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The Effect of Egyptian Calcined Clay on Residual Compressive Strength after Concrete Exposure to High Temperatures: A Model Case

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Abstract

Kaolin is a naturally clay mineral, primarily composed of the mineral kaolinite. When kaolin is subjected to the calcination process, it becomes a highly beneficial material with cementitious hardening properties. Certainly, the composition and effect vary depending on the source of the kaolin. Kaolin ore is found in Egypt in several areas and in large quantities. Therefore, Egypt exports kaolin ore and produces calcined clay from kaolin. This scientific paper focuses on studying the impact of Egyptian calcined kaolin clay as an enhancer of concrete's resistance to fire and high temperatures. The purpose was to use calcined clay to produce a special concrete suitable for structures that may be exposed to fire or high temperatures. Nine concrete mixtures were prepared. The control mix was designed to have medium compressive strength. Eight mixtures with partial replacement of Portland cement with Egyptian calcined clay from kaolin (K) were performed. Concrete specimens were subjected to high temperature at 700°C for one hour. After that, specimens were cooled with water. The reduction in compressive strength after heating and cooling was measured. The results show that the addition of Egyptian calcined clay in concrete improves the residual compressive strength after heating and cooling. The research suggests using Egyptian calcined clay in the concrete of facilities that may be exposed to fire or high temperatures.

Key Words: Calcined clay, Egyptian Kaolin, Concrete residual strength, High temperature

1. Introduction

Several research studies have shown that compressive strength decreases after exposure to high temperatures [1-2]. Tanya Kerr noted that the compressive strength of concrete decreased due to the decomposition of the calcium silicate hydrate phase at high temperatures [3].

The effect of high temperatures on high-performance concrete was the subject of G. F. Peng's research. X-ray diffraction (XRD) tests were conducted on hardened cement paste samples after exposure to various peak temperatures ranging from 400°C to 800°C. They found that the decomposition of the cement paste influenced the strength loss of high-performance concrete [4]. In other research, the effect of different durations (one, two, and three hours) of high temperatures (250, 500, 750, and 950°C) on the mechanical properties of heavy concrete was studied. Results showed that the heating exposure time was inversely proportional to the mechanical properties of all types of concrete [5].

Chi-Sun Poon and others studied Metakaolin concrete. They pointed out that the residual compressive strength after firing at 200°C and cooling showed high results at 10% and 15% kaolin replacement after 28 days [6]. Morsy found that the residual compressive strength at 400°C showed low results. It was found then that at 800°C, a 20% MK replacement resulted in the lowest residual strength [7]. Siddique and Klaus pointed out that fire resistance reached the best result with 20%

MK replacement [8]. Nadeem and others investigated that using MK as a partial cement replacement, especially at an early age, improves the mechanical properties of concrete [9].

Wang and others studied the effects of adding 10% metakaolin to cement paste exposed to temperatures from room temperature to 800°C. Results showed that compressive strength increased at 200°C and 400°C but decreased rapidly up to 800°C. The addition of metakaolin enhanced compressive strength, reduced shrinkage, and resulted in a denser microstructure, offering better thermal resistance compared to pure cement paste. [10].

Laidani and others examined 10% metakaolin incorporated cement paste exposed to temperatures up to 800°C. They found that the best results were at 200°C [11]. Many studies proved that replacing Portland cement with kaolin up to 20% improves mechanical properties [3-6]. Egypt has large reserves of kaolin in many localities in Sinai, Red Sea and Kalabsha near Aswan [12].

2. Experimental work

2.1 Materials

Ordinary Portland cement was used. It is classified (CEM I grade 42.5 N) according to European standard EN 197-1. [13] The cement produced by the Sinai cement factory complies with the requirements of the European standard EN 197-1 and the Egyptian Standards E.S.S [14]. Initial and final setting times for cement were measured according to BS EN 196-3:2016. [15] as shown in Fig.1. Cement properties were given in Table 1.

The admixtures Sikament 163-M (Super-plasticizer) produced by Sika Egypt factory, was used. It complies with ASTM-C 494 Type F. The coarse aggregate was crushed dolomite from North Sinai quarry, Egypt. The nominal maximum size of coarse aggregate was 19 mm, which satisfy the Egyptian Standard Specification E.S.S [14]. Fine aggregate was siliceous sand from North Sinai quarry, Egypt. It has Fineness modulus of 2.75.

Standard Test for determination of clay and other fine materials in fine aggregate by volume was carried out according to BS 812-124:2015 [16]. The test was done in new Damietta higher institute of Engineering, Damietta, Egypt as shown in Fig. 2.

The used calcined clay is shown in Fig. 3. It was produced by Asfour factory for mining and refractories, Helwan, Egypt. Asfour factory is using Egyptian kaolin from Sinai in Egypt to produce calcined clay by heating up 1000°C. The chemical and physical properties of Kaolin were shown in Table 2 & 3 respectively.

Fig. 1. Initial setting time test for Portland cement

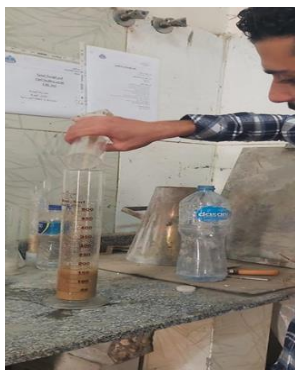

Fig. 2. determination of clay and other fine materials in fine aggregate by volume

Fig. 3. Sample form of calcined clay produced by Asfour factory,Egypt

Table 1: Physical properties of Portland cement

Test		Cement
Initial sitting time[Minutes]		69
Final sitting time[Minutes]		180
Specific surface area (cm^2/gm)		3500
Specific gravity		3.15
Compressive strength(N/mm^2)	7 days	23
	28 days	40

Table 2: Chemical composition of calcined clay

Chemical composition	Percentage %
AL2 O3	36 – 40
Fe2 O3	1.3 -1.8
SiO2	54 – 58
TiO2	1.5 – 2.5
CaO	0.3 – 0.4
MgO	0.1 – 0.2
K2O+ NaO	0.2 - 0.4

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Table3: Physical properties of calcined clay

Grain size distribution	Percentage %
> 100 µ	0.5 – 2
>63µ	17 – 22
<63µ	75 -82

2.2 Mix Proportions and Specimen

The aim of the research was to benefit from using Egyptian calcined clay as a fire-resistant material. The experimental program presents calcined clay as a partial cementitious material. Nine concrete mixtures were prepared. Based on fire-resistant construction needs, the control mix was designed to have a compressive strength of 35 MPa at 28 days. The other eight mixtures contained partial replacements of Portland cement with Egyptian calcined clay by percentages of 10%, 15%, 20%, 25%, 30%, 35%, 40%, and 45%.

Eighty-one standard cubes were used to prepare the concrete cubic specimens. Fifty-four of these specimens were used to measure the compressive strength before exposure to high temperatures at 7 and 28 days of curing. The other twenty-seven specimens were used to measure the compressive strength after heating and cooling. Twenty-seven standard cylinders (150 mm diameter & 300 mm height) were prepared for the splitting tensile test, and twenty-seven standard beams with dimensions of (10 mm * 10 mm * 50 mm) were prepared for the flexural strength test. The mixture descriptions and the quantities of various materials for each concrete mix are provided in Table 4. All specimen preparation and curing were conducted according to BS EN 12390-2:2019 [22] and E.S.S. [18]. All specimen preparations were done at the New Damietta Higher Institute for Engineering and Technology, Damietta, Egypt. (Fig 4)

Table 4. Concrete mix proportion

MIX	Cement (kg)	KA (kg)	Fine Agg. (kg)	Coarse.Agg. (kg)	Water Lit.	S.plasticizer. (lit)
Control Mix	452.38	-	625.91	1054	190	2.71
10%K+90%C	407.14	45.29	625.91	1054	190	2.71
15%K+85%C	384.51	67.85	625.91	1054	190	2.71
20%K+80%C	361.9	90.48	625.91	1054	190	2.71
25%K+75%F.A	339.29	113.1	625.91	1054	190	2.71
30%K+70%F.A	316.67	135.71	625.91	1054	190	2.71

35%K+65%F.A	294.05	158.33	625.91	1054	190	2.71
40%K+60% F.A	271.43	180,95	625.91	1054	190	2.71
45%K+55%F.A	248.81	203.57	625.91	1054	190	2.71

2.3 Testing Procedure

2.3.1 Mechanical properties

After 7 & 28 days of casting compressive strength test were done, indirect tensile strength and flexural strength test of concrete were conducted according to BS EN 12390-2 [17] as shown in Fig 5&6 to check the mechanical properties.

Compressive strength test was conducted in the laboratories of new Damietta higher institute for engineering and technology, Damietta, Egypt, flexural strength test & splitting tensile test were conducted in the laboratories of Horas University, Damietta, Egypt.

2.3.2 Residual compressive strength testing- Model-Case

The model case has been done. Three cubes from each mix were placed in a closed electric furnace up to 700°C; the samples were kept in the electric furnace at 700°C for one hour as shown in Fig.7. As a model case reflecting real- conditions, the concrete was heated for one hour and then cooled with water. The test was done in civil engineering & chemical engineering laboratories of New Damietta higher institute of engineering, New Damietta, Egypt.

The procedure of the study involved exposing the samples to the temperature, then removing them from the furnace. The heated samples were placed in a water tank for sudden cooling, as done in fired constructions.

Compressive strength was measured after 24 hours of removing the samples from the water tank. The results were shown in Table 6. The residual strength after heating and cooling was determined for each mix.

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Fig. 4. specemens preperation

Fig. 5 Flexural strength test

Fig. 6. Splitting tensile test

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Fig. (7) Standard cube in electric furnace

3. Results and dissections

3.1 Mechanical properties

The results of the compressive strength test on standard cubes (150 * 150 * 150 mm) showed that in the mix (10%K+90%C) have a small increase in compressive strength than control mix by 2.7%, while at a 15% replacement of Portland cement with Egyptian calcined clay, the compressive strength remained unaffected. when the replacement ratio was increased from 25% to 35%, the compressive strength decreased by a range of 4% to 10%. The decrease in compressive strength reached 18% in the mix with a 45% replacement of Portland cement.

This indicates that when replacing Portland cement with calcined clay, the optimal replacement ratio should be within the range of 5% to 20%.

The results of the flexural strength test showed a slight increase in both mixes with 10% and 15% replacement, with the increase being 1.6% and 5%, respectively. However, the flexural strength decreased as the replacement ratio of Portland cement increased from 20% to 45%, with the decrease ranging from 3.3% to 26%.

As for the indirect tensile strength, it increased in the mixes containing 10% and 15% Egyptian calcined clay, with increases of 6.4% and 3.2%, respectively. Conversely, the indirect tensile strength decreased as the replacement ratio increased from 20% to 45%, with the decrease ranging from 3.22% to 35%.

These results align with the findings of the compressive strength test. However, it is worth noting that, despite the noticeable decrease in the mechanical properties when replacing more than 20% of kaolin with calcined clay, the results remain somewhat acceptable. Table 5 represent the mechanical properties results.

Table 5. Mechanical properties results

Mix	Compressive Strength 28 day[N/mm^2]	Flexural Strength 28 day[N/mm^2]	Splitting tensile strength 28 day [N/mm^2]
Control Mix	37	6	3.1
10%K+90%C	38	6.1	3.3
15%K+85%C	37	6.3	3.2
20%K+80%C	35	5.8	3.0
25%K+75%F.A	33	5.8	3.0
30%K+70%F.A	32	5.1	2.85
35%K+65%F.A	32	5.0	2.7
40%K+60% F.A	31	5.0	2.2
45%K+55%F.A	30	4.4	2.0

3.2 Residual Compressive Strength in a Model Case

The compressive strength test results indicate that, for all mixtures, there was a decrease in compressive strength after exposure to high temperature. Because of more than one reason such as evaporation of water bound in the cement paste, dehydration of calcium silicate hydrate (C-S-H) gel, the different thermal expansion coefficients between concrete materials also loosing aggregate strength by decomposing at high temperatures into lime (CaO) and carbon dioxide (CO_2).

The percentage of residual compressive strength (R) was determined from the following relation. The residual compressive strength results were shown in Table 6, and Fig. 8.

$$R = \frac{\text{strength after high temperature and cooling}}{\text{strength before high temperature exposing}} \times 100$$

Table 6. The residual compressive strength results

Mix	Compressive Strength before fire exposure [N/mm^2]	Compressive Strength after fire exposure [N/mm^2]	R = Residual strength%
Control Mix	37	16.0	43%
10%K+90%C	38	19.5	51%

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15%K+85%C	37	19.0	52%
20%K+80%C	35	18.0	52%
25%K+75%F.A	33	19.0	58%
30%K+70%F.A	32	19.5	60%
35%K+65%F.A	32	19.5	61%
40%K+60% F.A	31	18.5	60%
45%K+55%F.A	30	18.0	60%

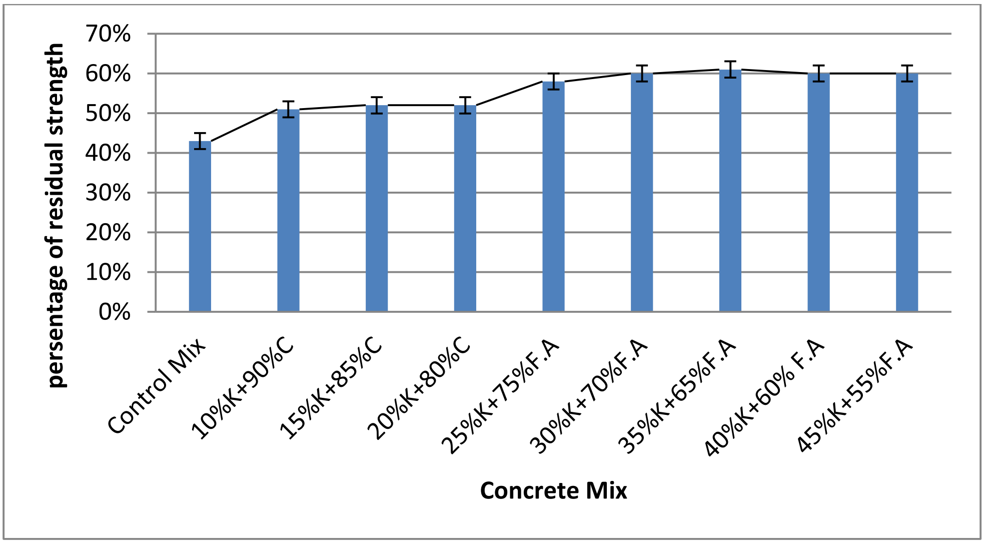

Fig. 8. Residual strength for concrete mixtures.

As evident from the results, the higher the percentage of Egyptian calcined clay in the concrete mix, the greater the residual strength after exposure to high temperatures.

As it can be seen in Table 2, the chemical composition of calcined Egyptian clay, made from kaolin found in Sinai, Egypt, primarily consists of two compounds: alumina (AL_2O_3), accounting for up to 40%, and silica (SiO_2), and accounting for up to 58%. These are the most important components for high-temperature resistance.

Alumina ($AL2O_3$) and silica (SiO_2) tends to enhance the fire resistance and hardness of the resulting material, when fired. Because of probability of Mullite Formation: Higher concentrations of alumina and silica in kaolin increase the potential for forming more Mullite during the firing process. Mullite provides excellent mechanical strength, thermal stability, and resistance. [18-19]

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4. Conclusions

Concrete was exposed to a temperature of 700° C for one hour, followed by cooling. Based on the results of the compressive strength test for the concrete before and after exposure to high temperatures followed by cooling, the following conclusions can be drawn.

As the replacement ratio of Portland cement with Egyptian calcined clay is increased, the residual strength after exposure to high temperatures also increased. The percentage of residual strength ranged from 51% to 61% of the original strength.

Egyptian Calcined clay can be used for improving fire-resistant concrete. It contains a high ratio of 40% alumina (AL_2O_3) and 58% silica (SiO_2).

The mechanical properties result of concrete containing Egyptian calcined clay as a partial replacement was enhanced the mechanical properties up to a replacement ratio of 15% of Portland cement.

High replacement of cement with calcined clay up to 45% decreased the compressive strength. However, at a 15% replacement of cement with calcined clay, the decrease in compressive strength was zero.

It is recommended to use Egyptian calcined clay as a replacement of cement up to 15% to improve the mechanical properties of concrete and its fire resistance.

Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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