, and properties

Specimens were made from four HSC mixtures (named I to IV) using ASTM Type I portland cement. Coarse aggregate was crushed limestone (13 mm nominal maximum size) with a fineness modulus (FM) of 5.40, a dry-rodded bulk density of 1520 kg/m^3, and a specific gravity of 2.60. Fine aggregate was natural sand with a FM of 2.85, a dry-rodded bulk density of 1456 kg/m^3, and a specific gravity of 2.63. The silica fume was in the form of slurry with a solids fraction of 54% (by mass). The mixture proportions and concrete properties are shown in Table 1. Mixtures I and II contained 10% silica fume by mass of total cementitious materials; Mixtures II and III had the same *w/cm*, but Mixture III did not contain

	Mixture I, *w/cm* = 0.22	Mixture II, *w/cm* = 0.33	Mixture III, *w/cm* = 0.33	Mixture IV, *w/cm* = 0.57
Water. kg/m^3	133	199	194	213
Coarse aggregate,' kg/m^3	846	846	846	854
Fine aggregate,' kg/m^3	734	734	134	868
Silica fume	66	66	0	0
HRWRA,† mL/m^3	400	354	154	0
Slump, mm	240	230	35	76
Air content, %				
Initial moisture content, %	5.0	6.1	6.3	7.3
28-day	75.3	66.0	53.2	40.6
58-day	86.7	79.5	58.9	41.9
400-day	98.2	81.2	72.3	46.9
58-day	34.3	31.2	36.6	34.4
400-day	47.2	43.7	44.1	36.7

silica fume. Mixture IV, with the highest *w/cm*, can also be considered HSC because it meets the ACI definition of HSC, that is, a compressive strength in excess of 40 MPa. Initial moisture contents (IMC) represent the amount of free water in the concrete and were obtained by drying small concrete samples (400-day old samples) at 105 C until the difference in mass losses between measurements is negligible (≤ 0.1 %).

Specimen preparation, instrumentation, and test setup

All specimens were 100 x 200 mm cylinders, and were cured under water at room temperature until test time. Before testing, the specimens were removed from the curing tank and the ends were ground to ASTM C 39 requirements for perpendicularity and planeness. Two cylinders from each mixture were instrumented with Type K thermocouples, placed at the center, surface, and midway between the center and the surface of the cylinder. The instrumented cylinders were used to develop the heating regimens required to attain the desired target temperatures and steady-state conditions.

Figure 2 shows the setup used for the stressed and unstressed tests. The specimen is placed at the center of the electric split-tube furnace with openings at the top and bottom to allow the loading rains to transmit compressive load from the test machine. The furnace is lined with a high-temperature steel alloy to protect the heating elements and insulation in the event of explosive spalling. The gaps between the loading rains and the furnace openings are filled with ceramic wool insulation. Steel cooling plates, containing interconnected internal channels for circulating cooling water, are inserted between the loading rams and machine platens to keep the platens from being heated. For the residual property tests, the cylinders were heated in a larger electric furnace that permitted three cylinders to be heated at the same time. In this case, the cylinders are stored within thick-walled, ventilated steel pipes with caps to contain fragments in the event of explosive spalling.

Strain is measured by a high-temperature compressometer, with a 102 mm gage length, mounted on the outside of the split-tube furnace. The spring-loaded compressometer rods are placed in contact with the specimen through slots in the furnace wall.

EXPERIMENTAL RESULTS

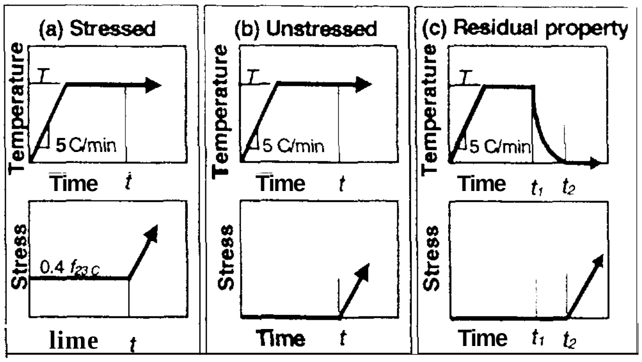
Heating characteristics

Figure 3(a) shows the temperature development in the furnace and a Mixture I cylinder when exposed to target furnace temperature of 500 C. The heating rate of the air in the furnace is 5 C/min or 300 C/h. It is noted that the concrete temperature lags the air temperature of the furnace. Figure 3(b) shows the temperature difference between the surface and center of the cylinder, and the rates of temperature rise on the surface and at the center of the cylinder.

As shown in these figures, the temperature distribution inside the specimen has a complex history compared with the furnace air temperature. Figure 3(b) shows that there are perturbations in the rates of temperature rise that occur at different times during heating. In general, three types of perturbations were observed with increasing temperature:[24]

- **A** sudden decrease in the rate of temperature rise at the center;
- An increase in the rate of temperature rise on the surface and beginning of a simultaneous decrease in the temperature rise at the center; and
- An increase in the rate of temperature rise at the center.

Examples of these perturbations are marked in Fig. 3(a) and (b) by vertical dashed lines. It is believed that these perturbations are related to different stages of the moisture transformation and transport process (vaporization and movement of free and chemically bound water) that occurs in the specimen during heating. The first two perturbations in the rates of temperature rise at the center and the surface of the specimen coincided with concrete temperatures of approximately 100 and 200 C (Fig. 3(a)). At slightly above 100 C. free water in the concrete begins to evaporate rapidly. **A** moisture front is driven by the heat toward the center of the specimen, causing a decrease in the rate of temperature rise at the specimen center and thus, an increase in the temperature difference between the cylinder's surface and center. When the center reaches approximately 200 C, a significant amount of chemically bound water is released. This caused a similar decrease in the rate of temperature rise at the center. In addition. the rate of temperature rise on the surface increases. presumably due to a reduction in the evaporative cooling effect, as marked by the second vertical dashed line in Fig. 3(a) and (b).



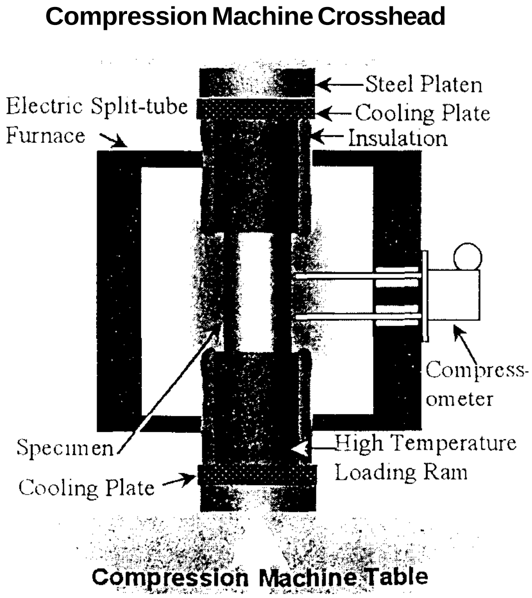


Fig. 2—Schematic showing test setup.

The temperature difference between the surface and center reaches a maximum of 36 C at a corresponding center temperature of270 C. This coincides with the third major perturbation in the rates of temperature rise in the cylinder. In this case, there is a rapid increase in the rate of temperature rise at center (third vertical dashed line). After this point, the rate of temperature rise on the concrete surface is lower than that of the center, causing the temperature difference to decrease, as shown in Fig. 3(b). This trend continues until a true steady-state thermal condition develops when the surface-to-center temperature difference is reduced to zero. Note that as the specimen center reaches the target temperature 7 of 450 C, the center is slightly hotter than the concrete surface.

In summary, the temperatures measured at different points in the cylinders reveal a complex process characterized by sudden changes in rates of temperature rise. It is believed that these perturbations are related to the transformation and subsequent transport of free water and chemically combined water that occur when concrete is heated.

Spalling tendency

Table 2 shows the test matrix and the incidences of explosive spalling. Each circle in the table represents a cylinder test and an open circle represents a cylinder that exploded while being heated to the target temperature. Explosive spalling is characterized by the sudden fragmentation of the cylinder during heating. This is accompanied by a loud bang and the instantaneous release of a large amount of energy that propels the fragments at high velocity in all directions. Examination of several exploded cylinders showed that there was a large intact core, which measured approximately 70 x 120 mm. Reassembly of the larger fragments showed that the core was surrounded by an approximately 20 mm thick concrete shell (Fig. 4). It appears that explosive spalling of the cylinders occurs by separation of the 20 mm thick shell from the core, and is consistent with the notion that explosive failure results from the build up of internal vapor pressure.

Table 2—Test matrix

Test methods and target temperatures, C		*w/cm* = 0.22	*w/cm* = 0.33		*w/cm* = 0.57
		Mixture I, 98 MPa	Mixture II, 88 MPa	Mixture III, 75 MPa	Mixture IV, 50 MPa
		With silica fume		Without silica fume	
Stressed	25	* * *	* * *	* * *	* * *
	100	** ** *	* * *	* * *	* * *
	200	* * *	* * *	* * *	* * *
	300	* * *	* * *	* * *	* * *
	450	* * *	* * *	* * *	* * *
	600	* * *	† † †	† † †	* * *
Unstressed	25	* * *	* * *	* * *	* * *
	100	* * *	* * *	* * *	* * *
	200	* * *	* * *	* * *	* * *
	300	* * *	* * *	* * *	* * *
	450	† † †	* ** †	* * *	* * *
	600	Not tested	† † †	† † †	* * *
	25	* * *	* * *	* * *	* * *
residual property			* * *	* * *	* * *
	300	** ** †	* * *†	* * *	* * *
	450	† † †	* * *	* * *	* * *

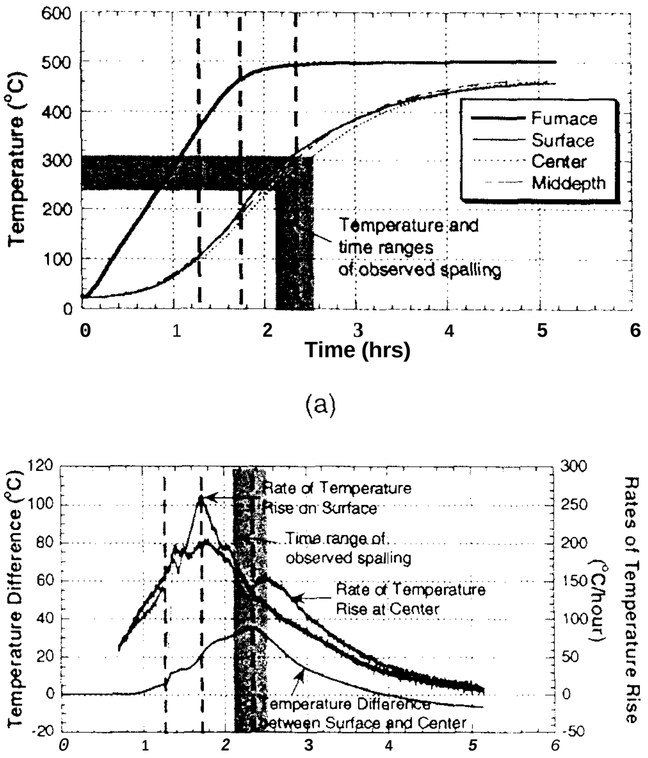
[*] Test specimen that failed in uniaxial compression.

[†] Test specimen that failed by explosive spalling.

A study of Table 2 shows the following tendencies for spalling:

- For the stressed tests, all cylinders of Mixtures II and III exploded while being heated to 600 C, while cylinders of Mixtures I and IV did not experience any explosive spalling throughout the entire teinperature range;
- For the unstressed tests, all cylinders of Mixture I and one of four cylinders of Mixture II exploded while being heated to 450 C, and all cylinders of Mixtures I1 and III exploded while being heated to 600 C (Mixture I specimens were not heated to 600 C due to the consistent failure while being heated to 450 C); and
- For the unstressed residual property test, one cylinder from each group of Mixtures I and II exploded while being heated to 300 C, and all Mixture I cylinders exploded while being heated to 450 C. (Specimens for these tests were not heated to 600 C for fear of damage to the exposed heating elements in the furnace that was used).

Considering all the mixtures, the mean of the estimated concrete temperatures at the centers of the cylinders when explosive spalling occurred was approximately 250 C, with an approximate range of ± *50* C. For Mixture I specimens. this temperature range was about 240 to 310 C, which is superposed as shaded bands over the temperature plots shown in Fig. 3(a) and (b). **As** can be seen in Fig. 3(b), the temperature range in which explosive spalling occurred coincides with the time of high thermal gradient between the surface and center. This suggests that, while internal pore pressure may be the primary cause for the explosive spalling of the



(b)

*Fig. 3—(a) Temperature development in Mixture **I** cylinder; und (b) temperature difference between surface and center **of** Mixture **I** cylinder:*

specimens, the buildup of thermally induced strains might have a secondary role in this failure.

Mechanical properties

Results of all tests are listed in Appendixes 1 to 3 and in Reference 24. Measured compressive strengths and elastic moduli are discussed in the following sections, which are grouped according to test condition. To compare the results from all mixtures, the values measured after exposure to elevated temperatures were divided by the corresponding average room temperature values.

Results of stressed tests—The normalized compressive strengths and static moduli of elasticity as functions of temperature are shown in Fig. 5 and 6. The symbols in these figures represent the individual test result, and the lines represent the mean for each mixture. As shown in Fig. 5, compressive strengths of all four HSC mixtures varied similarly with increasing temperature. At 100 **C,** all four mixtures had a strength loss between 25 and 33%, with Mixture I sustaining a smaller strength loss than the other mixtures. This is followed by a minor strength recovery, and there is essentially no difference in strength loss among the four mixtures at 200. 300, and 450 C. At 600 C, there is a significant additional strength reduction in Mixture IV, and a less significant further strength loss in Mixture I. Data for Mixtures II and III at 600C were not available due to explosive spalling.

Figure 6 shows the decrease in static modulus of elasticity. In contrast to strength loss, there is a general trend of progressive loss of modulus of elasticity with increasing temperature. Since data at elevated temperatures were incomplete (Appendix 1), it was not possible to conduct a rigorous analysis for statistically significant differences among the four mixtures. The incomplete data, however, indicate no difference among the mixtures.

Results of unstressed tests—The normalized compressive strengths and static moduli of elasticity with respect to temperature are shown in Fig. 7 and 8. Because of explosive spalling, data are not available for Mixture I above 300 C or for Mixtures II and III above 450 C. As can be seen from Fig. 7, the compressive strength-temperature relationships for the four HSC mixtures were similar to those observed for the stressed tests. At 100C, all mixtures had significant strength losses, ranging between 26% for Mixture IV and 35% for Mixture II. These relative strength losses are slightly larger than those of the stressed tests at the same temperature. Between 100 and 300 C, there is some strength recovery, and the range of relative strength losses narrowed to between 18 and 26% at 300 C. Note, however, that there was larger scatter at 300 C. At 450 C, there are further strength losses for Mixtures II, III, and IV, and occurrences of explosive spalling in Mixture I. At 600 C, there are strength data only for Mixture IV, which has a total strength loss of 70%. Analysis of variance (ANOVA) showed[24] that the higher mean

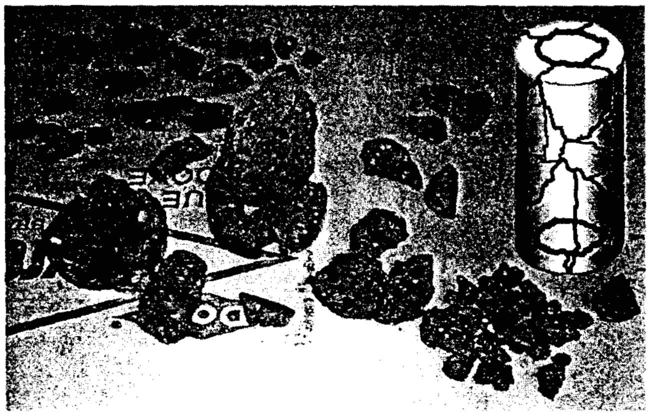
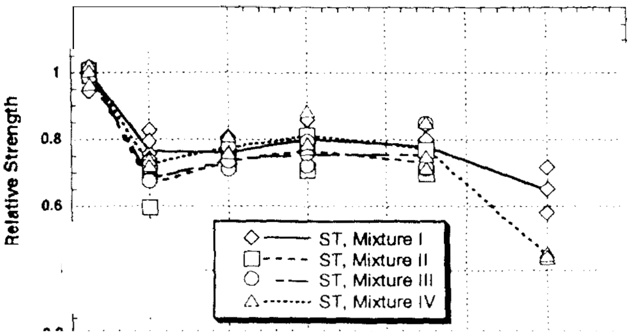


Fig. 4—Remnants of exploded cylinder and rendering of fracture formation.



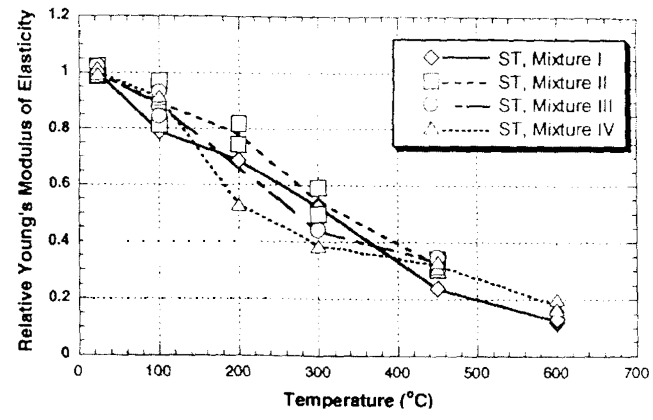


Fig. 6—Relative Young's modulus of elasticity as function of target temperature under unstressed test.

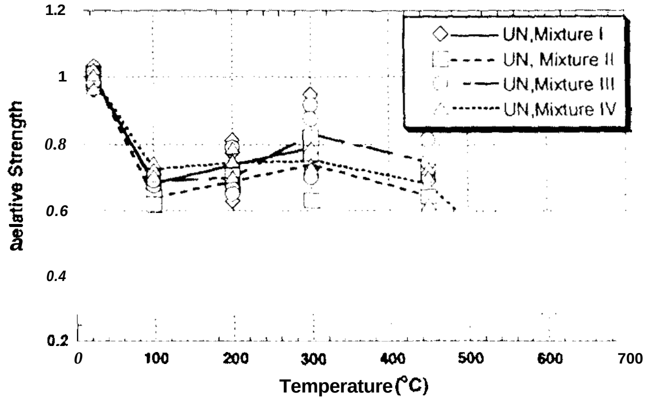


Fig. 7—Relative compressive strengths as function of target temperature under unstressed test.

strengths at 300 C are statistically significant, whereas differences in the mean strengths at 100,200,and 450 C arc not.

Figure 8 shows the static moduli of elasticity decreased progressively with increasing temperatures for all mixtures. The magnitudes of the losses in relative values were similar to those in the stressed tests. In general, the reduction in relative value of elastic modulus was independent of the mixture. The only exception was for heating to 200 C, for which Mixture IV had a slightly greater reduction.

Results of unstressed residual property tests — Normalized compressive strengths and moduli of elasticity are shown in Fig. 9 and 10. Compressive strengths of Mixtures III and IV varied similarly with increasing exposure temperature. Their strength-temperature relationships can be characterized by a strength reduction of between 25 and 30% at 100C, followed by a fairly constant residual relative strength from 100 to 300 C. Further strength loss resumed at above 300 C, and exposure to 450 C caused a 50% strength loss.

Mixtures I and II had similar strength losses of between 10 and 15% at 100 C. For exposure temperatures above 100 C, the strength of Mixture II continued to drop—almost linearly—with increasing temperature, while Mixture I had a higher strength at 200 C. Between 200 and 300 C, the relative strength of Mixtures 1 and II decreased at a similar rate. At 300 C, however, Mixture I sustained only about 13% strength loss, while Mixture II had about 30% loss. At 450 C, Mixture II sustained a strength loss of about 50%, which is similar to Mixtures III and IV. Data for Mixture I at 450 C were not available due to explosive spalling.

Overall, for exposure temperatures of 100,200,and 300 C, Mixture I (lowest *w/cm*) had the highest residual relative strength, Mixtures II and III had similar residual relative strengths, and Mixture IV tended to have the lowest residual strength. Thus, there appears to be **a** relationship between *w/cm* and the residual strength after exposure to elevated temperature. An ANOVA was performed,[24] and the results indicated that the effect of concrete mixture was statistically significant, but the interaction effect of temperature and mixture was also statistically significant. The latter result means that the effect of concrete mixture depends on the exposure temperature.

Since the residual property texts were performed at room temperature. it was possible to obtain the dynamic modulus of elasticity in accordance with ASTM C 215 before and after heating. The dynamic moduli of elasticity for the four mixtures decreased at a similar rate with increasing temperature (Fig. 10), and the losses were similar to the losses in static elastic moduli from the other test conditions. Mixtures II and III displayed almost identical values of relative residual dynamic clastic modulus. Mixture I displayed losses similar to Mixtures II and III, except at 100 C, where the loss was minor. Mixture IV displayed a consistently higher loss at all temperatures.

Table 3—Relative strength values as function of exposure temperature and test condition

Temperature, C	Condition	*n*	Average	S. D.	S. E.
100	Unstressed	12	0.686	0.0399	0.0115
	Residual	12	0.803	0.0815	0.0235
	Stressed	14	0.725	0.0617	0.0165
200	Unstressed	12	0.720	0.0614	0.0177
	Residual	12	0.810	0.1010	0.0292
	Stressed	12	0.758	0.0336	0.0097
300	Unstressed	13	0.781	0.0923	0.0256
	Residual	12	0.735	0.0898	0.02596
	Stressed	12	0.790	0.0525	0.0152
450	Unstressed	9	0.695	0.0707	0.0236
	Residual	9	0.501	0.0288	0.00966
	Stressed	11	0.769	0.0563	0.0170

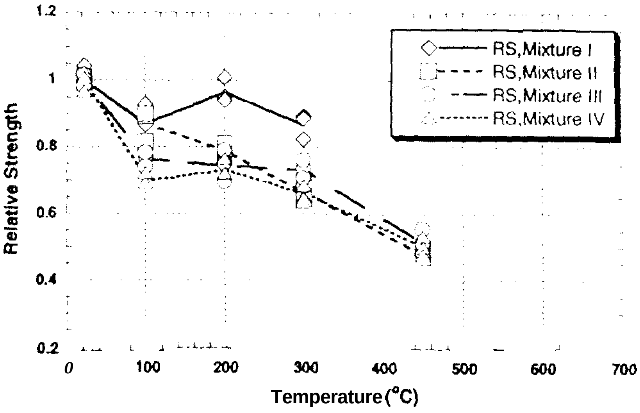


Fig. 9—Relative compressive strengths as function of target temperature under unstressed residual property test

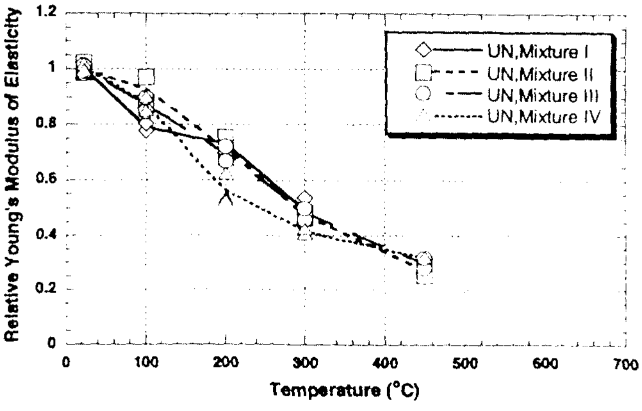


Fig. 8—Relative Young's modulus of elasticity as function of target temperature under unstressed test.

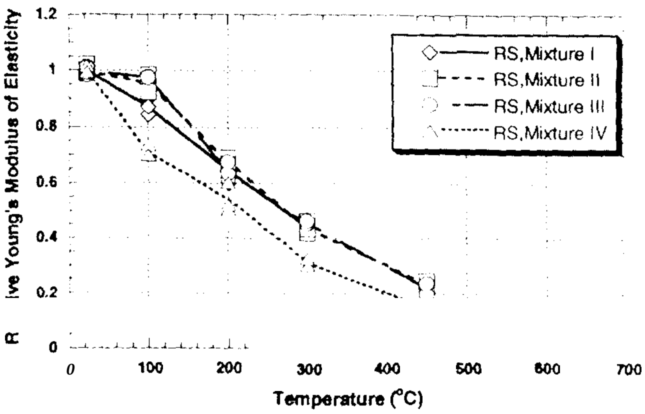


Fig. 10—Relative Young's modulus of elasticity as function of target temperature under unstressed residual property test.

EFFECTS OF TEST CONDITIONS, *w/cm*, AND SILICA FUME

The individual relative strength values reported in Appendixes 1 to 3 were used in the ANOVA to determine the significance of the effects of temperature, test condition, *w/cm*, and silica fume on strength loss.[24] Because specimens in the unstressed residual property test were not heated to 600 C and because of the large number of explosive failures of specimens that were being heated to 600 C for the other two test conditions, there are few test results for this exposure temperature. Hence, test results for 600 C exposure were excluded from the ANOVA. In addition to the four main factors, the significance of two-factor interactions was also examined. The results of the ANOVA indicate that the factors temperature, test condition, *w/cm*, and the interactions temperature-test condition and *w/cm*-test condition were statistically significant. A probability level of 0.05 or less was used to identify statistically significant effects. The elastic moduli values were not analyzed as rigorously as strength because of excessive missing data points.

Effect of test conditions

Individual relative strength values are listed according to the test conditions in Appendixes 1 to 3. The following mean strengths were obtained for the three test conditions for heating to 100, 200, 300, and 450 C:

- Unstressed tests: average relative strength = 0.72;
- Stressed tests: average relative strength = 0.76; and
- Residual property tests: average relative strength = 0.73

Overall, it was found that the stressed test produced the smallest relative strength loss, and there was no statistically significant difference between the losses obtained from the unstressed and residual property tests. As mentioned previously, the ANOVA showed that there were two statistically significant two-factor interactions that involve test condition: temperature-test condition and test condition-*w/cm*. These interactions mean that the effect of test condition depends on the exposure temperature and the *w/cm*. Thus, while the stressed test produced the smallest strength loss on average, this did not apply to all exposure temperatures and values of *w/cm*.

More in-depth analyses were performed by comparing the results for each exposure temperature and for the different values of *w/cm*. Table 3 shows the average relative strength values for the different test conditions grouped according to exposure temperatures (the standard error, SE, is the standard deviation, SD, divided by the square root of the number of individual results). An ANOVA was carried out within each temperature group, and the following summarizes the results:

- For exposure to 100 and 200 C, the residual property test condition resulted in the smallest strength loss, and there was no statistically significant difference in the strength loss obtained with the other two test conditions;
- For exposure to 300 C, there were no statistically significant differences among the strength losses measured by the three test conditions; and
- For exposure to 450 C, the greatest loss was measured in the residual property test condition, and there was no statistically significant difference in the strength loss measured by the other two test conditions.

Table 4—Relative strength as function of *w/cm* and test condition

w/cm	Condition	*n*	Mean	S. D.	S. E.
0.22	Unstressed	10	0.744	0.0950	0.0300
	Residual	9	0.903	0.0613	0.0204
	Stressed	14	0.793	0.0413	0.0110
0.33	Unstressed	24	0.712	0.0828	0.0169
	Residual	24	0.697	0.1318	0.0269
	Stressed	23	0.730	0.0530	0.0111
0.57	Unstressed	12	0.729	0.0446	0.0129
	Residual	12	0.653	0.0946	0.0273
	Stressed	12	0.774	0.0533	0.0154

In a similar way, Table 4 shows the average values of relative strength for the different test conditions grouped according to *w/cm*. An ANOVA was carried out within each *w/cm* group, and the following results were obtained:

- For *w/cm* = 0.22, the smallest strength loss occurred in the residual property test condition, and there was no statistically significant difference between the results for the other two conditions;
- For *w/cm* = 0.33, there were no statistically significant differences among the three conditions; and
- For *w/cm* = 0.57, the averages losses for the conditions were different; the smallest loss was obtained with the stressed test and the greatest loss was obtained with the residual property test.

In summary, the results of the ANOVA show that the test condition has a statistically significant effect on the measured strength loss due to high-temperature exposure. The strength loss measured by a given test condition, however, appears to depend on the exposure temperature and concrete mixture. For the lowest *w/cm (0.22)* and lower exposure temperatures (100 and 200 C), the strength loss measured by the residual property test was the smallest. On the other hand, for higher exposure temperature (450 C) and *w/cm* (0.57), the strength loss was the highest in the residual property test. These results appear to indicate that there is a complex relationship between the strength measured at an elevated temperature and the residual strength measured at room temperature after exposure to the same elevated temperature.

The test condition also appears to influence the tendency for explosive spalling, but no statistical analysis was applied to this observation. As mentioned previously, the presence of stress while the specimens were being heated seems to reduce the tendency for explosive spalling. This is clearly seen in the behavior of the Mixture I specimens (Table 2). None of the cylinders from Mixture I experienced explosive spalling for the stressed tests. This is clearly an area for additional study.

Effect of *w/cm*

The following mean strengths were obtained for the three values of *w/cm*:

- *w/cm* = 0.22: average relative strength = 0.81;
- *w/cm* = 0.33: average relative strength = 0.71; and
- *w/cm* = 0.57: average relative strength = 0.72.

The statistical analysis indicated that, overall, Mixture I (*w/cm* = 0.22) had the lowest strength loss, and there was no statistically significant difference between strength loss for *w/cm* = 0.33 and 0.57. As mentioned previously, there was a statistically significant two-factor effect involving *w/cm* and test condition. Thus, the effect of *w/cm* was not the same for each test condition. The average relative strengths shown in Table 4 were regrouped according to test condition, The results of separate ANOVAs for each test condition indicated the following:

- For the unstressed test, there were no statistically significant differences due to *w/cm*;
- For the residual property test, the strength loss for each *w/cm* was different. The smallest loss was for *w/cm* = 0.22, and the largest loss was for *w/cm* = 0.57; and
- For the stressed test, the strength loss for *w/cm* = 0.27, was less than for *w/cm* = 0.33.

In summary, the ANOVA showed that the effect of *w/cm* on strength loss during high-temperalure exposure depends on the test condition. For the mixtures used in this study, it appears that the strength loss was the smallest for Mixture I with the lowest *w/cm*. This conclusion, however, did not apply to the unstressed test, for which *w/cm* had no statistically significant effect on the strength loss.

As shown in Table 2, the *w/cm* has an effect on the potential for explosive spalling during high-temperature exposure. It is clear that Mixture IV, with *w/cm* = 0.57, was immune to explosive spalling under the test conditions used in this study. From the comparison of incidences of explosive spalling during heating under unstressed conditions, Mixtures II and III (*w/cm* = 0.33) had a lower spalling tendency than Mixture I (*w/cm* = 0.22). This relationship between *w/cm* and propensity for explosive spalling is consistent with the notion that explosive spalling is related to the resistance to water vapor transport.

Effect of silica fume

The ANOVA indicated[24] that the presence of silica fume did not have a statistically significant effect on the strength loss due to exposure to elevated temperatures of 100, 200, 300, and 450 C. The two-factor effect test condition-silica fume had a probability level of 0.0504, which means that the effect of silica fume depended somewhat on the test condition. Further analysis of the data revealed that for the unstressed test condition, Mixtures III and IV without silica fume had less relative strength loss than Mixtures I and II with silica fume. For the other two test conditions, the presence of silica fume had no overall statistically significant effect on strength loss. It was noted, however, that in the residual property tests, mixtures with silica fume exposed to 100 C had significantly less relative strength loss than mixtures without silica fume. For higher exposure temperatures, the differences were not statistically significant.

As shown in Table 2, Mixture II had two more incidences of explosive spalling than Mixture III; however, it is not apparent whether this difference is significant. Thus, there is no clear evidence that the presence of silica fume by itself affects the tendency for explosive spalling.

CONCLUSIONS

Cylinders made from four mixtures of high-strength concrete were subjected to three test conditions commonly used to evaluate the behavior of concrete exposed to elevated temperatures. Exposure temperatures ranged from 100 to 600 C; however, the 600 C results were not used in the data analysis due to the occurrence of explosive spalling in many specimens during heating. A relatively slow heating rate was used to control the thermal gradients within the cylinders. Relative strength, relative elastic modulus, and tendency towards explosive spalling were evaluated. Statistical analysis was used to discern statistically significant effects due to the experimental factors. The following summarizes the conclusions of this study:

1. Measurement of internal temperature histories during heating provided further insights into the heat-induced moisture transport process in high-strength concrete. These measurements revealed consistent perturbations in the rates of temperature rise at the surfaces and centers of the cylinders. These perturbations are believed to be related to the transformations and subsequent transport of free water and chemically combined water. Thus, it is confirmed that accurate modeling of temperature development in concrete needs to take into account the heat-induced moisture transformation and transport;

2. The concrete temperatures at the centers of the cylinders when explosive spalling occurred ranged from 200 to 325 C. The time of explosive spalling appeared to coincide with the time when a high temperature difference existed between the surface and center of the cylinder. This suggests that, while internal pressure may be the primary cause of explosive spalling, the presence of thermally induced stresses may play a secondary, but significant, role in this failure;

3. HSC that carried a preload equal to 40% of the room-temperature strength during heating (stressed test condition) sustained, on average, the smallest strength loss due to temperatures up to 600 C;

4. The relative strength losses measured by the three test conditions differed with exposure temperature. This is indicated by the statistically significant interaction effect involving temperature and test condition. For exposure temperatures of 100 and 200 C, the residual property test condition resulted in the lowest relative strength loss (on the order of 20%, compared with 25 to 30% for the stressed and unstressed conditions). On the other hand, for exposure to 450 C, the relative strength loss was highest for the residual property test condition (on the order of 50%, compared with 25 to 30% for the other conditions). From these results, it can be inferred that there is a complex relationship between the strength measured at elevated temperature and the residual strength measured at room temperature;

5. The HSC mixture with the lowest *w/cm* of 0.22 sustained, on average, the lowest loss in relative strength (approximately 20% compared with approximately 30% for *w/cm* = 0.33 and 0.57);

6. The effect of *w/cm* on relative strength was not the same for each test condition, This is indicated by the statistically significant interaction effect involving *w/cm* and test condition, For the unstressed test condition, there was no statistically significant difference in relative strength loss due to *w/cm*. For the stressed and residual property test conditions, however, Mixture 1 with *w/cm* = 0.22 experienced less loss in relative strength;

7. Overall, the presence of silica fume had no statistically significant effect on the relative strength loss. There was, however, some dependence on test condition. For the unstressed test condition, Mixtures III and IV without silica fume had less strength loss than Mixtures I and II with silica fume. For the other test conditions, the presence of silica fume had no overall statistically significant effects;

8. With respect to explosive spalling, it was observed that the tendency was reduced in the stressed tests in which a compressive stress equal to 40% of the room temperature

strength was maintained during heating. As expected, there was an increase in spalling tendency as the *w/cm* decreased. This is consistent with the notion that the tendency for explosive spalling is related to the resistance to water vapor transport during heating. There was no clear evidence that the presence of silica fume by itself affects the tendency for explosive spalling; and

9. The relationships between relative elastic modulus and temperature were distinctly different from those for relative strength. There was an approximately linear decrease in relative elastic modulus with increasing temperature. Rigorous statistical analyses were not carried out because of too many missing data.

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APPENDIXES

Appendixes 1 to 3 summarize measurements of mechanical properties of HSC at elevated temperature for the three test conditions. In these Appendixes, the test specimens are named using the following convention: test condition: ST = stressed test, UN = unstressed test, and RS = unstressed residual property test; concrete mixture: I, II, III, or IV; target temperature: 23 *to* 600 C; and specimen number: 1, 2, 3....

For example, the name RS-I-200-3 refers to the third replicate specimen of Mixture I that was heated to 200 C and tested using the residual property test condition.

Appendix 1—Summary of stressed test results

1	2	3	4	5	6	7	8	9	10	11	12
	Test name	Preload (.4f_{23} C), MPa	Dynamic E (ASTM C 215-91) Before heating. GPa	SD/CV of dynamic E, GPa/%	Static E **(ASTM** C469-94) at elevated tempera-ture, GPa	SD/CV of static E, GPa/%	Test strength, **MPa**	SDlCV of test strength, MPa/%	Strength loss. %	Mean strength loss, %	Spalling
Mixture I	ST-1-25-1	—	46.33	1 0212 2	44.37	—	101.40	—	0.0	—	—
	ST-1-25-2	—	43.12		45.12	0.57/1.3	94.53	3.44/3.5	0.0	*0.0*	—
	ST-1-25-3	—	45.61		45.49	—	98.39	—	0.0	—	—
	ST-1-100-1	39.18	47.14		—	—	75.97	—	22.6	—	—
	ST-1-100-2	39.18	46.84		—	—	74.36	—	24.2	—	—
	ST-1-100-3	39.18	46.70		—	—	82.94	4.55/5.9	15.5	21.7	—
	ST-1-100-4	39.18	46.20		—	—	79.60	—	18.9	—	—
	ST-1-100-5	39 18	4692		35.56	—	71.26	—	27.4	—	—
	ST-1-200-1	39.18	45.66		—	—	75.61	—	22.9	—	—
	ST-1-200-2	39.18	45 92		—	—	80.67	4.10/5.33	17.8	22.2	—
	ST-1-200-3	39.18	44 11		31.03	—	72.62	—	26.0	—	—
	ST-1-300-1	39.18	—		2383	—	7747	—	21.0	—	—
	ST-1-300-2	39.18	47.03		—	0.2010.8	77.36	5.01/6.2	21.1	18.1	—
	ST-I-300-3	39.18	46.68		23.55	—	86.10	—	12.2	—	—
	ST-I-450-1	39.18	46.42		10.71	—	79.45	—	19.0	—	—
	ST-I-450-2	39.18	46 74		—	—	75.00	2.82/3.6	23.6	20.3	—
	ST-1-450-3	39.18	46.71		—	—	80.23	—	18.2	—	—
	ST-1-600-1	39.18	45.38		5.38	—	71.76	—	26.9	—	—
	ST-1-600-2	39.18	46.41		—	0.40/7.1	65.28	6.88/10.5		33.8	—
	ST-1-600-3	39.18	46.28		5.95	—	58.01	—	40.9	—	—
Mixture II	ST-11-25-1	—	42.03	1 3313 1	39.76	—	88.87	—	0.0	—	—
	ST-11-25-2	—	40.63		39.69	0.81/2.0	87.66	0.82/0.9	0.0	0.0	—
	ST-II-25-3	—	43.15		41.12	—	87.31	—	0.0	—	—
	ST-II-100-1	32.31	41.12		39.01	—	60.94	—	30.7	—	—
	ST-II-100-2	32.31	42.02		—	4.45/12.4	52.43	5.55/9.5	40.4	33.2	—
	ST-11-100-3	32.31	41.62		32.72	—	62.87	—	28.5	—	—
	ST-11-200-1	32.31	43.44		33.01	—	65.62	—	25.4	—	—
	ST-11-200-2	32 31	4401						26.2	26.3	—
	ST-11-200-3	32 31	43 04		30.00	—	63.94	—	**27.3**	—	—
	ST-11-300-I	32 31	45 29						21.6	—	—
	ST-11-300-2	32.31	44.35		23.80	2.66112.1	62.36	4.73/7.0	29.1	23.1	—
	ST-11-300-4	32.31	—		—	—	71.54	—	18.7	—	—
	ST-11-450-1	32.31	43.44		13.75	—	61.44	—	30.1	—	—
	ST-11-450-2	32.31	43.17						23.1	**26.6**	—
	ST-11-450-3	32.31	—		—	—	—	—	—	—	—
					—	—	—	—	—	—	Yes (195 C)
	ST-11-600-2	32.31	44.58		—	—	—	—	—	—	Yes (215 C)
	ST-II-600-3	32.31	—		—	—	—	—	—	—	Yes (203 C)
Mixture III	ST-III-25-1	—	43.55	0.82/1.9	40.53	—	75.43	—	0.0	—	—
	ST-III-25-2	—	42.25		39.36	0.65/1/6	76.54	1.16/1.5	*0.0*	*0.0*	—
	ST-III-25-3	—	43.44		40.44	—	74.23	—	0.0	—	—
	ST-III-100-1	26.68	42.64		36.62	—	52.21	—	30.8	—	—
	ST-III-100-2	26.68	43.48		38.83	1.82/4.9	51.12	0.75/1.5	32.2	31.9	—
	ST-III-100-3	26.68	42.90		35.21	—	50.77	—	32.7	—	—
	ST-III-200-1	26.68	43.16		—	—	53.48	—	29.1	—	—
	ST-III-200-2	26.68	44.90		—	—	55.21	2.56/4.6	26.8	26.1	—
									22.4	—	—
									28.1	—	—
									24.2	24.3	—
									20.7	—	—
	ST-111-450-I	26.68	42.47		—	—	—	—	—	24.2	—
	ST-111-450-2	26.68	43.48		13.36	—	53.59	—	28.9	—	—

Appendix 1 (cant.)-Summary of stressed test results

1	2	3	4	5	6	7	8	9	10	11	12
	Test name	Preload (.4f$_{23}$ C)	Dynamic E (ASTM C 215-91) Before heating, GPa	SD/CV of dynamic E, GPa/%	Static E (ASTM C 469-94) at elevated temperature, GPa	SD/CV of static E, GPa/%	Test strength, MPa	SD/CV of test strength, MPa/%	Strength loss, %	Mean strength loss, %	Spalling
Mixture III	ST-III-450-3	26.68	43.12		14.36	0.71/5.1	63.91	5.90/10.3	15.2	24.2	—
	ST-III-450-4	26.68	—		—	—	53.86	—	28.6	—	—
	ST-III-600-1	26.68	42.71		—	—	—	—			Yes (325 C)
	ST-III-600-2	26.68	—		—	—	—	—			
	ST-III-600-3	26.68	—		—	—	—	—			
Mixture IV	ST-IV-25-1	—	—	0.73/2.0	32.74	—	51.91	—			
	ST-IV-25-2	—	36.45		33.72	0.51/1.5	51.03	1.51/23.0	0.0	0.0	—
	ST-IV-25-3	—	35.39		33.01	—	48.97	—	0.0	—	—
	ST-IV-100-1	18.80	36.86		30.06	—	37.53	—	25.9	—	—
	ST-IV-100-2	18.80	37.38		30.37	0.22/0.7	36.31	0.63/1.7	28.3	27.3	—
	ST-IV-100-3	18.80	37.17		—	—	36.67	—	27.6	—	—
	ST-IV-200-1	18.80	38.14		—	—	38.74	—			
	ST-IV-200-2	18.80	36.79		17.60	—	41.10	1.41/3.6			
					—	—	38.58	—			
					—	—	39.13	—			
					—	—	44.87	3.10/7.5			
					12.81	—	39.99	—			
					10.33	—	43.20	—			
	ST-IV-450-2	18 80	3765		11.04	0 50/4 7	38.04	3.59/9.2	24.9	22.6	—
	ST-IV-450-3	18 80	38 22		—	—	36.30	—	28.3	—	—
	ST-IV 600-1	18 80	38 00		5.85	—	23.13	—	54 3	—	—
	ST-IV-600-2	18 80	38 08		6.71	0.60/9.9	22.10	0.52/2.3	56.4	55 4	—
	ST-IV-600-3	18 80	37 99		5.56	—	22.59	—	55 4	—	—

Appendix 2—Summary of unstressed test results

1	2	3	4	5	6	7	8	9	10	11
	Test name	Dynamic E (ASTM C 215-91) Before heating, GPa	SD/CV of dynamic E, GPa/%	Static E (ASTM C 469-94) at elevated temperature, GPa	SD/CV of static E, GPa/%	Test strength. MPa	SD/CV of test strength, MPa/%	Strength loss, %	Mean strength loss, %	Spalling
Mixture I	UN-I-25-1	46.33	1.44/3.1	44.37	—	101.40	—	0.00	—	—
	UN-I-25-2	43.12		45.12	0.57/1.3	94.53	3.44/3.5	0.00	0.00	—
	UN-I-25-3	45.61		45.49	—	98.39	—	0.00	—	—
	UN-I-100-1	46.44			—	69.64	—	29.02	—	—
	UN-I-100-2	48.26		—	0.83/2.3	62.14	4.46/6.6	36.66	31.42	—
	UN-I-100-3	47.36		36.04	—	70.06	—	28.59	—	—
	UN-I-200-1	—		—	—	79.76	—	18.70	—	—
	UN-I-200-2	46.77		—	—	61.87	9.44/13.0	36.94	26.04	—
	UN-I-200-3	46.80		32.99	—	76.04	—	22.49	—	—
	UN-I-300-1	48.22		—	—	69.80	—	28.85	—	—
	UN-I-300-2	—		—	2.70/12.1	93.18	11.21/14.4	5.02	20.81	—
	UN-I-300-3	46.41		20.32	—	69.11		29.56		—
	UN-I-300-4	45.55		24.14	—	78.67	—	19.81	—	—
	UN-I-450-1	46.06		—	—	—	—	—	—	Yes (280 C)
	UN-I-450-2	46.67		—	—	—	—	—	—	Yes (310 C)
	UN-I-450-3	43.78		—	—	—	—	—	—	Yes (305 C)
Mixture II	UN-II-25-1	42.03	1 2312 8	39.76	—	88.87	—	0.00	—	—
	UN-II-25-2	40.63		39.69	0.81/2.0	87.66	0.82/0.9	0.00	0.00	—
	UN-II-25-3	43.15		41.12	—	87.31	—	0.00	—	—
	UN-II-100-1	43.88		39.00	—	58.06	—	33.98	—	—
	UN-II-100-2	44.M		35.40	2.55/6.8	56.50	1.77/3.1	35.76	35.91	—
	UN-II-100-3	42.33		—	—	54.53	—	38.00	—	—
	UN-II-200-1	43.03		30.28	—					
	UN-II-200-2	44.13		27.36	1.46/5.1	62.08	1.25/2.1	29.41	30.93	—
	UN-II-200-3	45.36		28.73	—	59.61	—	32.22	—	—
	UN-II-300-1	44.75		19.43						
	UN-II-300-2	42.52		18.65						
	UN-II-300-3	—		—	—	68 18	—	22 48	—	—
	UN-II-450-1	43.40		10.11	—	56 66	—	35 58	—	—

l	2	3	4	5	6	7	8	9	10	11
	Test name	Dynamic E (ASTM C 215-91) Before heating, GPa	SD/CV of dynamic E, GPa/%	Static E (ASTM C 469-94) at elevated temperature, GPa	SD/CV of static E. GPa/%	Test strength, MPa	SD/CV of test strength. MPa/%	Strength loss, %	Mean strength loss, %	Spalling
Mixture 11	UN-11-450-2	44 43	1.23/2.8	11 81	—	63 10	—	28 25	—	—
	UN-II-450-3	43 43		—	1.20/11 0	—	5 97/10.5	—	35 21	Yes (245 C)
	UN-II-450-4	—		—	—	51.18	—	41.81	—	—
	UN-II-600-1	—		—	—	—	—	—	—	Yes
	UN-II-600-2	—		—	—	—	—	—	—	Yes (240 C)
	UN-II-600-3	—		—	—	—	—	—	—	Yes (230 C)
Mixture III	UN-III-25-1	43 55	0.66/1.5	40.53	—	75.43	—	0.00	—	—
	UN-III-25-2	42 25		39.36	0.65/1.6	76.54	1.16/1.5	0.00	0.00	—
	UN-111-25-3	4344		40.44	—	74.23	—	0.00	—	—
	UN-III- 100-1	43 05		—	—	50.83	—	32.59	—	—
	UN-III- 100-2	42 I4		33 97	1.37/3.9	52.07	1.32/2.5	30.94	30 87	—
	UN-III-100-3	43.61		35.91	—	53.47	—	29.09	—	—
	UN-III-200-1	41.79		28.28	—	50.24	—	33.37	—	—
	UN-III-200-2	43.60		28.83	1.09/3.9	59.61	5.82/11.0	20.94	29.80	—
	UN-III-200-3			26.73	—	48.95	—	35.08	—	—
	UN-III-300-1			19.96	—	69.16	—	8.28	—	—
	UN-III-300-2	43.41		18.37	0.92/4.7	66.14	8.69/13.9	12.28	16.83	—
	UN-III-300-3	44.02		19.97	—	52.83	—	29.93	—	—
	UN-III-450-1	42.84		11.51	—	52.28	—	30.66	—	—
	UN-III-450-2	42.97		11.12	0.83/7.1	61.45	4.60/8.1	18.50	24.84	—
	UN-III-450-3	42 85		12.72	—	56.28	—	25.36	—	—
	UN-111-600-1	43.44		—	—	—	—	—	—	Yes (200 C)
	UN-III-600-2	42.80		—	—	—	—	—	—	Yes (205 C)
	UN-III-600-3	43.00		—	—	—	—	—	—	—
Mixture IV			1.69/4.5	32.74	—	51.91	—	0.00	—	—
				33.72	0.51/1.5	51.03	1.51/3.0	0.00	0.00	—
				33.01	—	48.97	—	0.00	—	—
				28.23	—	37.86	—	25.23	—	—
				29.82	1.12/3.9	36.74	1.05/2.8	27.44	27.34	—
				—	—	35.77	—	29.36	—	—
	UN-IV-200-1	38.07		20.67	—	40.01	—	20.99	—	—
	UN-IV-200-2	37.20		17.81	1.78/9.5	35.73	2.14/5.6	29.44	25.14	—
	UN-IV-200-3	—		17.41	—	37.98	—	25.00	—	—
	UN-IV-300-1	43.07		13.47	—	37.60	—	25.75	—	—
	UN-IV-300-2	37.56		14.07	0.42/3.1	40.05	1.62/4.2	20.91	25.54	—
	UN-IV-300-3	36.96		—	—	36.99	—	26.95	—	—
	UN-IV-450-1	37.36		10.63	—	31.41	—	37.97	—	—
	UN-IV-450-2	38.62		—	—	37.03	3.0/8.5	26.87	31.37	—
	UN-IV-450-3	37.45		—	—	35.81	—	29.28	—	—
	UN-IV-600-1	37.66		—	—	15.23	—	69.92	—	—
	UN-IV-600-2	36.81		—	—	17.23	1.41/8.7	65.97	67.95	—
	UN-IV-600-3	36.27		—	—	—	—	—	—	—

Appendix 3—Summary of residual property test results

1	2	3	4	5	6	7	8		9	10	11	12	13
							Dynamic E (ASTM C 215)						
	Test name	Mass loss, %	SD/CV of mass loss, %	Test strength, MPa	Residual strength, %	Mean/SD/CV of residual strength. MPa/MPa/%	Before heating, GPa	After heating. GPA	Residual dynamic E, %	SDlCV of residual dynamic E. %	Static E (ASTM C 469) after heating, GPa	$\frac{E_{dyn}}{E_{static}}$	Spalling
Mixture I	RS-I-25-1	0	—	90 56	97.9	—	47.30	—	100 3	—	44.37	1.07	—
	RS-I-25-2	0	—	90.60	97.9	100/3 64/3 6	47.10	—	99.9	0 23/0.23	45.12	1.04	—
	RS-I-25-3	0	—	96.40	104.2	—	47.10	—	99.9	—	45.49	1.04	—
	RS-I-100-1	1.02	—	75.64	81.8	—	46.06	34.70	75.3	—	37.98	0.91	—
	RS-I-100-2	0.75	0.14/15.8	80.34	86.8	87.2/5.56/6.4	44.10	37.60	85.3	5.86/7.1	40.59	0.93	—
	RS-I-100-3	0.84	—	85.92	92.9	—	42.40	36.30	85.6	—	39.19	0.93	—
	RS-I-200-1	4.38	—	93.29	100.8	—	44.60	29.77	66.7	—	27.04	1.10	—
	RS-I-200-2	3.57	0.41/10.5	87.84	94.9	96.6/3.66/3.8	46.79	34.46	73.6	3.52/5.0	29.72	1.16	—
	RS-I-200-3	3.85	—	87.08	94.1	—	46.72	33.35	71.4	—	30.32	1.10	—
	RS-I-300-1	6.19	—	82.85	89.5	—	46.06	20.19	43.8	—	—	—	—

Appendix 3 (cent.)-Summary of residual property test results

1	2	3	4	5	6	7	8		9	10			
							Dynamic E (ASTM C 215)						
	Test name	Mass loss, %	SD/CV of mass loss, %	Test strength, MPa	Residual strength, %	Mean/SD/CV of residual strength, MPa/MPa/%	Before heating, GPa	After heating, GPA	Residual dynamic E, %	SD/CV of residual dynamic E, %	(ASTM C 469) after heating, GPa	$\frac{E_{dyn}}{E_{static}}$	Spalling
Mixture I	RS-I-300-2	—	—	—	—	—	46.99	—	0.0	—	—	—	Yes (235 C)
	RS-I-300-3	6.02	0.10/1.73	—	—	87.0/3.80/4.4	45.43	19.65	43.3	0.60/1.4	—	—	—
	RS-I-300-4	6.07	—	76.41	82.6	—	47.11	19.97	42.4	—	19.68	1.01	—
	RS-I-300-5	5.94	—	82.19	88.8	—	47.18	20.52	43.5	—	20.14	1.02	—
	RS-I-450-1	—	—	—	—	—	48.13	—	0.0	—	—	—	Yes (240 to 280 C)
	RS-I-450-2	—	—	—	—	—	46.52	—	0.0	—	—	—	Yes (240 to 280 C)
	RS-I-450-3	—	—	—	—	—	45.94	—	0.0	—	—	—	Yes (240 to 280 C)
Mixture II	RS-II-25-1	0	—	88.87	101.1	—	43.20	—	98.9	—	39.76	1.09	—
	RS-II-25-2	0	—	87.66	99.7	100.0/0.95/0.9	43.90	—	100.5	0.99/1.0	39.69	1.11	—
	RS-II-25-3	0	—	87.31	99.3	—	44.00	—	100.7	—	41.12	1.07	—
	RS-II-100-1	1.22	—	78.53	89.3	—	42.50	39.39	92.7	—	39.65	0.99	—
	RS-II-100-2	1.13	0.07/5.8	79.11	90.0	87.0/4.66/5.4	41.70	39.24	94.1	1.50/1.6	38.52	1.02	—
	RS-II-100-3	1.09	—	71.78	81.6	—	43.60	39.70	91.1	—	37.16	1.07	—
	RS-II-200-1	6.03	—	67.75	77.0	—	43.44	28.58	65.8	—	27.23	1.05	—
	RS-II-200-2	5.08	0.47/8.6	69.84	79.4	79.2/2.06/2.6	42.93	30.95	72.1	3.19/4.6	27.80	1.11	—
	RS-II-200-3	5.55	—	71.32	81.1	—	43.74	29.78	68.1	—	26.85	1.11	—
	RS-II-300-1	8.09	—	58.84	66.9	—	44.00	18.84	42.8	—	16.84	1.12	—
	RS-II-300-2	7.80	0.15/1.8	56.62	64.4	67.0/2.60/3.9	43.12	19.81	45.9	0.90/2.0	17.39	1.14	—
	RS-II-300-3	7.91		61.22	69.6		43.00	20.05	46.6		18.57	1.08	—
	RS-II-300-4	—	—	—	—	—	43.41	—	0.0	—	—	—	Yes (250 C)
	RS-II-450-1	9.16	—	41.32	47.0	—	43.61	11.34	26.0	—	9.16	1.24	—
	RS-II-450-2	9.30	1.12/11.4	43.78	49.8	48.0/1.59/3.3	45.04	11.25	25.0	0.53/2.1	9.27	1.21	—
	RS-II-450-3	11.17	—	41.40	47.1	—	43.61	11.00	25.2	—	9.87	1.11	—
Mixture III	RS-III-25-1	0		75.43	100.0	—	44.10	—	100.0	—	40.53	1.09	—
	RS-III-25-2	0		76.54	101.5	100.0/1.55/1.6	43.40	—	98.4	1.60/1.6	39.36	1.10	—
	RS-III-25-3	0		74.23	98.4	—	44.80	—	101.6	—	40.44	1.11	—
	RS-III-100-1	0.83		58.12	77.1	—	41.99	38.55	91.8	—	39.20	0.98	—
	RS-III-100-2	0.69	0.10/12.3	55.94	74.2	75.6/2.15/2.8	41.30	40.64	98.4	3.32/3.5	39.23	1.04	—
	RS-III-100-3	0.88		59.08	78.4	—	40.50	38.80	95.8	—	39.17	0.99	—
	RS-III-200-1	6.73		59.58	79.0	—	43.28	27.97	64.6	—	24.69	1.13	—
	RS-III-200-2	6.18	0.29/4.5	52.47	69.6	74.6/4.73/6.3	42.46	30.47	71.8	3.95/5.7	25.47	1.20	—
	RS-III-200-3	6.30		56.73	75.2	—	41.93	29.79	71.0	—	27.00	1.10	—
	RS-III-300-1	8.09		55.54	73.7	—	42.36	19.35	45.7	—	18.04	1.07	—
	RS-III-300-2	7.54	0.30/3.9	57.52	76.3	73.7/2.65/3.6	43.10	20.80	48.3	1.36/2.9	18.47	1.13	—
	RS-III-300-3	7.61		53.50	71.0	—	43.58	20.79	47.7	—	—	—	—
	RS-III-450-1	9.31		41.75	55.4	—	43.34	11.65	26.9	—	9.32	1.25	—
	RS-III-450-2	8.54	0.44/4.9	36.60	48.5	51.8/3.47/6.7	45.00	11.67	25.9	0.58/2.2	7.82	1.49	—
	RS-III-450-3	9.31		38.72	51.4	—	43.26	11.64	26.9	—	9.42	1.24	—
Mixture IV	RS-IV-25-1	0	—	51.91	102.5	—	36.70	—	101.4	—	32.74	1.12	—
	RS-IV-25-2	0	—	51.03	100.8	100.0/2.98/3.0	36.45	—	100.8	1.93/1.9	33.72	1.08	—
	RS-IV-25-3	0	—	48.97	96.7	—	35.39	—	97.8	—	33.01	1.07	—
	RS-IV-100-1	1.33	—	35.21	69.5	—	37.17	30.54	82.2	—	24.36	1.25	—
	RS-IV-100-2	0.88	0.24/21.0	35.16	69.4	70.4/1.59/2.3	37.04	30.98	83.6	0.70/0.8	23.09	1.34	—
	RS-IV-100-3	1.27	—	36.58	72.2	—	37.51	31.08	82.9	—	23.16	1.34	—
	RS-IV-200-1	9.53	0.34/3.7	38.82	76.7	—	36.45	18.47	50.7	—	16.75	1.10	—
	RS-IV-200-2	8.96	—	36.45	72.0	73.6/2.66/3.6	36.50	23.20	63.6	6.59/11.1	20.00	1.16	—
	RS-IV-200-3	8.94	—	36.58	72.2	—	37.25	22.17	59.5	—	17.30	1.28	—
	RS-IV-300-1	9.59	0.92/9.0	34.91	68.9	—	36.62	12.73	34.8	—	9.94	1.28	—
	RS-IV-300-2	9.93	—	33.15	65.5	66.5/2.09/3.1	37.03	15.26	41.2	3.64/9.3	10.77	1.42	—
	RS-IV-300-3	11.33	—	32.96	65.1	—	36.67	15.03	41.0	—	—	—	—
	RS-IV-450-1	11.96	—	27.06	53.4	—	36.68	7.96	21.7	—	5.00	1.59	—
	RS-IV-450-2	12.30	0.34/2.9	25.46	50.3	50.6/2.71/5.4	36.30	7.84	21.6	0.32/1.5	4.90	1.60	—
	RS-IV-450-3	11.61	—	24.29	48.0	—	37.36	8.29	22.2	—	5.08	1.63	—