

# Short-term Study of the Influence of Aggregate Size on the Fire Resistance of Concrete

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**ABSTRACT:** This study aims to investigate the effect of aggregate size on the fire resistance of concrete. The binder for this investigation was 42.5R CEM II/A-L Portland limestone cement, and the crushed granite sizes were 20mm, 12.5mm, and a blend (20 mm + 12.5 mm). The concrete was designed with a mix ratio of 1:2:4 (batching by weight) and 0.55w/c. The workability of the concrete was determined using the slump method. The concrete specimens were cured for 7, 14, and 28 days by immersion and later exposed to heat temperatures of 26.8 °C (Room temperature), 60 °C, 120 °C, 180 °C, and 240 °C. The compressive strength of normal concrete (without heating) had the optimum with concrete produced with blended aggregate size and conversely the least with 20mm aggregate size concrete. When subjected to heat, the optimal performance noted for the influence of aggregate size on fire resistance was also with concrete produced with combined blend (20 mm + 12.5 mm) sizes. The p-value (Prob > F) for the whole model test is less than 0.05, indicating that there is a significant relationship between the grain size, temperature, and strength loss. The use of blended sizes of 12.5 mm and 20 mm is therefore recommended for concrete works and especially when fire resistance is a requirement.

**KEYWORDS:** Aggregate size, Compressive strength, Density loss, Concrete, Fire resistance

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## I. INTRODUCTION

Concrete is a brittle or quasi-brittle and widely used material, with applications ranging from structural elements to various types of useful materials (Chen et al., 2020). Aggregate serves as the skeleton of concrete, accounting for approximately 60 – 78 percent by volume and 63 – 85 percent by mass (Viera, 2015), and it has a significant influence on the properties of concrete. Quarry dust, naturally occurring sand (usually collected from sand deposits), and river sand obtained from river beds are the most common fine aggregates used for construction in Nigeria, while crushed granite and bush gravel are the most common coarse aggregates. Granite (a non-metallic industrial mineral) is an abundant resource in Nigeria (NBS, 2019; Olade, 2019) and particularly in Ekiti State, which derives its name from the state's hilly terrain. Crushed granite is the preferred coarse aggregate for conventional concrete (Shehu et al., 2016), whereas gravel (usually obtained from the natural disintegration of rock) is less used for concrete works due to a palpable fear that it cannot withstand much pressure (Sulymon et al., 2017), and has a very weak resistance to abrasion and some other concrete durability issues. Fire is one of the main dangerous and destructive disasters that endanger engineering structures including concrete (Xu et al., 2020). However, concrete is said to be more resistant to high temperatures than other building materials (Pallapu et al., 2020) due to its high specific heat energy and thermal conductivity but it expands, loses free water, and dehydrates hydrated cement products, resulting in a loss of integrity,

significant strength degradation, and heat insulation when exposed to fire. Bashir and Singh (2017) stated that when concrete is exposed to temperatures above 100 °C, its density and strength decrease. Further, Serrano et al., (2016) remarked that concrete's physical properties are impaired at temperatures above 280 °C, and its mechanical properties are diminished at temperatures above 280 °C, with a loss of about 15% in compressive strength at around 400 °C. Similarly, Aluko et al., (2020) stated that when concrete is exposed to heat, physio-chemical changes occur (evaporation of free water and decomposition of calcium hydroxide into lime and water, loss of chemically bound water at 100 °C, hydration of un-hydrated cement at 300 °C, and complete loss of capillary water at 400°C). Tensile strength and modulus of elasticity, among other concrete properties, are also adversely affected when exposed to fire at high temperatures. This degradation is influenced by heating rate, aggregate type, specimen size, moisture content, and specimen age (Kore & Vyas, 2019; Wu et al., 2020). Bashir & Singh (2017) and Kore & Vyas (2019) remarked that concrete's residual strength (after cooling) is affected by temperature, mix design, and loading conditions.

Pallapu et al., (2020) observed a corresponding reduction in the crushing load of concrete when subjected to a temperature ranging from 0 - 300°C in steps of 20°C in their work where 20mm size coarse aggregate was used. Chen et al., (2020) also investigated the fire resistance of cementitious composites containing recycled glass cullets (RGCs). A temperature range of 0 – 1200 °C with 300 °C steps was used with varying RGC sizes. Except when mortar containing <

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0.6mm was heated up to 300 °C, the behaviour revealed a general loss in compressive strength with increasing temperature.

Similarly, Umasabor & Okovido, (2018) assessed the fire resistance of concrete containing rice husk ash. 20mm granite (coarse aggregate) and a blend of RHA - Cement (binder) at varying cement replacement levels were used, and the specimens were heated at temperatures ranging from 100°C - 700°C for 2 hours. The residual compressive strength behaviour (after 200 curing days) of the specimens, particularly Portland Cement Concrete(PCC), demonstrated a reduction in strength with a corresponding increase in heating temperature from 100 °C to 700 °C at 100 °C intervals. In summary, the findings in the available literature indicated a loss in residual compressive strength of concrete specimens subjected to varying heat temperatures but there is a gap in the literature on the use of 12.5mm, the blended coarse aggregate size of 20mm, and 12.5mm in the investigation of Portland Cement Concrete (PCC) fire resistance. As a result, this study aims to bridge the knowledge gap and broaden knowledge frontiers by providing remarkable data on the performance of aggregate sizes and types on fire resistance of PCC.

## II. METHODOLOGY

### A. Material Sampling

A Portland limestone cement (42.5R CEM II/ A – L) obtained from a commercial retail store was used. Potable water devoid of impurities, silt, and organic elements was equally used. River sand free of debris and impurities and conforming to FMWH, (1997) grading zone II was used as fine aggregate, while crushed granite of 20 mm, 12.5mm, blended (20mm + 12.5mm in equal proportion) was used as coarse aggregate.

### B. Sample Preparation and Methods

Water absorption and specific gravity of the coarse aggregates (20mm, 12.5mm, and blended) were performed following BS 812, Part 2 (1995) while the aggregate crushing value of the 20mm, 12.5mm, and blended coarse aggregates and particle size distribution of granite (sourced from the quarry) were performed according to BS 812-110 (1990) and BS 812-103.1 (1985) respectively. For fine aggregate (River sand), the specific gravity and particle size distribution (dry sieving method) were performed following BS 1377, Part 2 (1990) while the clay and silt content was determined by the field settling method described by BS 812, Part 1, (1975).

A water-cement ratio (W/C) of 0.55 and a design mix ratio of 1:2:4 (by weight) were adopted in the production of the concrete. The workability of the fresh concrete was determined by using the slump cone following BS 1881-102(1983). Afterward, the fresh concrete was compacted in three layers into the prepared 150 × 150 × 150 mm steel cube. After 24 hours, the concrete cube specimens of varying coarse aggregate sizes (20 mm, 12.5mm, blended (20mm + 12.5mm in equal proportion) were demoulded, labeled appropriately, and cured by full water immersion for 7, 14, and 28days respectively. The

set of cubes at required curing ages were removed from the curing tank and exposed to the air to dry out moisture. Concrete specimens (Control samples) of each coarse aggregate size were crushed under loading of a compression machine (without first subjecting them to heating for the stated curing ages). Marked concrete specimens were later subjected to heat temperature at 60°C, 120°C, 180°C, and 240°C in the oven in relation to curing ages and varying coarse aggregate size and type. After heating, the specimens were allowed to cool for 45 minutes (slow cooling) before they were subjected to compressive strength test.

### C. Statistical Analysis

Design expert version 6.0.6 with Response Surface Methodology (RSM) was used to analyze the effect of granite size and temperature on strength loss. RSM is a collection of mathematical and statistical techniques that uses quantitative data from the input variables. It is a useful method for evaluating the effects of multiple factors and their interactions on one or more response variables. Fitting a quadratic surface with the RSM method is a good option as it helps to analyse the interplay between the parameters. It builds an empirical model, improves and optimises process parameters, and discovers the interactions between various influencing factors (Behera et al., 2018). The tool was used to obtain Analysis of Variance (ANOVA), some inferential statistics, and 3D plot. ANOVA is a statistical procedure used to compare the means of parameters in different groups.

## III. RESULTS AND DISCUSSION

### A. Aggregate Characteristics

Some physical properties of the aggregates are shown in Table 1. The clay and silt content of the river sand is lower than 4% as stipulated by FMWH, (1997). The larger the coarse aggregate, the higher the water absorption rate. The crushing resistance of the aggregates (aggregate crushing value, ACV) under applied compressive load showed that 20mm granite size offered the best ACV with 28.4% while blended aggregates gave the least value of 14.8%. The values are although lower than the specification of ≤ 45% given by FMWH, (1997) for coarse aggregate. Specific gravity of aggregates (fine and coarse) contributes to concrete strength (Al-Gburi and Yusuf, 2022).

**Table 1: Some physical properties of the aggregates.**

Properties	River Sand	Granite		Blended aggregate
		20mm	12.5mm	
<b>Water absorption</b>	2.3	1.3	1.3	1.82
<b>Specific gravity</b>	2.67	2.83	2.8	2.78
<b>Aggregate Crushing Value</b>	-	28.4	24.6	14.8
<b>Clay and fine content</b>	0.46	0.23	0.23	0.57

The values as presented in Table 1 are in tune with reported values for fine aggregates and coarse aggregates

(Bamigboye et al., 2019; Fanijo et al., 2020). The obtained results showed that the materials are good for concrete works.

**B. Particle Size Distribution**

The results of the particle size distribution for fine aggregate (River Sand) and sourced coarse aggregate (crushed granite) are presented in Figure 1. The aggregates fell within the sand and gravel class as given by BS 1377 (1990). River sand belongs to Zone 2 of the fine aggregate grading envelope (FMWH, 1997). The coefficient of Uniformity ( $C_u$ ) - obtained by dividing  $D_{60}$  by  $D_{10}$  ( $D_{60}/D_{10}$ ) - and Coefficient of Curvature ( $C_c$ ) - obtained by dividing  $(D_{30})^2$  by  $(D_{60} \times D_{10})$  - of crushed granite are 5.4 and 1.92 respectively. River sand has  $C_u$  of 3.7 and a  $C_c$  of 0.76. Crushed granite (as sourced from quarry) is well-graded gravel, GW ( $C_u > 4$  and  $1 \leq C_c \leq 3$ ) while the river sand is poorly-graded sand according to the Unified Soil Classification System (USCS). This makes the river sand suitable for concrete work (Coduto, 1999). The values obtained for crushed granite agree with the findings of Ogunbayo *et al.*, (2018), while river sand agrees with the report of Olonade *et al.*, (2017).

of the concrete at varying ages and temperatures. It is observed that the density has notable influence on the compressive strength of concrete at all temperatures. As shown in Figure 3, the compressive strength behaviour of the normal concrete (room temperature) followed the trend of PCC with expected strength gain corresponding to an increase in curing age. Values of 10.12 N/mm<sup>2</sup>, 14.11 N/mm<sup>2</sup>, and 17.13 N/mm<sup>2</sup> were obtained for concrete made from 12.5mm granite at 7 days, 14 days, and 28 days respectively. 9.9 N/mm<sup>2</sup>, 14 N/mm<sup>2</sup>, and 16.29 N/mm<sup>2</sup> were obtained for concrete made from 20mm granite size at 7 days, 14 days, and 28 days respectively while 11.39 N/mm<sup>2</sup>, 15.06 N/mm<sup>2</sup>, and 18.98 N/mm<sup>2</sup> were obtained for concrete containing blended aggregates (12.5 mm and 20 mm) at 7 days, 14 days and 28 days respectively. Concrete made with 12.5 mm and blended sizes gave better compressive strength as compared with concrete made with 20 mm granite size. The better performance of 12.5 mm granite concrete may be due to the ease of compaction of smaller-sized aggregate concrete while the optimal behaviour of concrete made with blended aggregates may be attributed to the presence of medium-sized aggregates where some voids are filled in the interfacial transition zone (ITZ) which Wei *et al.*, (2020) reported is responsible for higher strength gain.

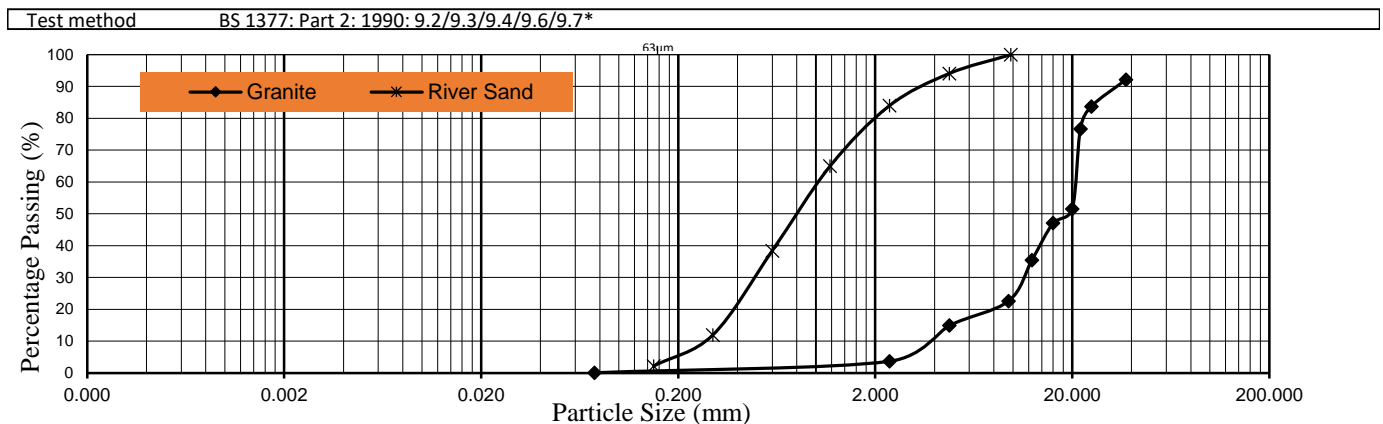


Figure 1: Sieve analysis of river sand and granite (as sourced from quarry).

**C. Workability of the Concrete**

Slump values for fresh concrete using different coarse aggregates are shown in Table 2. The fresh concrete specimens indicated a true slump with concrete made from blended aggregates having the highest value of 44 mm. The fact that concrete of lower size of granite exhibit better workability i.e. lowest slump is consistent with the findings of some researchers (Ogundipe *et al.*, 2018).

**D. Compressive Strength Behaviour Before and After Heating**

Strength is an index of concrete quality and compressive strength is referred to as the most important property (Owens, 2009; Viera, 2015). The behaviour of varying concrete specimens subjected to heating is depicted in Figures 2, 3, and Table 3. Figure 2 presents the apparent density behaviour

Also, the higher compressive strength attained with concrete containing smaller granite size aligns with reports of some researches (Umasabor & Osayogie, 2020; Al-baghdadi et al., 2021). Concrete specimens showed reduced residual strength with increment in heating temperature as presented in Figure 3 and Table 3. The reduction may be attributed to the (loss of some pore water) water-evaporation rate which is dependent on the pore system of the specimens as well as the decrease in apparent density (Seghir *et al.*, 2019). Generally, the residual

Table 2: Workability of fresh concrete.

Particle size (mm)	Concrete mix ratio	Slump value (mm)	Slump type	Degree of workability
20	1:2:4	42	True slump	Low
12.5	1:2:4	40	True slump	Low
Blended	1:2:4	44	True slump	Low

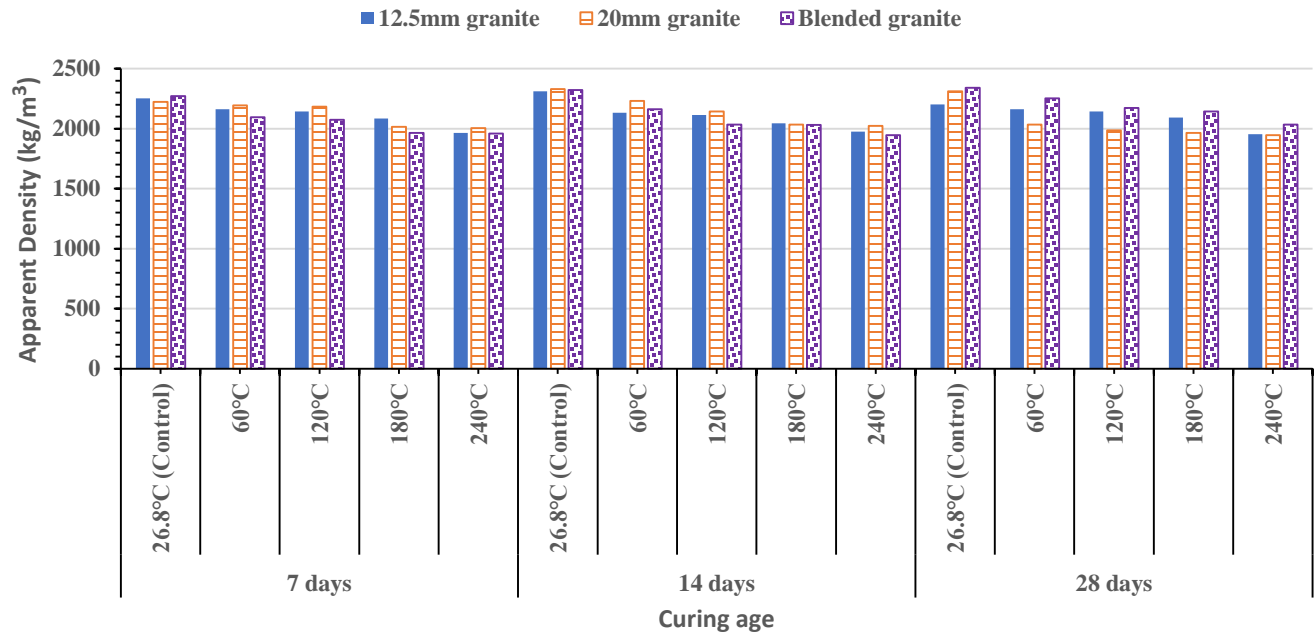


Figure 2: Density behaviour of concrete.

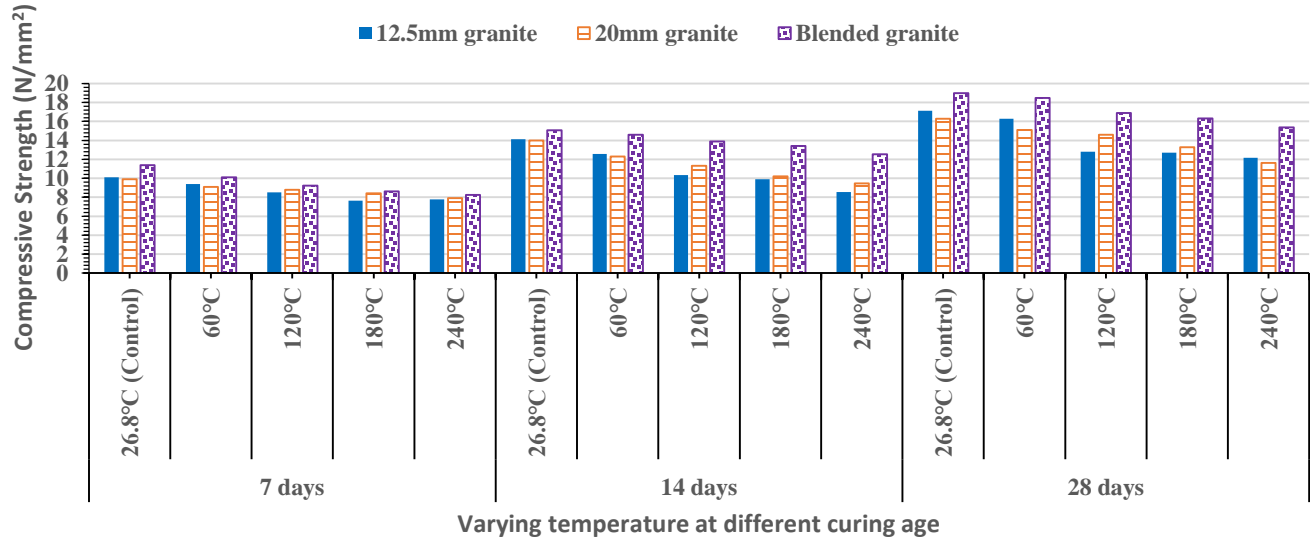


Figure 3: Compressive strength behaviour of concrete.

compressive strength of the concrete sample was reduced with corresponding higher temperatures. This consequently resulted in higher strength loss in %. This agrees with the available literature (Grubeša et al., 2018; Umasabor & Okovido, 2018; Rahim Zai & Salhotra, 2020). Comparatively, the effect of aggregate size on the fire resistance of concrete showed that concrete made with blended aggregate offered the highest heat resistance, followed by 20mm granite size concrete. This behaviour may be attributed to the pore system as well as concrete moisture content which are the influencing factors on the fire resistance of concrete (Chandra & Berntsson, 2002). Expectedly, there was also a decrease in the apparent density of hardened concretes with a corresponding increase in temperature.

*E. Effect of Coarse Aggregate Size and Temperature on Strength Loss*

Granite sizes were 12.5 mm, 20 mm, and blended sizes and temperatures vary from 60 to 240 °C. The strength loss ranges from 7.02 – 27.66% ( $12.27 \pm 2.24$ ), 3.05 – 39.29% ( $19.73 \pm 2.28$ ), 2.63 – 28.73 % ( $16.38 \pm 3.96$ ) for concrete cured at 7 days, 14 days, 28 days respectively as shown in Table 4.

Concrete samples cured for 7, 14, and 28 days showed an increase in strength loss as the size of granite increased. The behaviour is depicted in the response surface plot. The effect of grain size and temperature on the heat resistance of concrete cured at 7 days, 14 days, and 28 days are shown in Figure 4. The 3D plots presented in Figures 4 (a) and (b) are quadratic (i.e. saddle in nature) which suggests that both A (Granite Size) and B (Temperature) have effects on strength loss for 7 and 14

days of cured concrete. Conversely, the plot (plane) as presented in Figure 4C, implies that there are only the main effects and no interaction effects. This is evident in the straight contour lines (Anthony, 2014).

The general implication of the increase in strength loss is that the lower the granite size, the better its performance in resisting heat. The goodness of the fit for the model that gave the best fit for heat resistance of concrete cured for 7, 14, and 28 days are expressed by Coefficient of Determination ( $R^2$ ).

The  $R^2$  values are 0.9424, 0.9775, and 0.8526 for 7, 14, and 28 days cured - concrete respectively as shown in Table 4. These values suggest that respective models could explain 94.24%, 97.75%, and 85.2% of the variability in the response for heat resistance of concrete cured for 7, 14, and 28 days respectively. The ANOVA summary generated by RSM is shown in Table 5. The p-value is Prob > F for the whole model test. Since Prob > F is less than 0.05, the relationship between the independent variables (effect of grain size and temperature) and dependent variable (strength loss) is significant as p-values of 0.0012, 0.0001, and 0.0002 were obtained for 7, 14, and 28 days cured concrete.

**Table 3: Strength and apparent density loss of concrete at elevated temperature.**

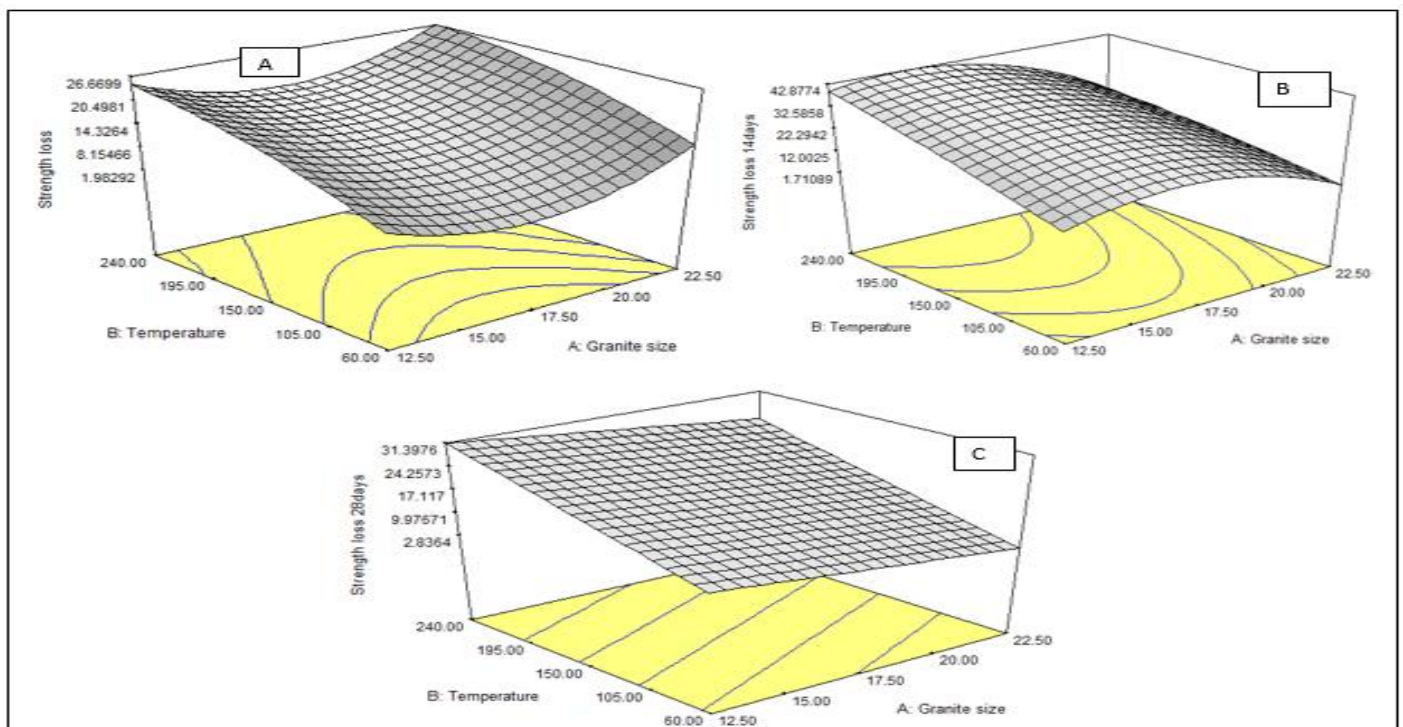
Curing age (days)	Granite size (mm)	Temperature (°C)	Strength (N/mm <sup>2</sup> )	Strength loss (%)	Density (kg/m <sup>3</sup> )	Apparent density loss (%)
7	12.5	26.8	10.12	-	2252	-
		60	9.41	7.02	2163	3.95
		120	8.5	16.01	2143	4.84
		180	7.65	24.41	2084	7.46
		240	7.79	23.02	1965	12.74
	20	26.8	9.9	-	2222	-
		60	9.1	8.08	2193	1.31
		120	8.8	11.11	2183	1.76
		180	8.4	15.15	2015	9.32
		240	7.9	20.2	2005	9.77
	Blended	26.8	11.39	-	2272	-
		60	10.12	11.15	2094	7.84
		120	9.21	19.14	2074	8.72
		180	8.62	24.32	1965	13.51
		240	8.24	27.66	1965	13.73
14	12.5	26.8	14.1	-	2311	-
		60	12.56	10.92	2133	7.7
		120	10.34	26.67	2114	8.52
		180	9.89	29.86	2044	11.55
		240	8.56	39.29	1975	12.74
	20	26.8	14	-	2331	-
		60	12.19	12.93	2232	4.25
		120	11.33	19.07	2143	8.07
		180	10.19	27.21	2034	12.74
		240	9.47	32.36	2024	13.17
	Blended	26.8	15.06	-	2321	-
		60	14.6	3.05	2163	6.81
		120	13.88	7.84	2035	12.32
		180	13.42	10.89	2035	12.54
		240	12.54	16.73	1946	16.16
28	12.5	26.8	17.13	-	2203	-
		60	16.27	5.02	2163	1.82
		120	12.82	25.16	2143	2.72
		180	12.7	25.86	2093	4.99
		240	12.18	28.9	1955	11.26
	20	26.8	16.29	-	2311	-
		60	15.1	7.31	2035	11.94
		120	14.6	10.38	1985	14.11
		180	13.29	18.42	1965	14.97
		240	11.61	28.73	1946	15.79
	Blended	26.8	18.98	-	2341	-
		60	18.48	2.63	2252	3.8
		120	16.88	11.06	2173	7.18
		180	16.31	14.07	2143	8.46
		240	15.38	18.97	2035	13.07

**Table 4: Inferential statistics results of granite size and temperature strength loss.**

Statistics	Curing age (days)		
	7	14	28
Mean	17.27	19.73	16.38
Std. Dev.	2.24	2.28	3.96
R-Squared	0.9424	0.9775	0.8526
Adj R-Squared	0.8944	0.9587	0.8199

**Table 5: ANOVA Summary.**

	Source	Sum Squares	DF	Mean Square	Value	Prob > F
7 Days	Model	494.56	5	98.91	19.64	0.0012
	A	17.43	1	17.43	3.46	0.1121
	B	376.02	1	376.02	74.67	0.0001
	A <sup>2</sup>	94.45	1	94.45	18.76	0.0049
	B <sup>2</sup>	14.11	1	14.11	2.80	0.1452
	AB	1.05	1	1.05	0.21	0.6642
	Residual	30.21	6	5.04	-	-
14 Days	Model	1348.77	5	269.75	52.04	< 0.0001
	A	581.92	1	581.92	112.25	< 0.0001
	B	701.08	1	701.08	135.24	< 0.0001
	A <sup>2</sup>	199.41	1	199.41	38.47	0.0008
	B <sup>2</sup>	3.27	1	3.27	0.63	0.4576
	AB	44.94	1	44.94	8.67	0.0258
	Residual	31.10	6	5.18	-	-
28 Days	Model	816.05	2	408.03	26.03	0.0002
	A	171.40	1	171.40	10.94	0.0091
	B	644.65	1	644.65	41.13	0.0001
	Residual	141.07	9	15.67	-	-



**Figure 4: 3D plot of the effect of granite size and temperature on strength loss.**

#### IV. CONCLUSION

The study assessed the compressive strength properties of concrete mixes produced with varying coarse aggregate sizes (12.5mm, 20mm, and a blend of 12.5 & 20mm aggregates) and exposed to elevated temperature (60°C - 240°C). Typical of the behaviour of normal concrete cured by immersion, there was strength gain corresponding to an increase in curing age. Also, the compressive strength of the concrete mixes in relation to aggregate size revealed that concrete produced with blended aggregate sizes of 12.5mm and 20mm had the best compressive strength, as the temperature increases the residual compressive strength decreases. However, concrete made with blended aggregate size possessed the highest fire resistance. The use of blended aggregate sizes in concrete is therefore recommended for concrete works. However, there is a need for further investigation of the long-term performance and durability of the concrete mixes in terms of curing age and exposure to elevated temperatures.

#### AUTHOR CONTRIBUTIONS

**F. O. Ayodele:** Conceptualization, Methodology, Investigation, Writing - Original draft preparation. **O. R. Olulope:** Methodology, Writing - Review & Editing. **I. S. Ayeni:** Conceptualization, Investigation, Writing - Review & Editing

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