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EFFECT OF ELEVATED TEMPERATURE ON COMPRESSIVE STRENGTH OF BLENDED CEMENT MORTAR

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Abstract

An experimental investigation was conducted to evaluate the performance of blended cement mortars exposed to elevated temperature. The blended cement used in this investigation was ordinary Portland cement (OPC), metakaolin (MK) and silica fume (SF). The mortars had binder : sand ratios of 1: 5.23. Eighteen different mixtures were designed to have a mortar flow of 94 ± 5 %. Three specimens from each mix were tested for compressive strength at ambient temperature, control sample. The other specimens were exposed to a gradual increase in temperature up to 200 °C, 400 °C, 600 °C and 800 °C for over two hours in an electrical symmetrical furnace to determine the residual strength. It has been concluded that MK and SF improve compressive strength before and after exposure to elevated temperature. The ternary blend of 10% MK, 10% SF and 80 % OPC yields the optimum improvement in compressive strength. While as for the binary replacement, the optimum improvement of the compressive strength was achieved by using 20% SF.

Keywords: elevated temperature resistance; silica fume; metakaolin, mortar; blended cement

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

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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 of the behavior of high-strength mortar at high temperatures gains importance for predicting the mortar properties.

Mineral additions for the manufacturing of concrete generally include both natural pozzolans of volcanic origin and artificial pozzolans such as fly ash and silica fume. Currently, other alternatives to these materials are being investigated using clay minerals (i. e., kaolinite, montmorillonite, illite that can be thermally activated by dehydration in the temperature range of 700 to 800 °C). The most typical example is kaolin, which upon heating produces metakaolin (MK). The properties of MK as a pozzolanic material have been reported previously [1 – 5]. Also, the influence of curing temperature on reaction rate constants and on the behavior and stability of hydration phases have been studied [6]. MK shows a high level of pozzolanic activity, similar to SF. For this reason, it is very important to quantify the heat evolution during hydration in MK/cement systems. Also, as reported by Gruber et al. and Boddy et al., the performance of concrete incorporating MK, at appropriate replacement levels, is similar to that of concrete containing silica fume [4 – 5]. When used as a partial replacement for OPC, metakaolin is capable of reacting with portlandite to form supplementary calcium-silicate-hydrate (C-S-H) similar in composition and structure to those obtained from Portland cement [7].

Metakaolin has also been used for making cementitious materials called hydroceramics, i.e. ceramic-like materials synthesized from a solid aluminosilicate and an alkali-rich solution at low temperature, < 100 °C. It has been reported that metakaolin of high lime reactivity (6 – 7.5 MPa) can be produced by thermal decomposition of kaolin, a naturally occurring clay basically containing kaolinite [Al_2O_3-$Si_2O_5(OH)_4$] mineral and trace of silica and other minerals which can be blended with high quantity of fly ash (over 45 %) lime and industrial gypsum to form strong binder of low leachability [8 – 9].

In the particular case of MK, it appears to have excellent potential as an active addition for producing mortars and concretes [10]. However, this material shows a particular nature in its chemical and mineralogical composition. The hydrated phases (C_2ASH_8 and C_4AH_{13}), formed during the pozzolanic reaction at early curing periods, tend to be present as metastable phases. With longer curing times, the conversion of these hydrates to hydrogarnet (stable phase) can be expected [11]. This transformation will depend on different factors (for example, temperature reached inside the specimen).

Metakaolin is typically incorporated into concrete to replace 5 % to 20 %, by mass. MK improves concrete performance by reacting with calcium hydroxide to form secondary C-S-H. Because of its white color, high-reactivity MK does not darken concrete as SF typically does (the white-colored SF is very limited in tonnage), which makes it suitable for color-matching and other architectural applications [12 – 13].

Since the early 1970s, silica fume, a by-product of the silicon metal and ferrosilicon alloy industries, has been used as a mineral admixture in concrete to enhance strength and low permeability. There are other properties that are favourably affected by the incorporation of silica fume, including: modulus of elasticity [14] drying shrinkage [15] bonding (concrete steel) [16] and resistance to reinforcing steel corrosion and sodium sulfate attack due to low permeability to water and chloride ions [17 – 18]. However, there are some unfavourable properties associated with the addition of silica fume to concrete, such as loss of slump and reduction in ductility [19]. During the last 10 years, the use of silica fume in cement and concrete has increased. The application of silica fume as a mineral admixture in concrete is almost a routine nowadays for the production of tailor-made high-performance concretes [20 – 26].

The aim of the current research work is to determine the effect of elevated temperature on compressive strength of blended cement mortar containing MK and SF used in binary and ternary blends with Portland cement. The cement replacement was 0 %, 5 %, 10 %, 20 % and 30 %, by mass of binder.

Experimental details

An experimental program was designed to investigate the residual compressive strength of blended cement mortar containing MK and SF following exposed to elevated temperatures. For this purpose, 18 mortar mixtures were prepared with 0 %, 5 %, 10 %, 20 % and 30 % combinations of MK and SF, by mass of cement. Each mix comprised five groups. The first group was tested directly in ambient temperature to determine the compressive strength after curing. The second, third, fourth and fifth groups were tested after two hours exposure at 200 °C, 400 °C, 600 °C and 800 °C respectively.

Materials

Cement

The cement used in this research was OPC complying with ASTM C-150 requirements Type I. The chemical composition and physical properties of OPC are shown in Table 1.

Kaolin

A sample of kaolin (K) clay collected from Sina quarry was ground to a Blaine fineness of 3 500 cm^2/gm. Figure 1 shows the diffractograms of the K sample analyzed by X-ray diffraction.

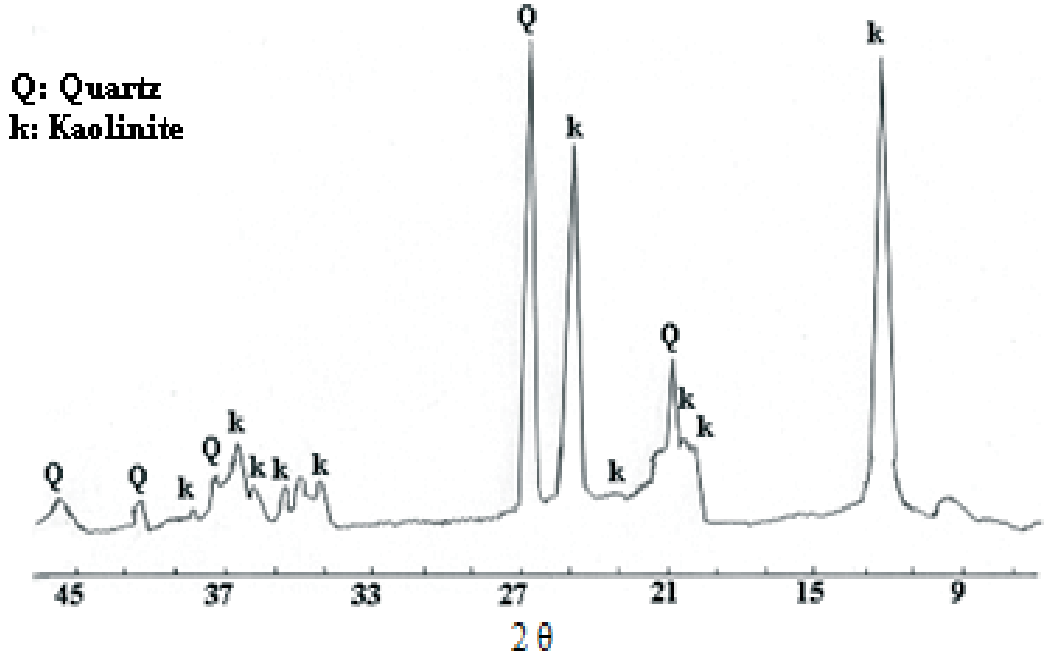

Figure 1. X- Ray Diffraction of Kaolin

Metakaolin

The ground clay samples; kaolin, were thermally treated in an electrical furnace at 850 °C for a period of 2 hours then cooled gradually. Figure 2 shows the diffractograms of MK sample analyzed by X-ray diffraction. The chemical compositions and physical properties of these materials are shown in Table 1.

Silica Fume

Silica fume was supplied from our local Egyptian production. Its chemical oxide compositions and physical properties are given in Table 1.

Sand

Natural sand was used with nominal size of 5 mm, specific gravity of 2.65 and volumetric weight of 1.57 t/m^3. The gradation of fine aggregate satisfied ASTM C 33 requirements.

Preparation of Cement Mortar, Testing and Evaluation

The cement mortars were cast using 5 x 5 x 5 cm cubes. The blended cement and standard triple graded sand in the proportion 1 : 5.23 by weight at 94 ± 5 % flow

Table 1. Chemical Compositions and Physical Properties of Cementitious Materials

Chemical composition (%)	**OPC**	**MK**	**SF**
SiO_2	20.39	58.52	96.1
Al_2O_3	5.6	35.54	0.5
Fe_2O_3	3.43	1.15	0.7
CaO	63.07	1.24	0.21
MgO	2.91	0.19	–
Na_2O	0.38	0.25	0.31
K_2O	0.35	0.05	0.49
SO_3	0.7	0.06	0.1
C_3A	9.04	–	–
P_2O_5	–	0.09	–
TiO_2	–	0.04	–
Loss on ignition	2.06	2.74	1.14
Specific gravity	3.15	2.34	2.32
Specific surface (cm^2/gm)	2500	3500	225000

[27]. After 24 hours moist curing, the cubes were demoulded and cured in water until testing. The mix proportions of the 18 mortar mixtures are shown in Table 2.

Mixtures of Cement–Metakaolin-Silica Fume

The OPC was partially substituted by combination mixtures of metakaolin and silica fume with 5, 10, 15, 20 and 30 %, by mass of OPC.

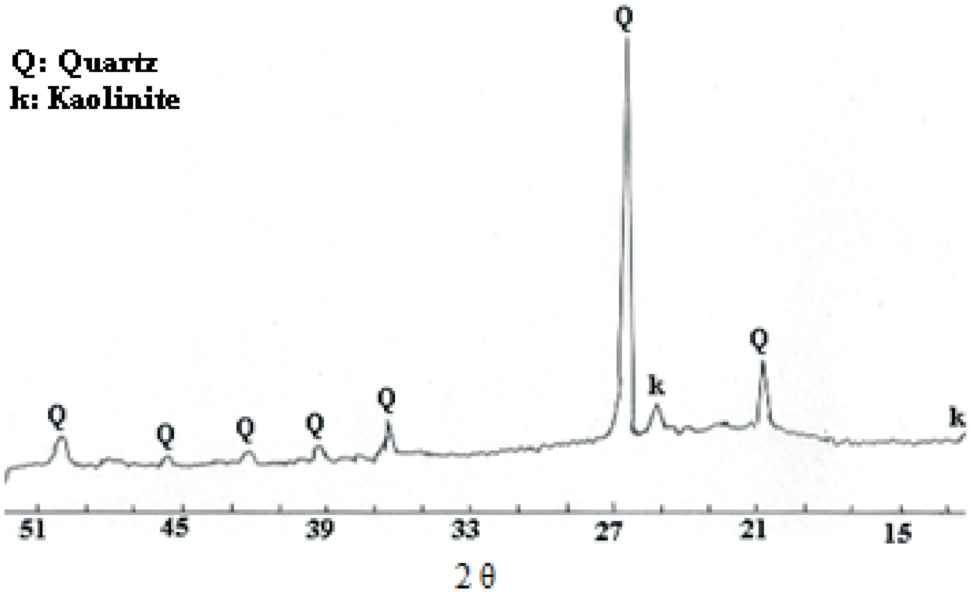

Figure 2. X- Ray Diffraction of Metakaolin

Table 2. Proportions of Mortar Mixtures

Mix	Blended Cement			Batched quantities (kg/m^3)				Water Binder Ratio
				Blended Cement				
	% OPC	% MK	% SF	OPC	MK	SF	Sand	
M0	100	0	0	300	0	0	1570	1.082
M51	95	5	0	285	15	0	1570	1.0502
M52	95	0	5	285	0	15	1570	0.9867
M101	90	10	0	270	30	0	1570	1.140
M102	90	5	5	270	15	15	1570	0.9867
M103	90	0	10	270	0	30	1570	1.0
M201	80	20	0	240	60	0	1570	0.9957
M202	80	15	5	240	45	15	1570	0.9973
M203	80	10	10	240	30	30	1570	1.0342
M204	80	5	15	240	15	45	1570	1.0673
M205	80	0	20	240	0	60	1570	1.1323
M301	70	30	0	210	90	0	1570	1.062
M302	70	25	5	210	75	15	1570	1.0607
M303	70	20	10	210	60	30	1570	1.0763
M304	70	15	15	210	45	45	1570	1.1333
M305	70	10	20	210	30	60	1570	1.1827
M306	70	5	25	210	15	75	1570	1.1333
M307	70	0	30	210	0	90	1570	1.3156

Curing and Heating Regimes

The specimens were demolded after 24 h of casting and cured under water at 25 °C in a water tank. After 28 days of water curing, they were transferred to an environmental chamber maintained at 25 °C and 75 % relative humidity. The specimens were dried at 105 °C for 24 hours then thermally treated in an electric furnace at 200, 400, 600 and 800 °C for 2 hours to achieve the thermal steady state [28]. The heating rate was set at 2.5°C/min based on the experience of our previous research [29]. The specimens were allowed to cool naturally to the room temperature.

Test results and discussion

There are three test methods available for finding the residual compressive strength of concrete subjected to elevated temperatures: stressed test, unstressed test, and unstressed residual strength test. The first two tests are suitable for assessing strength during high temperatures, while the later is excellent for finding the residual properties after exposure to high temperature. It was found that the last method can lead to the lowest strength and may be more suitable for getting the limiting values for residual strength, and hence it was selected for this research [30].

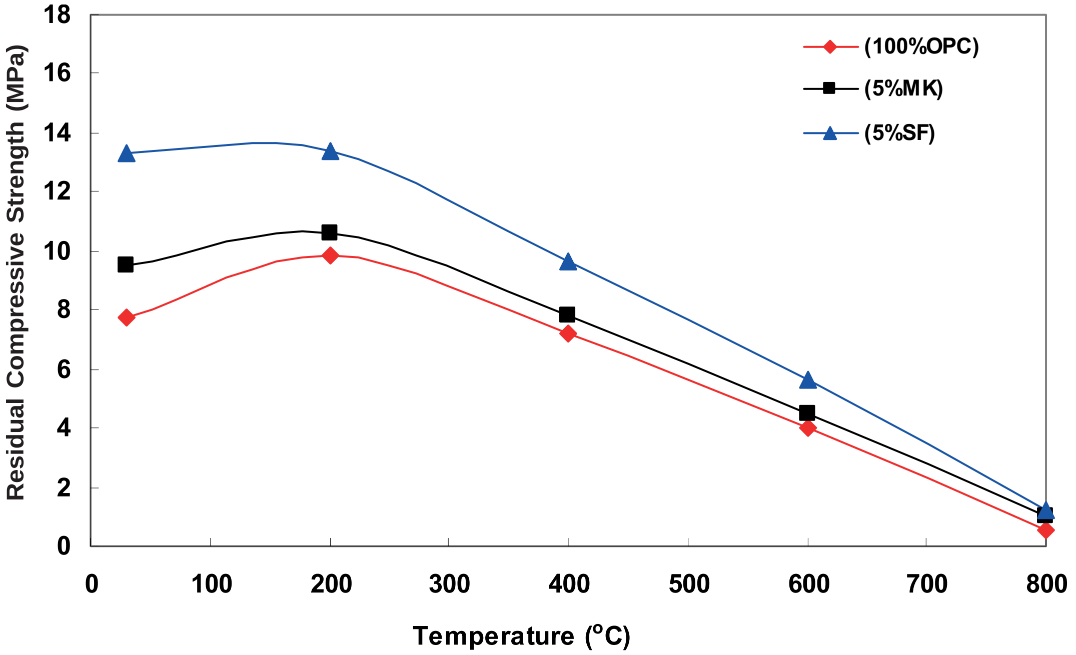

Figure 3. Residual Compressive Strength of Control and Blended Mortars of 5 % Replacement Exposed to Elevated Temperature

Figure 3 illustrates the residual compressive strength of control and blended cement mortars with 5 % pozzolana replacement exposed to elevated temperature. It is clear that, the residual compressive strength increases as the treatment temperature increases up to 200 °C then it decreases as the treatment temperature increases up to 800 °C.

Obviously, the blended cement mortars of mixes showed an increase in compressive strength at 200 °C. This increase may be due to the hydration of unhydrated MK and/or SF particles which were activated as a result of temperature rise. A similar increase in strength was observed in 100 % OPC mortar. This increase may be due to further hydration of unhydrated cement grains as a result of steam effect under the condition of the so-called internal autoclaving formed in cement paste [31]. The residual compressive strength of blended cement mortar is better than the control mortar. The pozzolanic activity of this silica fume is more than this metakaolin. This is due to the plain surface area of silica fume is greater than that of metakaolin. However, the replacement of OPC by 5 % SF and/or MK, improved the residual compressive strength of mortars.

Figure 4 shows the residual compressive strength of control and blended cement mortars of 10 % pozzolana replacement exposed to elevated temperature. The residual compressive strength increases as the treatment temperature increases up to 200 °C, then it decreases as the treatment temperature increases up to 800 °C. However, the replacement of OPC by MK and SF can improve the residual compres-

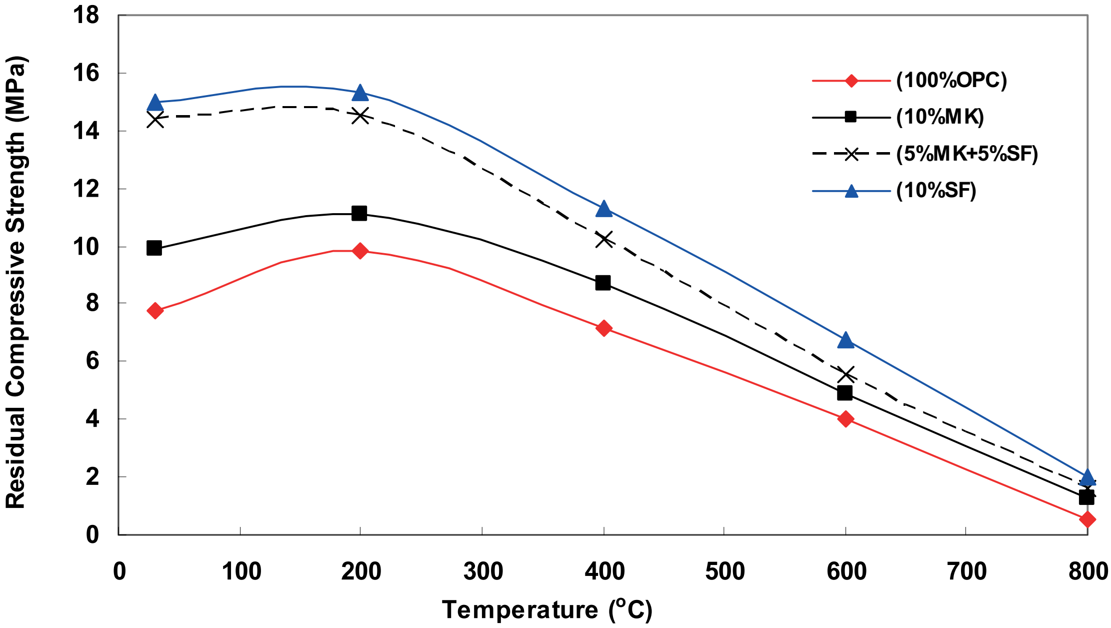

Figure 4. Residual Compressive Strength of Control and Blended Mortars of 10 % Replacement Exposed to Elevated Temperature

sive strength of blended cement mortars after exposure to elevated temperature. Evidently, the increases of compressive strength are due to the internal autoclaved process in OPC mortar; which leads to hydration of unhydrated cement grains. The improvement in residual compressive strength of the blended cement mortar is due to the pozzolanic activity. The decreases in residual compressive strength are due to dehydration of hydrated cement product. The residual strength depends on the type and the percentage of pozzolanic mixtures.

The replacement of OPC by 10 % SF proves to be the most effective replacement to improve residual compressive strength. The combination of 5 % MK and 5 % SF replacement of OPC has lower residual strength than 10 % SF. In blended cement mortar containing 10 % MK, the residual strength is lower than 10 % SF and combination of 5 % MK and 5 % SF.

Figure 5 demonstrates the residual compressive strength of control and blended cement mortars of 20 % pozzolana replacement exposed to elevated temperature. It is clear that, the residual compressive strength of control and blended mortars of 20 % pozzolana replacement exposed to elevated temperature increases as the exposure temperature increases up to 200 °C followed by a gradual decrease as the temperature increases up to 800 °C. The replacement of OPC by 20 % pozzolana, by an equal combination of MK and SF (10 % MK + 10 % SF), gave the optimum residual compressive strength. The replacement of OPC by 20 % SF also gave the optimum residual compressive strength. The replacement of OPC, by a combination

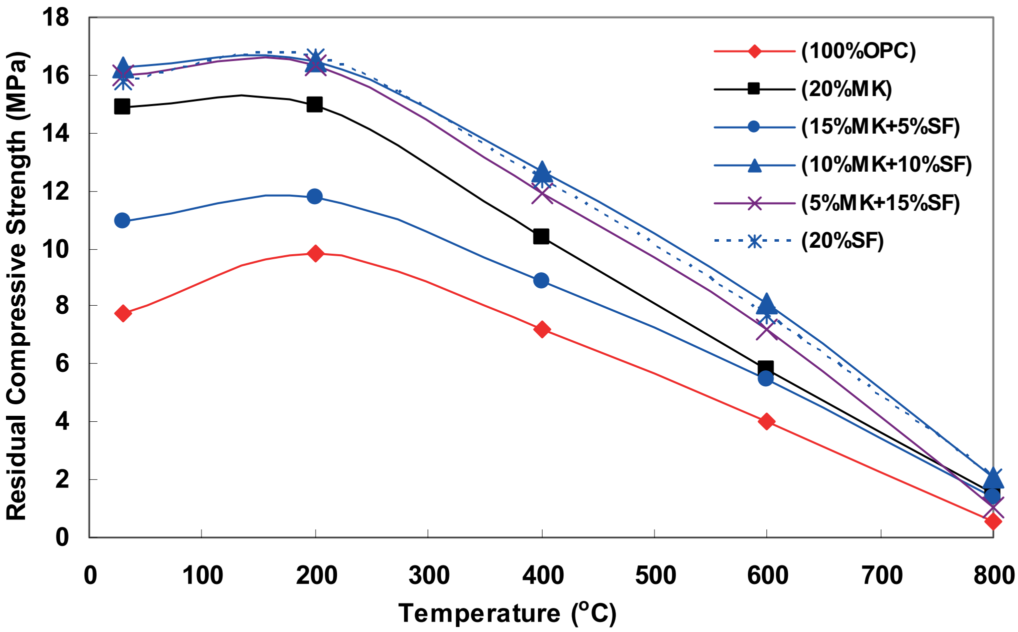

Figure 5. Residual Compressive Strength of Control and Blended Mortars of 20% Replacement Exposed to Elevated Temperature

of 5 % MK and 15 % SF showed a higher residual compressive strength than the separate replacement of 20 % MK and the combination replacement of 15 % MK and 5 % SF.

Figure 6 shows the residual compressive strength of control and blended cement mortars containing 30 % pozzolana replacement exposed to elevated temperature. It is clear that, the residual compressive strength corresponding to mortar of different combinations of MK and SF subjected to different exposure temperatures increases as the temperature increases up to 200 °C then it decreases as the temperature increases up to 800 °C. The combination of 5 % MK and 25 % SF seemed to be the optimum cement replacement that gave the maximum residual strength. Where 30 % separate cement replacement with SF came in the second place. The combination of 10 % MK and 20 % SF, combination of 20 % MK and 10 % SF came in the third and fourth place respectively. The equal combination of MK (15 %) and SF and separate replacement of MK came in the fifth place. The pure OPC mortar came in the sixth place. Finally, the combination of 25 % MK and 5 % SF came in the last place according to their residual compressive strength.

Figure 7 collects the maximum mixtures plotted through Figures 3 to 6. It is clearly apparent that the optimum replacement of OPC by 20 % as equal combinations of MK and SF and by separate replacement of SF. The combination of 25 % MK and 5 % SF came in the second place. The separate OPC replacement by 10 % SF came in the third place. Finally, 5 % SF came in the last place.

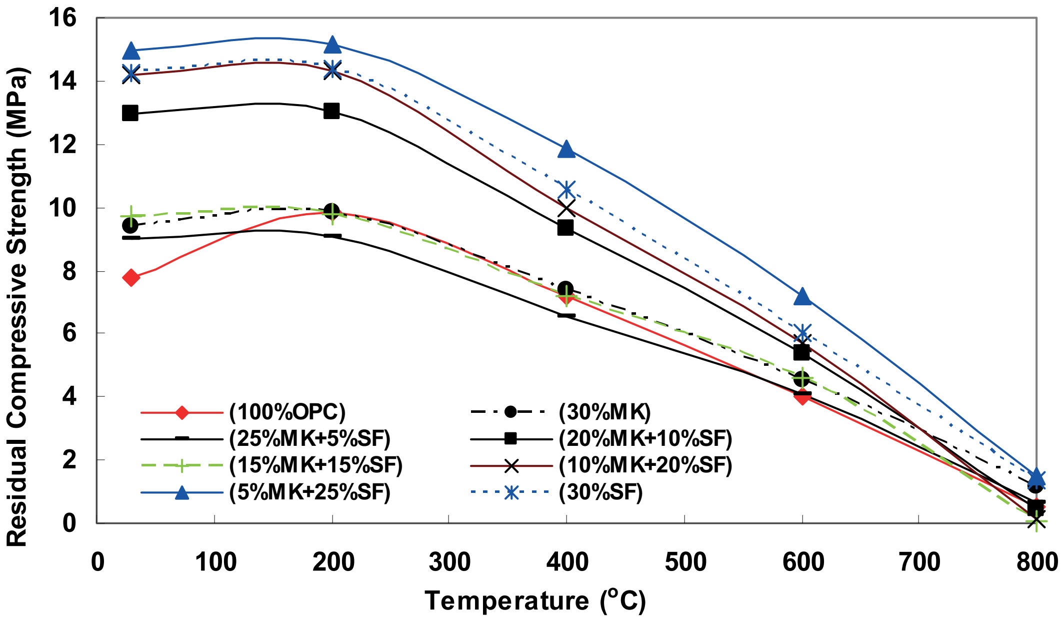

Figure 6. Residual Compressive Strength of Control and Blended Mortars of 30 % Replacement Exposed to Elevated Temperature

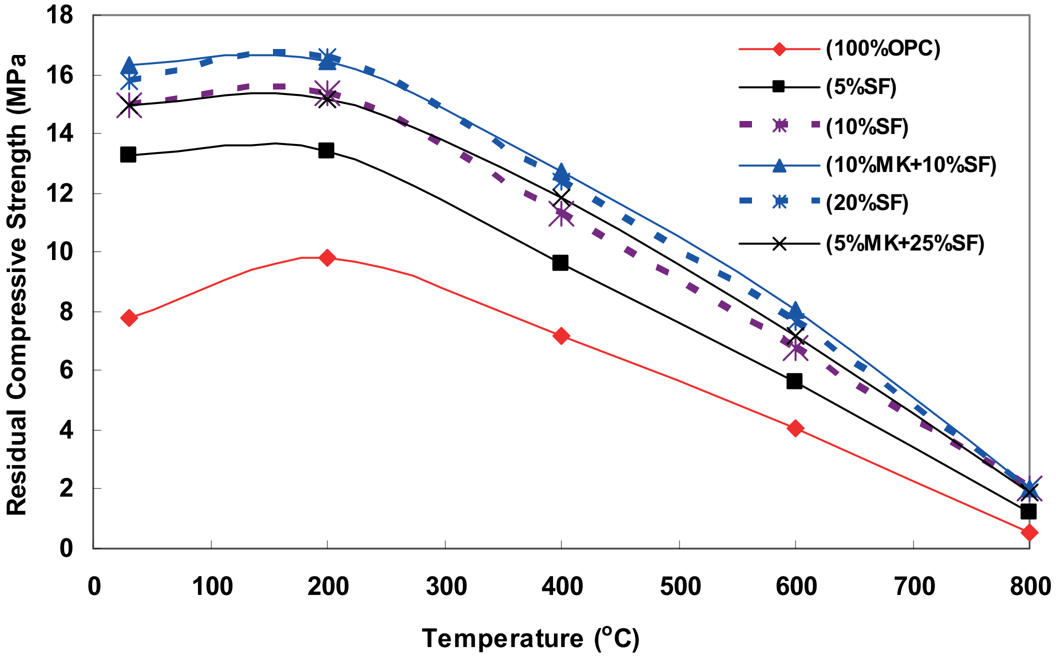

Figure 7. Maximum Residual Compressive Strength of Mortars for Various Replacements Exposed to Elevated Temperature

Conclusions

The following conclusions can be drawn from the present study:

1. At cement replaced by 20 % by mass, the equal combination of MK and SF gave the best control and residual compressive strength. This blend came in the first place.
2. Based on the mechanical properties of SF blended mortar, a 20 % separate SF content seems to be, generally, more favorable than the other investigated ratios.
3. At cement replaced by 30 % by mass, the optimal combination of 5 % MK and 25 % SF gave a good control and residual compressive strength. This blend came in the second place.
4. The 10 % cement replacement by separate SF improves compressive strength before and after exposure to elevated temperature. This blend came in the third place.
5. The 5 % cement replacement by SF came in the fourth place for the residual compressive strength.
6. The studied MK and SF have a very positive effect on the mortar strength at the age of 28 days and after exposure to elevated temperature.

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