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Effect of elevated temperatures on the residual mechanical properties of high-performance mortar

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Abstract

The effect of high temperature on the mechanical properties of high-strength mortar was investigated. Specimens were heated up to elevated temperatures (300, 600, 900 °C) without loading. After being exposed to these oven temperatures, the residual modulus of elasticity, flexural strength and compressive strength of the specimens were determined. The effect of the rate of heating, duration of exposure to maximum temperature and the role of graphite powder, which is known as a high-temperature refractory material on the behavior of the mortar specimens, were observed. Temperatures up to 600 °C resulted in considerable losses in mechanical properties, and at 900 °C, specimens lost almost all of their strength. Higher rate of heating and exposure to the maximum temperature for a shorter period of time resulted in higher residual properties. The useful effect of graphite addition on the residual compressive strength and modulus of elasticity of the mortar specimens as percentages of initial values for each of the heating cycles are clearly observed.

Keywords: Mortar; Compressive strength; Elastic moduli; Residual properties; Temperature

1. Introduction

Occasionally, concrete structures are subjected to high temperatures (reactor vessels, thermal shock, fire, coal gasification vessels, some industrial applications, etc.). In most cases, such elevated temperatures result in considerable damage to concrete structures and masonry walls. Recently, high-strength concrete and high-strength mortar are widely used in different parts of civil engineering structures. As they become more commonly used, the risk of being exposed to high temperatures also increases. Thus, better understanding the behavior of high-strength mortar at high temperatures gains importance for predicting the properties and behavior of both the masonry walls and the high-strength concrete elements in civil engineering structures.

The factors that influence the strength of mortar and concrete upon heating are mainly grouped as material and environmental factors. Material factors include aggregate, aggregate–cement paste bond, thermal incompatibility between components of the composite and properties of cement paste. On the other hand, environmental factors include heating rate, duration of exposure to maximum temperature, cooling rate, loading conditions and moisture regime, which are also important when the behavior of mortar and concrete specimens at high temperatures is studied. The effects of material and environmental factors were investigated by Khoury [1], Sarshar and Khoury [2], Hertz [3] and Ahmed et al. [4].

Previous studies have shown that strength and modulus of elasticity of hardened cement paste, mortar and concrete specimens decreased with the increase in temperature [5–7]. Dias et al. [5] have shown that at high temperatures beyond 300 °C, both strength and elastic modulus of hardened cement paste dropped markedly. In a recent study, Xu and Chung [6] have seen that sand addition decreased the specific heat and increased the thermal conductivity of cement paste. Studies on mechanical properties of mortar that was exposed to high temperatures have shown that, like in the case of hardened cement paste, strength and Young's modulus of mortar specimens decreased with increasing temperatures [7]. Recently, many studies have been conducted on the behavior of high-performance concrete at elevated temperatures [8,9]. Chan et al. [8] have shown that

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at elevated temperatures, compressive strength of both the normal- and high-strength concretes dropped by more than 60% when the specimens were heated up to 800 °C. The effect of high temperatures on modulus of elasticity was similar to that on the compressive strength [9]. Flexural strength, on the other hand, is more affected by elevated temperatures than compressive strength [10–12].

Graphite is unique in its position among materials of construction, resembling both metals and ceramics in some of its properties. Its low thermal expansion, in combination with its high thermal conductivity and strength at high temperatures, makes it most resistant to thermal shock of any material. However, no previous study was encountered in the literature on the use of graphite for improving the temperature resistance of mortar or concrete. Nishikawa and Takatsu [13], on the other hand, used graphite powder in cement paste and observed its effect on the strength and fracture properties of the cement pastes at room temperature.

2. Experimental details

2.1. Materials and mixtures

Mixture proportioning designs and fresh properties of the mortars are given in Table 1. G5 specimens had graphite powder to cement ratio of 5% by weight and G0 specimens had no graphite content. In G5 mixture, the fine part of the sand (sieved from 0.5-mm sieve) was replaced by the quantity of the graphite added. Fresh densities were determined immediately after mixing, which was followed by the flow test performed according to ASTM C230.

ASTM Type I Portland cement, commercial grade silica fume from Norway, river sand, graphite powder, which is a byproduct obtained in an industrial process for producing bearing from raw carbon graphite, and a superplasticizer conforming to ASTM C494 for Type B/D/G were used in the production of the mortar. The sand (fineness modulus of 3.8, specific gravity of 2.6 and water absorption of 1.5%) and graphite powder with maximum particle size of 500 μm and bulk specific gravity of 0.57 had well-graded size distributions. The thermal conductivity is about 0.53 W/m K for cement paste and 0.58 W/m K for mortar [6]. On the other hand, the thermal conductivity of graphite is about 14 W/m K [11]. The coefficients of thermal expansions of sand and cement paste are 11×10^{-6} and 16×10^{-6} per °C, respectively [10]. Graphite has a coefficient of thermal expansion of 3.5×10^{-6} per °C [14].

All test batches were mixed using an electrically driven mechanical mixer conforming to the requirements of ASTM C305. Test specimens were cast from the same batch into prismatic (40 × 40 × 160 mm) and cylindrical (50 × 100 mm) steel moulds. The specimens were kept in the moulds for 24 h at room temperature of 20 °C. After demoulding, the specimens were left 6 days in a curing bath of 22 ± 1 °C and then in a curing room at a temperature of 20 °C and relative humidity of 55 ± 5% until testing.

Table 1
Mixture proportioning and fresh properties of mortars

	Weight (kg/m^3)	
Ingredients	G0	G5
Cement	494	494
Sand	1482	1457
Graphite	0	25
Sand + graphite	1482	1482
Silica fume	49	49
Water	190	190
Superplasticizer	12	15
Water–cement ratio	0.38	0.38
Water–binder ratio	0.35	0.35
Graphite–cement ratio	0	5
Fresh density (g/cm^3)	2.24	2.16
Flow (ASTM C230) (%)	80	80

2.2. Testing of the specimens

The effect of elevated temperatures on the mechanical properties of high-strength mortars with none and 5% graphite powder (G0, G5) was investigated. Mortar specimens were exposed to 300, 600 and 900 °C and the resultant properties are compared with the properties of mortars at 20 °C. The effects of the rate of heating (2 and 8 °C/min) and the duration of exposure to maximum temperature (1 and 10 h), as well as the effect of graphite content (none and 5%) on the properties of the mortar specimens, were observed.

All of the specimens were tested on the 28th day. A furnace that was capable to operate up to 1400 °C had been used. A step-by-step heating had been used for each thermal cycle to set the desired rate of heating. A typical heating cycle is shown in Fig. 1.

Each time, three prisms and three cylinders were put into the furnace so that they did not touch each other and the walls of the furnace. The furnace was automatically shut off at the end of the set exposure time and the specimens were not taken out until the furnace cooled down to room temperature, after which they were taken out and tested. The cooling rate of the furnace was about 0.4 °C/min. The compressive strength, static modulus of elasticity and flexural strength of the specimens have been investigated for their residual values.

Compressive strength was measured using 50 × 100-mm cylinders according to ASTM C39. In compression test, loading rate was 0.25 MPa/s, which is within the range that is specified by ASTM C39. For each heating cycle, three cylinders were tested. During compression test, the stress–strain data were recorded using a computer-aided data acquisition system where the load and deformations were measured by a load cell and an electronic dial gage, respectively. The static modulus of elasticity was calculated from stress–strain data under compression according to ASTM C469. For flexural strength of the mortars, 40 ×

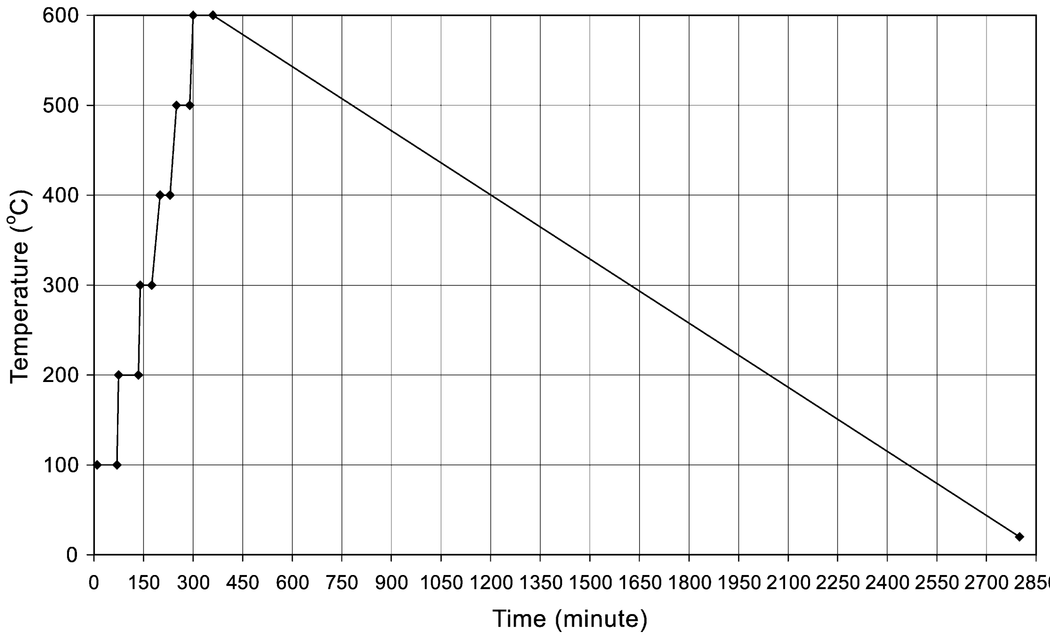

Fig. 1. An example of programming a heating cycle (maximum temperature = 600 °C, rate of heating = 2 °C/min, exposure time at maximum temperature = 1 h).

40 × 160-mm prisms were tested according to ASTM C348. In bending test, central point loading was used and the span length was 120 mm. For each heating cycle, three prisms were tested.

3. Test results and evaluations

The test results have shown that elevated temperatures had important effects on the mechanical properties of G0 and G5 specimens. Although the general trends of the influence of high temperatures on mortar properties were similar, residual compressive and flexural strengths, as well as modulus of elasticity, were affected differently by differences in heating rate and period of exposure to the maximum temperature. Exposure to 900 °C had detrimental effects on the physical and mechanical properties of mortar specimens. When the specimens were taken out of the furnace after they have been cooled from 900 °C, hair cracks were clearly visible on their surfaces. After these specimens were stored for 1 day in the curing room, it was observed that G0 specimens had been completely disintegrated by themselves and large cracks were observed on G5 specimens, as seen in Fig. 2.

3.1. Residual compressive strength

The residual compressive strengths of heated G0 and G5 specimens are shown in Table 2. Graphite powder addition resulted in decrease of compressive strength of mortars at room temperature, as also observed by Nishikawa and Takatsu [13]. Fig. 3 shows these values as percentages of the compressive strengths of the unheated G0 and G5 specimens. Test results have shown that G0 specimens lost 12–29% of their initial compressive strengths at 300 °C. These results agreed fairly well with those obtained by other researchers for similar test conditions [7]. On the other hand, for G5 specimens, the strength losses were between 0% and 15% of the initial compressive strength of unheated specimens at 300 °C. As seen in Fig. 3, especially for rate of heating of 8 °C/min and exposure time of 1 h at 300 °C, G5 specimens retained all of their initial compressive strengths where G0 specimens have lost 12% of their initial strengths. This result can be attributed to the expected stabilizing

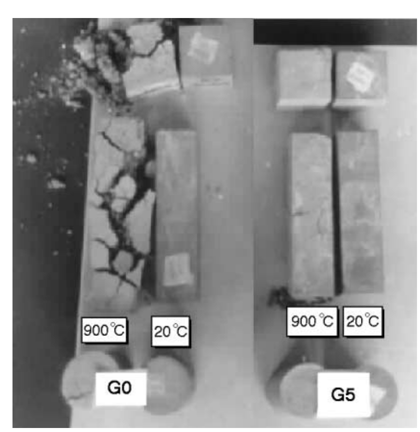

Fig. 2. G0 and G5 specimens that were exposed to 900 °C and stored for 1 day in curing room.

Table 2
Residual mechanical properties of mortars for each heating cycle

Maximum temperature (°C)	Rate of heating °C/min	Exposure time (h)	Compressive strength (MPa)				Modulus of rupture (N/mm^2)				Static modulus of elasticity (MPa)			
			G0		G5		G0		G5		G0		G5	
			Specimens	Mean	Specimens	Mean	Specimens	Mean	Specimens	Mean	Specimens	Mean	Specimens	Mean
20	0	0	61.8	62.9	43.7	44.3	11.40	11.46	8.78	8.45	34286	33,727	18555	17,887
			63.6		44.0		11.12		8.34		32827		17718	
			63.3		45.2		11.86		8.23		33528		17388	
300	2	1	47.2	48.8	38.8	37.7	6.85	7.26	6.43	6.45	18488	19,182	14765	13,051
			49.7		36.8		7.29		6.85		18756		10952	
			49.5		37.5		7.64		6.07		20302		13436	
300	2	10	46.5	44.7	39.5	39.3	7.46	7.29	5.56	5.45	20613	19,101	11212	10,123
			45		40.3		7.11		5.22		18718		9534	
			42.6		38.1		7.29		5.56		17972		9623	
300	8	1	54.9	55.3	46.3	44.3	9.38	9.73	6.95	6.95	21314	22,536	18525	17,361
			58.3		44.9		10.07		6.85		24284		15195	
			52.7		41.7		9.73		7.05		22010		18364	
300	8	10	51.5	50.7	41.1	40.4	7.94	7.76	5.20	5.55	24239	21,671	13486	14,397
			49.5		40.8		7.64		5.56		19260		13065	
			51.2		39.3		7.70		5.90		21515		16640	
600	2	1	22.5	23.8	18.6	20.0	1.74	1.85	1.74	1.78	3165	3542	3913	3529
			22.8		20.5		2.08		1.54		2820		3004	
			26.1		20.9		1.74		2.06		4642		3670	
600	2	10	22	21.7	21.1	17.8	1.74	1.62	1.54	1.49	3877	3422	3354	3200
			20.8		16.2		1.74		1.39		2700		2819	
			22.3		16.1		1.39		1.54		3690		3427	
600	8	1	32.2	30.8	22.1	19.6	3.13	2.55	2.43	2.20	5628	6030	3035	3410
			28.6		19.1		2.43		1.74		6930		3920	
			31.6		17.6		2.09		2.43		5532		3275	
600	8	10	22.9	24.4	15.1	16.9	1.74	1.51	1.74	1.51	4146	4241	2830	3389
			26.8		18.9		1.74		1.39		4900		3480	
			23.5		16.7		1.04		1.39		3677		3857	
900	2	1	7.7	8.0	7.7	7.9	0.69	0.81	0.69	0.93				
			8.2		7.2		0.69		0.90					
			8.1		8.8		1,04		1.21					
900	2	10	6.8	6.5	6.8	7.1	0.69	0.69	0.69	0.76				
			6.1		7.6		0.69		0.69					
			6.6		6.9		0.69		0.90					
900	8	1	9.3	9.0	8.6	8.1	1,04	0.81	1.04	1.18				
			8.6		7.9		0.69		1.04					
			9.1		7.8		0.69		1.46					
900	8	10	7.3	7.0	8.2	8.0	0.69	0.69	0.69	0.69				
			7.0		6.7		0.69		0.69					
			6.7		9.1		0.69		0.69					

effect of graphite on the residual strength of mortar that was exposed to elevated temperatures because of its high thermal conductivity and low coefficient of thermal expansion. After 300 °C, the residual compressive strengths of G0 and G5 specimens fell markedly. This has been attributed to the development of microcracks due to the differences in thermal expansion of sand particles and cement paste, as well as the decomposition of the calcium hydroxide within the cement paste [15]. Fig. 3 shows that at 600 °C, about 51–65% of the strength at room temperature had been lost for G0 specimens, whereas G5 specimens lost about 55–62% of their initial compressive strength. With further increase in temperature up to 900 °C, the specimens lost about 90% of their initial strengths and a change in their color to pink was observed.

3.2. Residual flexural strength

The modulus of rupture of the heated G0 and G5 prismatic specimens is given in Table 2. Graphite powder addition resulted in decrease of flexural strength of mortars at room temperature, which is in good agreement with the results obtained by Nishikawa and Takatsu [13]. The variations of the residual flexural strength as percentage of the unheated specimens with temperature for various heating rates and exposure times are illustrated in Fig. 4. The deteriorating effect of elevated temperatures on flexural strength of high-strength mortars was more severe than on compressive strength. This may be due to the fact that the microcracks that form in the specimens at elevated temperatures were more destructive when the specimens were

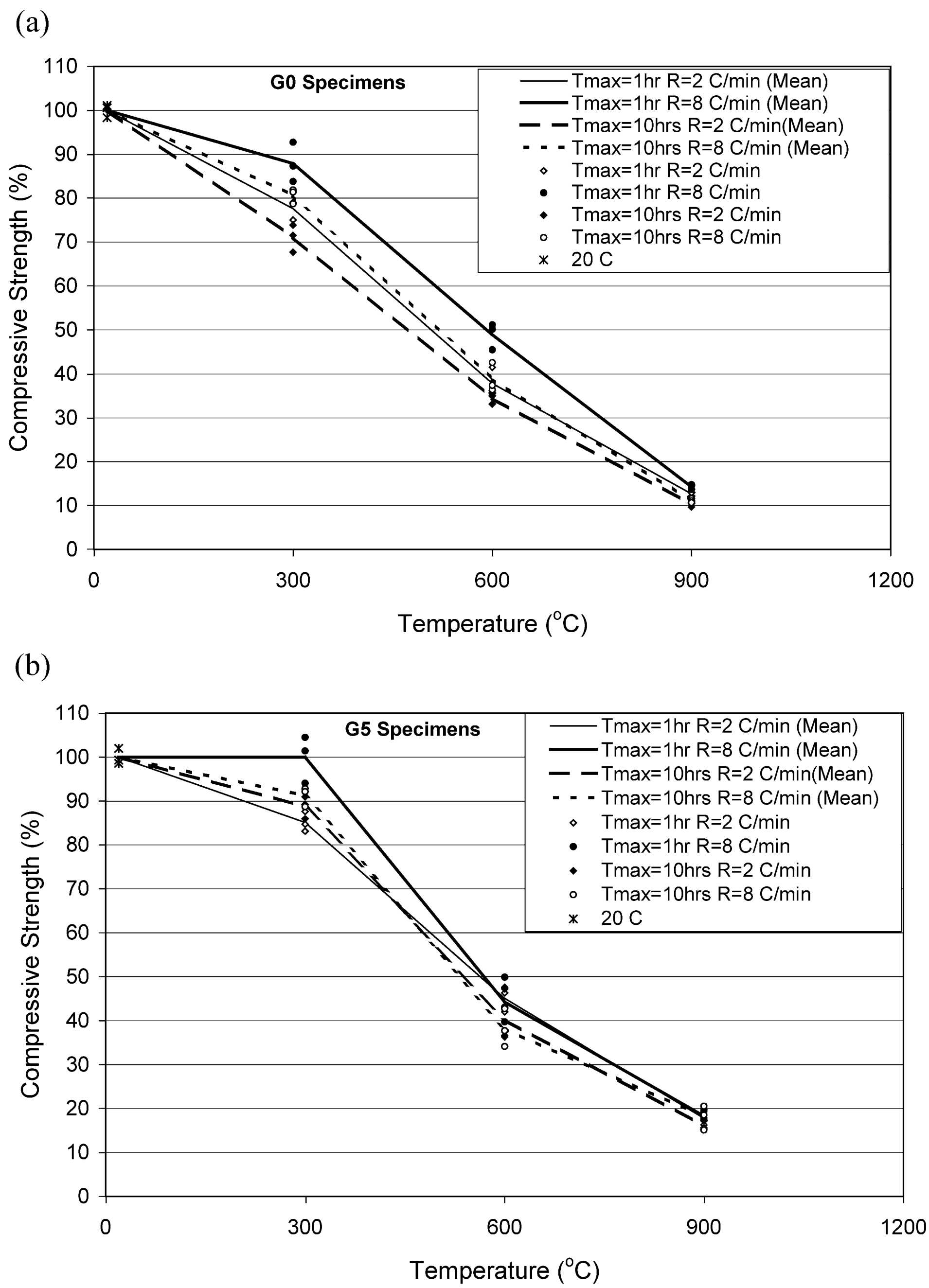

Fig. 3. Residual compressive strengths of (a) G0 and (b) G5 mortar specimens for different heating cycles.

subjected to tensile stresses. At 300 °C, flexural strength of G0 specimens dropped to about 64% of the initial value. However, the specimens, exceptionally, retained about 85% of their initial strengths when the rate of heating was 8 °C/min and the exposure time was 1 h. Similarly, residual flexural strength of G5 specimens that were exposed to 300 °C dropped to about 65% of the initial value. After 300 °C, flexural strengths of G0 and G5 specimens for each heating cycle dropped markedly. At 600 °C, the losses in flexural strengths reached up to 87% for G0 specimens and 82% for G5 specimens in terms of the initial unheated strengths. Moreover, at 900 °C, G0 and G5 specimens lost more than 90% of their initial flexural strengths. These results agreed fairly well with those obtained by other researchers for similar test conditions [11,12].

3.3. Residual static modulus of elasticity

Table 2 shows that static modulus of elasticity of the high-strength mortars showed considerable decreases at

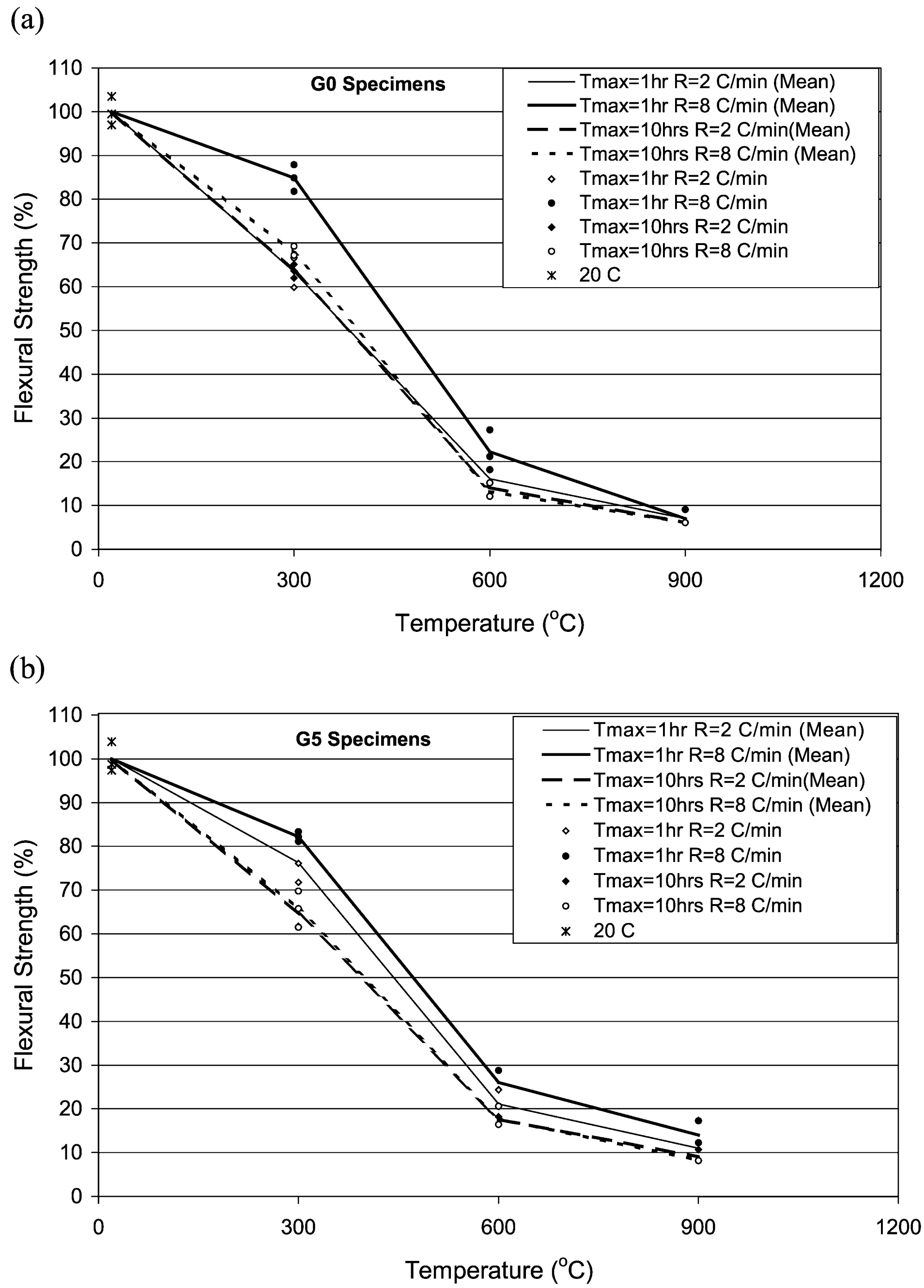

Fig. 4. Residual flexural strength of (a) G0 and (b) G5 mortar specimens for different heating cycles.

elevated temperatures. As it can be seen from Fig. 5, for G0 specimens, maximum of 67% of the modulus of elasticity of the unheated specimens was retained at 300 °C. On the other hand, G5 specimens retained up to 97% of their initial static modulus of elasticity at 300 °C. At 600 °C, G0 specimens could only retain about 10–18% of the initial modulus of elasticity. Similarly, G5 specimens retained about 18–20% of their initial modulus of elasticity after being exposed to 600 °C. When the specimens were exposed to 900 °C, they lost their strength so much that it was not possible to accurately measure the static modulus of elasticity of the cylindrical specimens. For both G0 and G5 specimens, the losses in modulus of elasticity were larger than the losses in compressive strengths for the same heating cycles.

3.4. Effect of rate of heating

Figs. 3–5 show that high-strength mortars retained more strength at elevated temperatures when they are heated fast. G0 and G5 specimens, which have been exposed to 300 and 600 °C, retained up to 10% and 15% more residual compressive strength when they were heated at a rate of

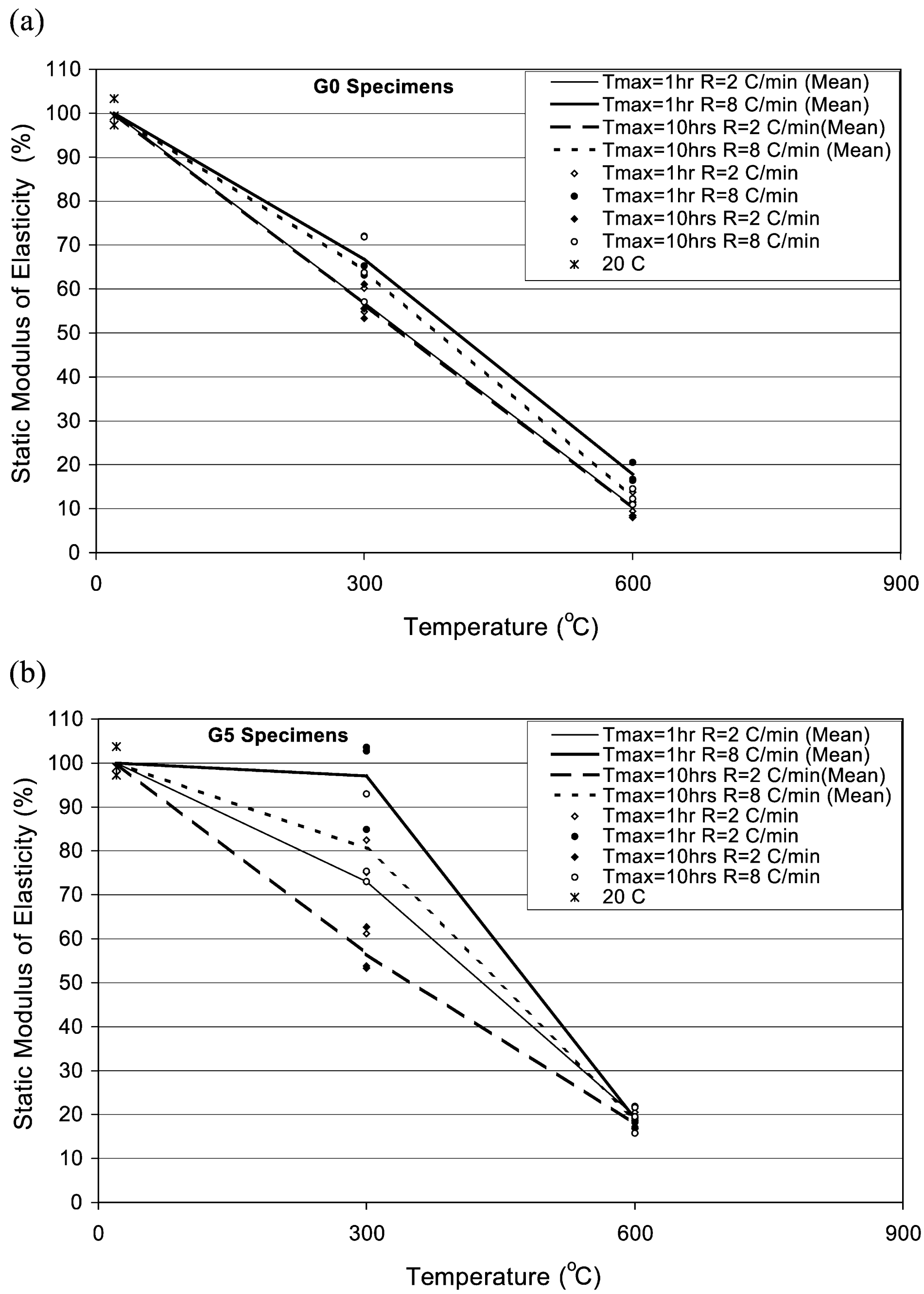

Fig. 5. Residual static modulus of (a) G0 and (b) G5 mortar specimens for different heating cycles.

8 °C/min instead of 2 °C/min, as seen in Fig. 3. At 900 °C, the results did not depend on the rate of heating and mortar specimens lost almost all of their original strength after being exposed to this very high temperature.

3.5. Effect of exposure time at maximum temperature

Figs. 3–5 show that for all of the mechanical properties of G0 and G5 specimens, short (1 h) exposure at maximum temperature resulted in less loss of strength in comparison with the long (10 h) exposure time. In Fig. 3, it is clearly seen that 1-h exposure of G0 specimens at maximum temperature of 300 °C resulted in 7% less loss in compressive strength in comparison with the long exposure time (10 h) for both slow- and fast-heating cases.

4. Conclusions

(1) For high-performance mortars with none and 5% graphite, serious drops in compressive strength started at 300 °C, and at 900 °C, specimens lost almost all of their

initial compressive strengths. At 300 °C, up to 29% of the initial compressive strength was lost and this value reached 65% at 600 °C.

(2) The specimens that were exposed to elevated temperatures showed higher decrease in flexural strength than compressive strength. When exposed to 300 °C, high-strength mortars showed losses up to 36% in flexural strength, and at 600 °C, losses reached up to 87% of the initial flexural strength. When the temperature increased up to 900 °C, almost all of the flexural strength was lost.

(3) With increasing temperature, linear decreases in static modulus of elasticity of G0 and G5 specimens were seen. At 300 °C, the loss reached 44% of the initial value, and at 600 °C, specimens retained maximum 20% of the initial static modulus. At 900 °C, the retained static modulus of elasticity was negligible.

(4) For the mechanical properties studied, fast-heated specimens showed better results than the slow-heated ones. Also specimens showed better residual properties when exposure time at maximum temperature was 1 h instead of 10 h. When the exposure time and the rate of heating were both considered, best results were recorded when rate of heating was faster (8 °C/min) and exposure time was shorter (1 h).

(5) For the mechanical properties studied, 5% graphite content in high-strength mortar specimens increased the residual mechanical properties as percentages of initial values for each of the heating cycles. The effect of graphite was more significant especially for compressive strength and static modulus of elasticity at 300 °C. The losses at 300 °C were approximately 12% and 16% lower, respectively, in the mortar specimens containing 5% graphite powder. This has been explained as that graphite that has low coefficient of thermal expansion in comparison with sand and hardened cement paste reduced the amount of microcracks, which occur due to the differences in thermal expansion of sand particles and the cement paste.

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