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Effect of Raw Materials on the Mechanical Properties of Concrete Exposed to Elevated Temperatures: A review

Ahmed F. Abdullah(1) and Mohamed M. Rashwan(2)

Assistant Lecturer, Faculty of Engineering, Assiut University, Egypt(1)
E-mail: ahmed.fouad@aun.edu.eg
Professor, Faculty of Engineering, Assiut University, Egypt (2)
E-mail: mohamed.rashwan@aun.edu.eg

Abstract

One of the primary physical factors that affects the durability of structures is high temperature. By causing long-term damage to the structures, this effect might render them unusable and result in the loss of life and property. This essay examines the constituent elements of concrete and how they affect the mechanical characteristics of concrete that has been exposed to high temperatures. The characteristics of the raw material, such as cementitious materials, aggregate, and fibres, have a significant impact on the concrete's behaviour at high temperatures. The primary findings of many studies on the best ways to use cementitious materials including metakaolin, slag, and fly ash to improve the characteristics of concrete are also presented in this study. Since aggregates make up a large amount of concrete, particular attention has been paid to the mechanical and thermal characteristics of various aggregate types at high temperatures. Finally, because to their greater tensile strengths, steel or polypropylene fibres can be used to improve the mechanical properties of concrete at high temperatures.

Keywords
Concrete; Raw Materials; Elevated Temperatures; Mechanical Properties.

1. Introduction

Most concrete constructions are typically only exposed to a temperature range that is no more than that imposed by ambient environmental conditions. But in some crucial situations, these structures might be subjected to even higher temperatures (e.g., jet aircraft engine blasts, building fires, chemical and metallurgical industrial applications in which the concrete is near to furnaces, and some nuclear power-related postulated accident conditions).

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One of the main physical factors that contribute to the durability issue with structural concrete is elevated temperature. The temperature gradient that is created on concrete results in chemical and physical reactions like the dehydration of cement paste, the breakdown of aggregates, mass loss, deformation, and strength loss, all of which have a detrimental effect on the mechanical and thermal properties of concrete **[1]**. Depending on the cement mortar, the type of aggregate, the peak temperature, and the time that the concrete is exposed to the temperature, several factors affect how the elevated temperature affects the concrete.

1.1. Mechanical Properties of Concrete at Elevated Temperatures

Concrete properties after such exposure are critical in terms of serviceability and failure criteria. Compressive strength, tensile strength, modulus of elasticity, and stress-strain response are the main mechanical properties of concrete that are of interest after exposure to elevated temperatures. These properties are commonly used to assess the extent of concrete strength loss and deterioration at high temperatures. The properties of concrete that remain after cooling from high temperatures are referred to as its residual properties. After heating to a high temperature, the residual compressive strength of concrete goes through three major stages:

1) Room temperature – 300 ^{o}C, concrete compressive strength remains constant or even slightly increases.
2) 300 – 800 ^{o}C, concrete loses a significant amount of its compressive strength.
3) 800 ^{o}C after that, almost all the concrete compressive strength has been lost.

According to the available literature, hydrothermal processes cause physical and chemical changes that result in a decrease in tensile strength as the temperature rises, much like compressive strength experiences. Fibers and additional cementitious materials have been found to improve the residual tensile strength of concrete after being exposed to high temperatures by greatly reducing the loss of residual tensile strength. After a heating cycle, concrete often degrades more quickly in terms of splitting tensile strength than compressive strength. This has been explained by the fact that compared to compressive strength, splitting tensile strength is more susceptible to heat and micro-cracks. As a result, concrete with a high residual tensile strength performs better and has greater resistance to explosive spalling and fracture propagation at high temperatures.

2. Raw Materials

Due to their excellent performance at high temperatures, pozzolanic concretes like metakaolin and slag are utilised widely across the world. Elevated temperature can have a negative impact on the mechanical qualities of concrete. By utilising the right aggregates or mineral additions in the concrete, these unwanted effects can be reduced. The role of the concrete's primary components that are heated is covered in the sections that follow.

2.1. Cementitious Materials

Ordinary Portland Cement is the type of cement that is most frequently used in building (*OPC*). In recent years, blended cements have been created by partially replacing *OPC* with secondary cementitious elements such fly ash and rice husk. In addition to being cost-effective, reducing industrial waste and CO_2 emissions, blended cements also give concrete durability against high temperatures.

2.1.1. Metakaolin

The process of calcining natural clay yields metakaolin ***(MK)***. The calcining temperature primarily regulates its pozzolanic reactivity. Utilizing metakaolin powder can increase early strength and durability of concrete, reduce autogenous shrinkage, and refine pore structure. Table 1 presents the effect of *MK* on the mechanical properties of concrete exposed to elevated temperature, in terms of its compressive strength (f_c), splitting tensile strength (f_s) and flexural strength (f_f). The table also presents the main results concluded by different studies for the optimum use for *MK* as a partial replacement of cement.

It is obvious that optimal mixes (mixes that contain the ideal ratio of MK) have higher compressive strengths than control mixes. This improvement reached 40% at room temperature, but reached 80% at maximum temperature. Their appearance as a porous material, which enables them to store a higher water content for the pozzolanic reaction, explains why this is the case **[1]**.

Table 1: Effect of Metakaolin as a Partial Replacement of Cement on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			**[1]**	**[2]**	**[3]**	**[4]**	[5]	[6]
Binder Materials	Cement	Grade	52.5	42.5	42.5	42.5	--	52.5
		Content *(kg/m^3)*	400	400	300	500	500	480
	Metakaolin	% Replacement	10-20	5-25	5-20	5-20	5-20	3-15
		Optimum Ratio	15	18	20	10	10	9
Water/Binder *(w/b)*			0.5	0.48	0.6	0.2	0.3	0.35
Peak Temperature *(°C)*			800	800	800	750	800	800
$f_{c\ (28)}$ *(MPa)*	Room Temperature	Control Mix	47.2	29.2	34.4	82	86	90
		Optimum Mix	45.3	36	48	88	123	100
	Peak Temperature	Control Mix	13	11.3	14.6	33	22	10
		Optimum Mix	24	15.2	17	36	20	40
$f_{s\ (28)}$ *(MPa)*	Room Temperature	Control Mix	2.6	--	--	5.3	--	--
		Optimum Mix	3.4	--	--	5.7	--	--
	Peak Temperature	Control Mix	0.7	--	--	1.75	--	--
		Optimum Mix	0.6	--	--	1.9	--	--
$f_{fr\ (28)}$ *(MPa)*	Room Temperature	Control Mix	--	--	3.6	9.5	--	7.9
		Optimum Mix	--	--	4.2	10.5	--	8.2
	Peak Temperature	Control Mix	--	--	--	3.2	--	0.2
		Optimum Mix	--	--	--	3.2	--	0.8

2.1.2. Slag

Slag concretes offer stronger long-term strengths despite having a slower early strength development than Portland cement concretes. Additionally, they are more durable and have less permeability. The variation in outcomes can be attributed to the ratio of water to binder, the chemical makeup of the slag, and the grade of cement, as indicated in Table 2 where the ideal ratio for Slag (S) is in the range of (10-70%) %.

According to Li et al. [7], the compressive strength values of unheated concrete mixtures declined marginally with increasing slag levels of 0%, 10%, 30%, and 50%, respectively, and were 48.3, 48, 47, and 46.4 MPa. When the temperature reached 700 ^{o}C, the concrete with 0%, 10%, 30%, and 50% slag had relative compressive strengths of 24%, 26%, 24%, and 21%, respectively. The discharge of free water and physically bound water was primarily blamed for the decreased compressive strength of the heated concrete [8].

Table 2: Effect of Slag as a Partial Replacement of Cement on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[8]	[9]	[10]	[7]	[11]	[12]
Binder Materials	Cement	Grade	42.5	--	52.5	42.5	--	--
		Content *(kg/m^3)*	430	500	450	415	500	360
	Slag	% Replacement	30-70	30-50	20-60	10-50	30-40	50
		Optimum Ratio	70	40	20	10	40	50
w/b			0.47	0.3	0.45	0.41	0.3	0.5
Peak Temperature *(^{o}C)*			800	400	350	700	800	700
Age (days)			28	90	28	90	60	28
% Wight Loss at peak temperature		Control Mix	7.5	--	3	7.2	--	--
		Optimum Mix	9	--	3	7.5	--	--
f_c *(MPa)*	Room Temperature	Control Mix	32	--	35	48.3	86	48
		Optimum Mix	29	--	28	48	81	45
	Peak Temperature	Control Mix	13	--	40	12	22	7.2
		Optimum Mix	12.5	--	33	12.5	33.6	13.5
$f_{s\,(28)}$ *(MPa)*	Room Temperature	Control Mix	--	3.6	3.2	--	--	--
		Optimum Mix	--	4	2.8	--	--	--
	Peak Temperature	Control Mix	--	3	2.3	--	--	--
		Optimum Mix	--	3.7	2.2	--	--	--

2.1.3. Fly Ash

The main shape of the Fly Ash ***(F)*** particles is spherical, and they have a ball bearing action, which improves the workability of fresh concrete, prolong setting time, reduces permeability, and decreases the impact of sulphate attacks. According to the information in Table 3, the compressive strength of F mixes is approximately 30% lower than that of control mixes at room temperature. This strength loss was mostly caused by the spherical glass body of fly ash, which had poor bonding ability [13]**.** At peak temperature the compressive strength for *F* mixes is higher than that of control mixes by about 60%, this is attributable to the fact that fly ash mostly contributes to the pozzolanic effect, which affects the interfacial characteristics.

2.1.4. Silica Fume

Because they are much smaller than cement particles, Silica Fume (SF) particles are a great filler for boosting the matrix's packing density. Table 4 shows the impact of SF on the mechanical properties of concrete exposed to high temperatures. It is evident that, whether at room temperature or at higher temperatures, the compressive strength for SF mixes is higher than that of control mixes by about 30%. Tanyildizi [14] investigated that, with increasing percentages of silica fume (10% & 20%), concrete's strength development improved; nevertheless, at 30%, concrete's strength reduced. We can conclude that the addition of SF greatly densifies the concrete's pore structure, which causes explosive spalling because water vapors build up pore pressure.

Table 3: Effect of Fly Ash as a Partial Replacement of Cement on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[13]	[15]	[16]	[17]	[18]
Binder Materials	Cement	Grade	42.5	--	42.5	42.5	42.5
		Content (kg/m^3)	400	500	376	500	340
	Fly Ash	% Replacement	10-50	30-90	30	10-30	40-60
		Optimum Ratio	20	30	30	20	50
w/b			0.45	0.35	0.55	0.77	0.45
Peak Temperature (^oC)			400	800	550	800	800
% Wight Loss at peak temperature		Control Mix	7	--	--	--	9
		Optimum Mix	5	--	--	--	5
$f_{c\,(28)}$ *(MPa)*	Room Temperature	Control Mix	45.3	34	35	38	22.5
		Optimum Mix	35.6	32	30	45	39
	Peak Temperature	Control Mix	26.3	10	27.5	13.7	8
		Optimum Mix	26	12	28	19.4	20
$f_{s\,(28)}$ *(MPa)*	Room Temperature	Control Mix	--	--	--	3.2	--
		Optimum Mix	--	--	--	3.4	--
	Peak Temperature	Control Mix	--	--	--	0.74	--
		Optimum Mix	--	--	--	1.43	--

Table 4: Effect of Silica Fume as a Partial Replacement of Cement on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[19]	[14]	[5]	[20]	[21]
Binder Materials	Cement	Grade	52.5	42.5	--	52.5	--
		Content *(kg/m³)*	390	500	500	450	500
	Silica	% Replacement	10	10-30	5-10	1.5-4.5	1.5-4.5
		Optimum Ratio	10	20	10	3.0	4.5
w/b			0.4	0.77	0.3	--	0.25
Peak Temperature *(°C)*			550	800	800	600	800
% Wight Loss at peak temperature		Control Mix	6.1	--	--	--	10.3
		Optimum Mix	5.5	--	--	--	7.8
$f_{c\,(28)}$ *(MPa)*	Room Temperature	Control Mix	59.5	38	86	42.6	82.5
		Optimum Mix	69.8	50	108	61	85.2
	Peak Temperature	Control Mix	48	15	20	21.8	20.2
		Optimum Mix	54	22	19	38	27
$f_{s\,(28)}$ *(MPa)*	Room Temperature	Control Mix	4.91	--	--	--	7.7
		Optimum Mix	5.65	--	--	--	8.6
	Peak Temperature	Control Mix	3.71	--	--	--	2.3
		Optimum Mix	4.51	--	--	--	2.9

2.1.5. Rice Husk Ash

The particle size of rice husk ash (RHA) is comparable to that of silica fume and cement. The RHA has a beneficial impact on the compressive strength of concrete as it ages. In terms of chemical makeup and specific surface area, RHA and SF are quite comparable, although RHA is not an ultra-fine material like SF. RHA has an internal porosity that contributes to its high specific surface area. The impact of RHA on the mechanical properties of concrete exposed to high temperatures is shown in Table 5. The compressive strength of RHA mixes is greater than that of control mixes at room temperature, and its structure is more compact. The trends of the change in compressive strength are a little different as the temperature rises. The compressive strength modifies somewhat at 400 °C. It drops off significantly above 400 °C. The specimens' compressive strengths are 30–40% of those at ambient temperature when heated to 800 °C [22].

Table 5: Effect of *RHA* as a Partial Replacement of Cement on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[23]	[22]
Rice Husk Ash		% Replacement	(5-10-15)	(10-15-20)
		Optimum Ratio	5	20
Burning of Raw Rice Husk		Temperature *(^oC)*	500	600
		Duration *(hr)*	5	1.0
Peak Temperature *(^oC)*			700	800
Age *(days)*			200	56
f_c *(MPa)*	Room Temperature	Control Mix	22	65
		Optimum Mix	40	70
	Peak Temperature	Control Mix	4.9	18
		Optimum Mix	5.4	28

2.2. Aggregate

Since aggregates constitute between (60 – 80) % of the volume of concrete, it is widely acknowledged that the nature of the aggregates plays a major role in how much heat is transferred through the concrete. The conductivity of the concrete is significantly influenced by the mineralogical properties of the aggregates: quartzite and sandstone have the highest conductivities, granite and limestone are in the middle, and basalt has the lowest.

2.2.1. Fine Aggregate

In order to minimize the negative environmental effects of the concrete industry, several different types of solid wastes and industrial by-products, such as coal Bottom Ash (BA) and blast-furnace slag, have found extensive use in concrete as Fine Aggregate (FA). Yuksel et al. [24] investigated how elevated temperatures affected the concrete properties with fine aggregate made of coal bottom ash and slag. The results of the tests demonstrated that even if these concretes were to be subjected to a high temperature response, fine aggregate could be largely replaced with slag or BA. The concrete incorporating slag fine aggregate showed less loss in strength properties and mass than conventional concrete, as indicated in Table 6, after being exposed to high temperatures. These enhancements in mechanical and physical properties are made possible by the slag aggregate's chemical make-up and surface finish. Additionally, as the ideal slag ratio is between (40 - 100) %, the chemical makeup of slag may be to cause for the inconsistent results.

Table 6: Effect of Fine Aggregate on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[25]	[26]	[24]	
Fine Aggregate		Type	Slag	Slag	Slag	BA
		% Replacement	25-100	30-100	10-50	10-50
		Optimum Ratio	100	50	40	40
Peak Temperature (^oC)			800	800	800	800
$f_{c\ (28)}$ *(MPa)*	Room Temperature	Control Mix	45	41	51	51
		Optimum Mix	50	44.6	48	42
	Peak Temperature	Control Mix	6.8	9.7	20	20
		Optimum Mix	5.5	9.1	15	12
$f_{s\ (28)}$ *(MPa)*	Room Temperature	Control Mix	3.5	--	--	--
		Optimum Mix	3.7	--	--	--
	Peak Temperature	Control Mix	0.53	--	--	--
		Optimum Mix	0.37	--	--	--
$f_{fr\ (28)}$ *(MPa)*	Room Temperature	Control Mix	5.3	4.9	--	--
		Optimum Mix	6.4	5.9	--	--
	Peak Temperature	Control Mix	3.2	1.1	--	--
		Optimum Mix	2.6	0.8	--	--
% Wight Loss at peak temperature		Control Mix	20	--	4.6	4.6
		Optimum Mix	16	--	5.25	6

2.2.2. Coarse Aggregate

The classification of Coarse Aggregates (CA) into siliceous, calcareous, or silico-calcareous aggregates depends on whether silica or calcium content predominates. Because of their exposure to high temperatures during manufacture or because of their light weight and low density, some aggregates are also categorised as thermally stable. The impact of CA on the mechanical characteristics of concrete exposed to high temperatures is shown in Table 7, in terms of the type of *CA* and its Maximum Nominal Size (*MNS*), *FA/CA* ratio, and the percentage of strength loss (% loss) due to elevated temperatures. Concrete constructed of granite coarse aggregate demonstrated superior mechanical properties at both room temperature and its peak, followed by concrete formed of quartzite and limestone [27].

Table 7: Effect of Coarse Aggregate on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Ref.	Coarse Aggregate		$\frac{FA}{CA}$	Peak Temp. (^{o}C)	$f_{C\,(28)}$ *(MPa)*			$f_{s\,(28)}$ *(MPa)*		
	Type	*MNS (mm)*			Room Temp.	Peak Temp.	% Loss	Room Temp.	Peak Temp.	% Loss
[27]	Granite	19	0.67	650	36	19	47	4	1.8	55
	Quartzite				28	10	64	3.2	1.0	68.8
	Limestone				21	7	66	2.5	0.6	76
[28]	Basalt	16	0.49	800	86	25	71	6.9	1.4	79.7
	Gravel		0.57		77	23	70	6	1.2	80
	Dolomite		0.54		75	22	70.6	5.4	1.1	79.6
	Granite		0.55		71	21	70.4	4.9	0.95	80.6
[29]	Limestone	30	0.73	750	40.9	8.2	80	--	--	--
	Siliceous		0.78		34.7	7.0	79.8	--	--	--

2.3. Fibers

Concrete under mechanical stress with a thermal load produces pore pressure in the concrete matrix as well as thermal shrinkage and dilation gradients. Steel fibres and polypropylene fibres, or both, commonly referred to as hybrid fibres, are introduced into the concrete in order to prevent the explosive spalling characteristic of concrete exposed to high temperatures. The effects of high temperatures on concrete made of steel and polypropylene fibres, respectively, are outlined in the following sections.

2.3.1. Steel Fibers

Steel Fibers (*STF*), which tie and hold the cracks together to provide post-cracking strength, are added to concrete to boost its tensile strength. It is also important to note that adding the right amount of *STF* to concrete results in increased performance in both the fresh and hardened states. Table 8 presents the effect of *STF* on the mechanical properties of concrete subjected to elevated temperature, in terms of *STF* shape and its aspect ratio (length/diameter = *L/D*), volume of fraction ($\%V_f$), and the optimum ratio. It can be observed that the compressive strength of the optimum mixes is higher than that of control mixes. At room temperature this enhancement reached 22 %, however at peak temperature this enhancement reached 40 % [30].

2.3.2. Polypropylene Fibers

The melting point of Polypropylene Fibers (PP) is reached before the spalling temperature. The *PP* fibres begin to melt at around 170 ^{o}C, increasing the mortar's permeability and allowing the vapours to escape, lowering the pore pressure. The impact of *PP* fibres on the mechanical characteristics of concrete subjected to high temperatures is shown in Table 9. Cree et al. [31] carried out a study showed a decrease of compressive strength for mixes contain *PP* fibers in both room and peak temperature, while behnood et al. [32] obtained improvements in mechanical properties of *PP* fibers concrete. This variation might be caused by the specimen's curing circumstances, the testing conditions, and the heating rate. The information in Table 9 leads to the conclusion that the residual mechanical properties of concrete subjected to high temperatures can be greatly improved by the addition of 2 kg/m^3 *PP* fibres.

Table 8: Effect of *STF* on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Reference			[33]	[30]	[34]	[35]
Steel Fibers		Shape	End-Hooked	Straight	Straight	Corrugated
		L/D *(mm/mm)*	50/0.5	50/0.8	13/0.2	12/0.2
		$\%V_F$	0.5-1.5	0.25-1.0	1.0	1-3
		Optimum Ratio	1.0	1.0	1.0	2.0
Peak Temperature *(°C)*			400	600	800	800
$f_{c\,(28)}$ *(MPa)*	Room Temperature	Control Mix	90	24.2	40.55	--
		Optimum Mix	103	29.6	49.86	168.5
	Peak Temperature	Control Mix	20	12.5	4.6	--
		Optimum Mix	23	17.5	16.45	38
% Wight Loss at peak temperature		Control Mix	--	10.46	12	--
		Optimum Mix	--	9.63	8	--

Table 9: Effect of *PP* Fibers on the Mechanical Properties of Concrete Exposed to Elevated Temperatures.

Ref.	Peak Temp. (°C)	*PP* Fibers Content (kg/m^3)	$f_{C\,(28)}$ *(MPa)*			$f_{s\,(28)}$ *(MPa)*	
			Room Temp.	Peak Temp.	% Loss	Room Temp.	Peak Temp.
[31]	450	0	60	55.8	7	--	--
		1.0	56	50.4	10	--	--
		2.0	56.4	42.3	25	--	--
[36]	600	0	72.2	59.3	18	4.27	1.85
		1.5	74.7	48.2	35	4.86	1.5
[32]	600	0	61	20	67.2	4.3	1.2
		1.0	65.5	21.5	67.1	4.4	1.25
		2.0	67.8	22.5	66.8	4.1	1.15
		3.0	63.3	20.7	67.3	3.7	1.04

[37]	800	0	75	28	62.7	--	--
		1.8	85	30	64.7	--	--

3. Conclusions

Cementitious Materials

- Adding metakaolin to concrete that has been subjected to high temperatures improves its mechanical properties and the optimum ratio for metakaolin in the range of (10 – 20) %.
- Addition of slag to concrete reduces the compressive strength, this reduction reached 10%, whether under normal conditions or in the case of elevated temperatures.
- The use of fly ash as a partial replacement of cement increased the resistance of concrete against elevated temperatures and the optimum ratio for fly ash in the range of (20 – 30) %.
- The compressive strength for silica fume mixes is higher than that of control mixes, either at room temperature or at elevated temperatures and the optimum ratio for silica fume in the range of (10 – 20) %.
- So far, not enough experimental data have been published on the elevated temperature resistance of rice husk ash concrete to determine the optimum ratio for using.

Aggregates

- By substituting slag for natural sand up to 100%, concrete mechanical properties improve.
- Performance of the coal bottom ash in concrete was demonstrated to be superior to slag as fine aggregate replacement.
- At both room temperature and peak temperature, the mechanical properties of concrete formed with coarse granite aggregate were high, followed by quartzite and limestone concretes.

Fibers

- To improve the mechanical properties of concrete at high temperatures, steel fibre dosage can be adjusted from 0% to 3% volume fraction, with best results recorded at (1 – 2) %.
- ***PP*** fibres, with the best content observed at (2 kg/m^3), can improve the mechanical properties of concrete when subjected to high temperatures.

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