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Stability assessment of concrete produced with cement exposed to fire

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Abstract
Cement is an important building material in the construction industry because it has a high overall strength and binds concrete mixtures together. However, if a fire occurrence or accident exposes already-produced cement to heat at temperatures of 100 °C and above, what would be the stability of those exposed cements and the possibility of their being usable for construction work? Should cement exposed to open flames be condemned and disposed of, or is it still usable? This study investigates the effect of cement exposed to open fire on the overall strength of concrete, the potential strength reduction, and whether it can still be used for construction work. A grade of 42.5 N cement was subjected to an open fire flame between 100 and 300 0C. Three different temperature levels of 100, 200, and 300 °C were chosen for this investigation. The burnt cement in its cold and hot forms was used as a binder in producing concrete cubes (CC). Seventy-two (72) CC samples of 150 x 150 x 150 mm were produced from the burnt cement, both in cold and hot form, as specified by BS EN 12390-3. Twelve (12) CC were also produced with unburned cement and served as a standard for burnt cement samples. All of the compressive strengths (CS) were examines at 7, 14, 21, and 28-day. Results show that Cement exposed to open fire had a negative effect on the stability of the concrete. The burnt cement at temperatures of 100, 200, and 300 0C in cold form reduces the CS of concrete by 34, 50, and 48%, respectively. In hot form, it reduces the CS of concrete by 35, 46, and 40%, respectively. The reduction in CS is attributed to heating calcium, silica, aluminum, and iron. Lightweight concrete can be made with burnt cement at temperatures of 100, 200, and 300 0C. It can also be used in the production of concrete blocks. The variation amongst the predicted coefficient of regression (R2) of 0.9997 and the adjusted coefficient of regression (R2) of 0.9998 is less than 0.2, which is considered to be a fair agreement.

Keywords: Stability, Concrete, Cement, fire, workability, exposure

1. Introduction

Cement is a fine gray powder that is made with calcined lime and clay (Dunuweera and Rajapakse, 2018). However, the most common application is in mortar and concrete (Aljerf, 2015) [1], where the cement is combined with inert materials known as aggregates (Mac-Eteli and Sopakirite, 2021) [17]. Cement is an important building material in the world today, used in both residential and commercial construction work (Mac-Eteli *et al*, 2022). Cement production is quite ubiquitous; materials commonly used are shells, limestone, chalk, clay, shale, blast, slate, slag, and furnace, (Chattopadhyay, 2020; Peray, 2001) [7, 22]. Cement is produced by heating shells, limestone, chalk and clay to about 1300–1450 °C and combine with silica, calcium, iron, aluminum, and other materials in an accurate chemical reaction (Kanare, 2020; Khan, 2008; Gabriel, 2008) [13, 14, 11]. When the constituent materials are heated to a high temperature, they produce a rock-like solid that is ground to form cement. Cement manufacturing process requires massive amounts of heat (Aljerf, 2015; Dong *et al*., 2012) [1, 9].

Heat, an important factor, is required during the cement production process, the production of concrete, and the preparation of partial cement replacement (Deolalkar, 2007) [8]. The cement manufacturing is an important industrial activity on the African continent and in many other countries around the world. As the government and private sectors focus on infrastructure and housing development, demand for cement continues to rise. Fire and explosion hazards can occur due to the nature of several processes that occur during cement manufacturing, transportation of the produced cement, and storage units (Olusegun, 2022) [21].

Major issues confronting the construction industry include the need to increase concrete's durability, strength gain rate, long-term strength, and exposure to fire flame (Kadhum, 2010) [12], which has led to research into numerous approaches to improve concrete. Cement, a crucial element for the production of concrete (Mac-Eteli *et al*, 2022), necessitates a significant quantity of heat. There is a long history of research into the use of calcined materials for concrete production, and there are a large number of publications in the area of heating materials used for concrete production, such as the thermal investigation in measuring the impact of temperature on a cement paste (Khoury, 1992; Lucia *et al*., 2005; Mindess *et al* 2002) [15, 16, 19] as well as the thermal treatment of phosphogypsum and its effect on mineralogical alteration for efficient concrete application (Roberto *et al*., 2000; Gabriel, 2000) [23, 10].

Mohammed (2013) [20] studied the stability and serviceability of reinforced concrete (RC) beams subjected to external loads and exposed to fire. A study shows a significant decrease in strength properties after being subjected to fire.

Umran (2002) [24] examined the impact of fire on bending and compressive strength (CS) of cement concrete. The test samples were exposed to a fire between 25 and 700 ℃. The author reported that the bending resistance was observed to be more sensitive to fire compared to the CS. Also, he stated that exposure times beyond 60 minutes have a noticeable effect on the CS.

Cement is an important building material in the construction industry because it has a high overall strength and binds concrete mixtures together. However, if a fire occurrence or accident exposes already-produced cement to heat at temperatures of 100 ℃ and above, what would be the workability of those exposed cements and the possibility of their being usable for construction work? Should cement exposed to open flames be condemned and disposed of, or is it still usable? This study investigates the effect of cement exposed to open fire on the overall strength of concrete, the potential strength reduction, and whether it can still be used for construction work. This will serve as a knowledge database for an effective practice.

2. Materials and Method

2.1 Materials

Portland limestone cement of the 42.5 N grade suggested by BS EN 197-1 (2011) was utilized, and crushed stone and fresh water sand, respectively, in line with EN 932 (932), were used for the coarse and fine aggregates. The aggregates were sourced from a construction site at Niger Delta University. Water free of impurities was utilized for mixing the concrete.

2.2 Method

A grade of 42.5 N cement was subjected to an open fire between 100 and 300 0C. Three different temperature levels of 100, 200, and 300 ℃ were chosen for this investigation. The burnt cement in its cold and hot forms was used as a binder in producing concrete cubes (CC). Seventy-two (72) CC samples of 150 x 150 x 150 mm were produced with the burnt cement both in cold and hot form according to EN 12390-3. Twelve (12) CC were also produced from unburned cement and served as a standard for samples produced from burnt cement. The proportions of the concrete mixture were chosen to be 1:2:4 by weight. As recommended by BS EN 12390-2, the CC were cured and safeguarded against dehydration. All of the CS were examined at 7, 14, 21, and 28 days.

3. Results and Discussion

The results of the stability study on concrete produced with cement exposed to open flame are presented and discussed below.

3.1 Compressive strength of concrete produced with burnt cement in cold form

Table 1 and Figure 1 show the CS results of cold-formed concrete made with burnt cement. Table 1 and Figure 1 show that the CS decreases at first, attains a minimum CS with an increase in temperature level, and then increases with an increase in temperature level. Table 1 also presents the results of concrete made with unburned cement. A reduction in CS of 34, 50, and 48% was recorded for the three different temperature levels of 100, 200, and 300 oC, respectively. Figure 1 shows that the CS of concrete with a mix ratio of 1:2.4 is 20.7 MPa, 15.4 MPa, and 16.3 MPa when cement used as a binder is heated to 100 oC, 200 oC, and 300 oC, respectively. The reduction in strength is attributed to heating the gypsum directly.

Table 1: Compressive strength of concrete produced with burnt cement in cold form

Heating Temperature	7-day CS (Mpa)	14-day CS (Mpa)	21-day CS (Mpa)	28-day CS (Mpa)
0°C	26.8	28.9	28.8	31.4
100°C	17.2	16.9	20.2	20.7
200°C	7.8	28.9	15.4	15.4
300°C	11.0	13.5	13.7	16.3

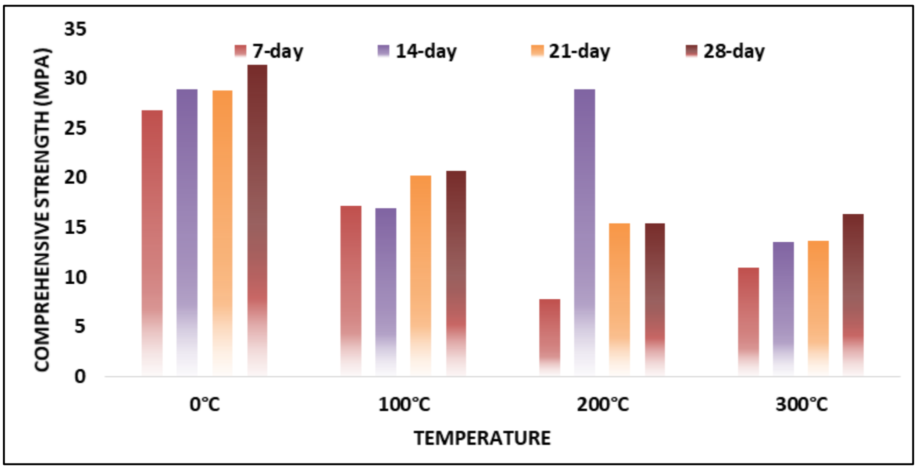

Fig 1: CS against Calcination temperature for cold mix

3.2. Compressive strength of concrete produced with burnt cement in hot form

The CS results of concrete produced with burnt cement in hot form are as given in Table 2 and Figure 2. Referring to Table 2 and Figure 2, it is evident that the CS decreases initially, attains a minimum CS with an increase in heating temperature levels of 0 to 200 0C, then increases with an increase in heating temperature levels at 300 0C. A reduction in CS of 35, 46, and 40% was recorded for the three different temperature levels of 100, 200, and 300 oC, respectively. Results show that the CS of concrete with a mix ratio of 1:2.4 is 20.4 MPa, 16.8 MPa, and 18.6 MPa when cement used as a binder is heated to 100 oC, 200 oC, and 300 oC and used as hot form, respectively. The reduction in strength is also attributed to heating the gypsum directly.

Table 2: Compressive strength of concrete produced with burnt cement in hot form

Heating Temperature	7-day CS (Mpa)	14-day CS (Mpa)	21-day CS (Mpa)	28-day CS (Mpa)
0°C	26.8	28.9	28.8	31.4
100°C	12.2	15.8	20.0	20.4
200°C	17.1	23.6	26.1	16.8
300°C	10.4	16.0	18.4	18.6

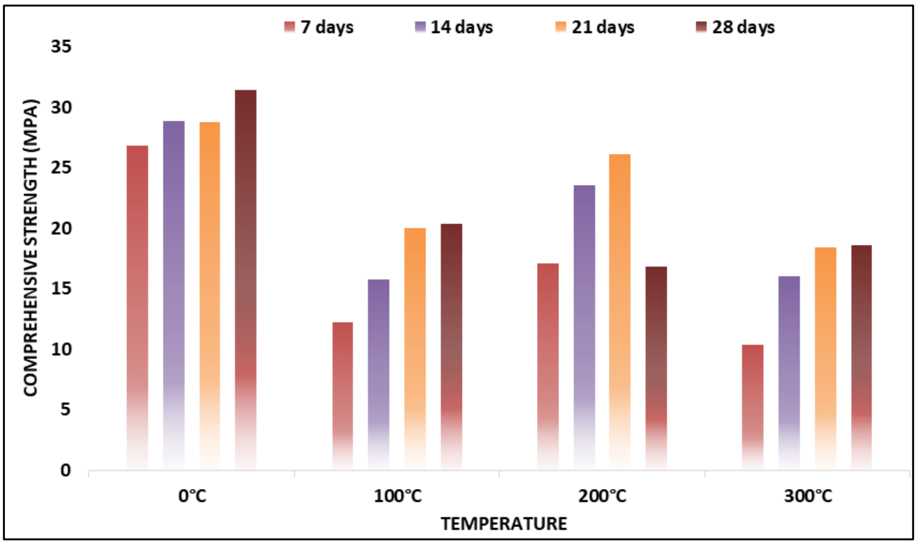

Fig 2: CS against Calcination temperature for hot mix

3.3. Comparison of CS for Cold and Hot form

Figures 3, 4, and 5 show a comparison of the CS of concrete produced with burnt cement in both cold and hot form. **Figure 3 shows that the CS of concrete produced with 100 ^{0}C burnt cement in both cold and hot form increases with age.** The CS of the cold form is 40%, 7%, 1%, and 1.5% higher than the CS of the hot form at 7, 14, 21, and 28 days, respectively. Referring to Figure 4, it is noted that the CS values of concrete with 200 ^{o}C burnt cement in hot form increase initially, attain a maximum strength at 21 days of curing, and reduce at 28 days. Whereas in the cold form, the CS increases as the curing age increases, attains a maximum strength at 14 days, and then reduces at 21 and 28 days. The CS of the hot form at 200 ^{o}C is 119%, 69%, and 9% higher than the CS of the cold form at 7, 21, and 28 days, respectively, while the CS of the cold form is 25% higher than the CS of the hot form at 14 days. The CS of the hot form at 300 ^{o}C is 18.5%, 24%, and 14% higher than the CS of the cold form at 14, 21, and 28 days, respectively, while the CS of the cold form is 6% higher than the CS of the hot form at 7 days.

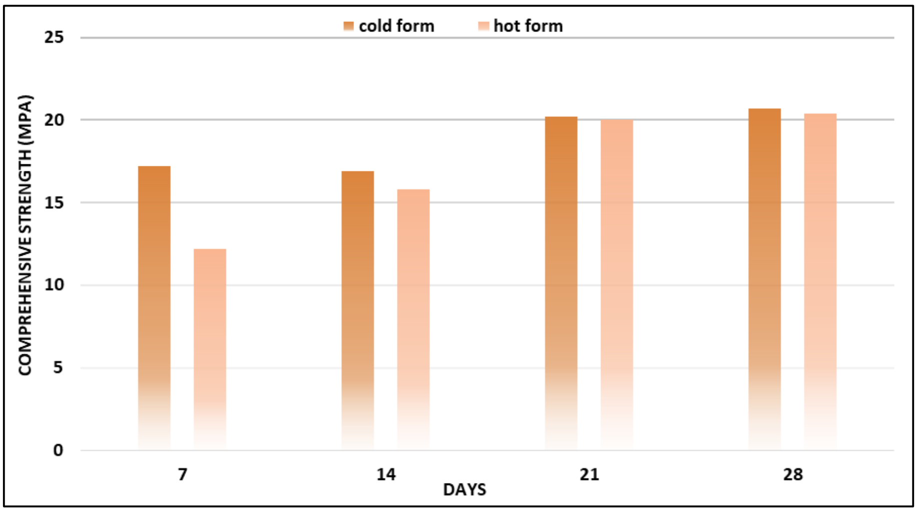

Fig 3: Comparison of the CS of cold and hot form for 100^{0}C

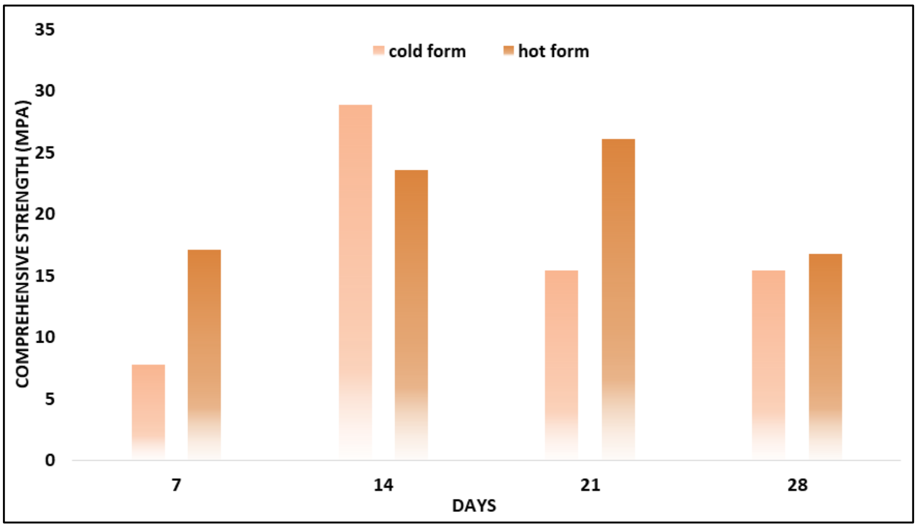

Fig 4: Comparison of the CS of cold and hot form for 200^{0}C

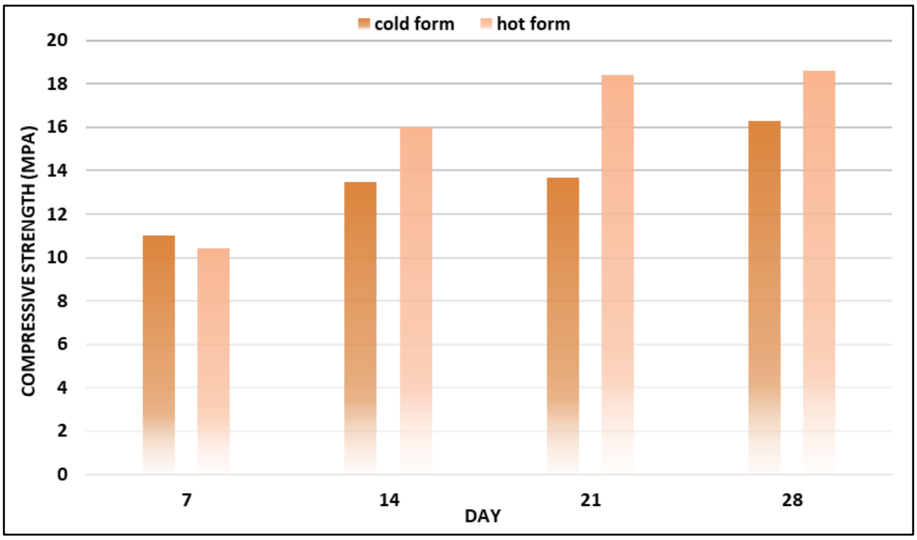

Fig 5: Comparison of the CS of cold and hot form for 300^{0}C

3.4 Statistical Data Analysis, Model Development, Optimization and Test Results Application

This section's main points are on the development of mathematical models; statistical analysis of the variance of developed mathematical models, and optimization for effective application. Having considered four levels of calcination temperatures of 0, 100, 200, and 3000C experimentally, only compressive strength at 28 days' response was statistically analyzed using Design Expert.

3.4.1 Design summary for calcination temperatures

The design summary for calcination temperatures of 0, 100, 200, and 300^{0}C is depicted in Tables 3 and 4.

Table 3: Design factors and response

	Factor 1	Response 1
Run	Temperature	Compressive strength (MPa)
1	300	16.3
2	200	15.4
3	300	16.3
4	200	15.4
5	0	31.4
6	100	20.7
7	100	20.7
8	0	31.4
9	200	15.4
10	100	20.7
11	0	31.4
12	0	31.4
13	300	16.3

Tables 4: Summary of design method and factors constraints

Design Summary				
File Version	13.0.5.0			
Study Type	Response Surface		**Subtype**	Randomized
Design Type	I-optimal	Coordinate Exchange	**Runs**	13.00
Design Model	Quadratic		**Blocks**	No Blocks
Build Time (ms)	228.00			

Table 5: Response Summary

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001		0.7996	0.7425	
Quadratic	**< 0.0001**		**0.9998**	**0.9997**	**Suggested**
Cubic			1.0000		
Quartic					**Aliased**

3.4.2 Model Development and Analysis of variance (ANOVA)

The empirical model is considered to be significant by the model's F-value of 30127.76. An F-value this big might happen owing to noise just 0.01% of the time. Empirical model terms are considered significant when their P-values are less than 0.0500. α and α^2 are important model terms in this instance.

Table 6: ANOVA summary for the compressive strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	585.78	2	292.89	30127.76	< 0.0001	significant
α -Temperature	432.91	1	432.91	44531.32	< 0.0001	
α^2	107.55	1	107.55	11063.18	< 0.0001	
Residual	0.0972	10	0.0097			
Lack of Fit	0.0972	1	0.0972			
Pure Error	0.0000	9	0.0000			
Cor Total	585.87	12				

Table 7: Fit Statistics

Std. Dev.	**0.0986**	R^2	**0.9998**
Mean	21.75	**Adjusted R^2**	0.9998
C.V. %	0.4532	**Predicted R^2**	0.9997
		Adeq Precision	335.8792

The variation amongst the predicted coefficient of regression (R^2) of 0.9997 and the adjusted coefficient of regression (R^2) of 0.9998 is less than 0.2, which is considered to be a fair agreement. The ratio of signal to noise is measured by adequate precision. A ratio of at least 4 is preferred. The ratio of 335.879 shows a strong signal.

The empirical model for compressive strength (CS) as a response and calcination temperature (**α**) as a factor from the ANOVA study is of the form Eq. (1)

$$SC = 0.000290(\alpha)^2 - 0.137494(\alpha) + 31.43038 \qquad (1)$$

Where;

α is the calcination temperature

CS is the compressive strength

For a specific degree of fire temperature, the CS may be predicted using the empirical model (Eq.1)

3.4.3 Validation of the empirical model
The Table 8 analysis reveals that the compressive strength prediction made by the empirical model is significant. The values represented in Table 8 demonstrate how conservatively Equation 1 predicts the CS.

Table 8: Analytical model for load-carrying capacity

Calcination Temperature	Experiment CS at 28-day (MPa)	Predicted CS at 28-day Equation (eq.1) (MPa)
0°C	31.4	31.43
100°C	20.7	20.6
200°C	15.4	15.5
300°C	16.3	16.28

4. Conclusion
The stability assessment of concrete produced with cement exposed to open fire have been investigated and the following conclusions are drawn from the findings:

- Cement exposed to open fire had a negative impact on the stability of the concrete.
- The burnt cement at a temperature of 100, 200, and 300 ^{0}C in cold form reduces CS of concrete by 34, 50 %, and 48% respectively.
- The burnt cement at a temperature of 100, 200, and 300 ^{0}C in hot form reduces CS of concrete by 35, 46, and 40% respectively.
- Burnt cement at a temperature of 100, 200, and 300 ^{0}C can be used in light weight concrete. It can also be used in sandcrete block production.
- The variation amongst the predicted coefficient of regression (R^2) of 0.9997 and the adjusted coefficient of regression (R^2) of 0.9998 is less than 0.2, which is considered to be a fair agreement.
- The reduction in CS is attributed to heating calcium, silica, aluminum, and iron.

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