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Effect of Mild Temperature Exposure on the Compressive Strength of Grade 20 Concrete: An Experimental Investigation for Tropical Construction Applications

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Abstract- ***Concrete elements in tropical environments are frequently subjected to sustained mild temperatures arising from solar radiation, proximity to heat-generating equipment, and bush fires, yet the thermal response of the low-grade concretes most used in such regions remains poorly documented. This study investigated the residual compressive strength of Grade 20 concrete after exposure to mild temperatures of 40, 60, 80, 100 and 120 °C. Seventy-two 100 mm cube specimens were produced from a 1:2:4 mix with a water/cement ratio of 0.6, water-cured for 7, 14, 21 or 28 days, heated for one hour at the target temperature, air-cooled for 24 hours, and tested in uniaxial compression against unheated control specimens. At early ages (7 and 14 days), exposure up to 100 °C increased strength by as much as 16.4 %, an effect attributed to accelerated hydration and free-water loss. This benefit disappeared with maturity: at 21- and 28-days strength decreased monotonically with temperature, the largest loss (23.3 %) occurring at 21 days and 120 °C. At the design age of 28 days, reductions were 1.6, 7.9, 10.1, 11.1 and 16.4 % at 40–120 °C respectively, and the residual strength at 120 °C (26.3 N/mm²) still exceeded the characteristic strength of 20 N/mm². Grade 20 concrete therefore exhibits acceptable thermal tolerance within the mild-temperature range, supporting its continued use in warm climates and providing baseline data for assessing low-grade concrete after mild thermal events.***

Keywords: Grade 20 Concrete, Mild Temperature, Compressive Strength, Residual Strength, Curing Age, Tropical Climate

I. INTRODUCTION

Concrete is the most widely used construction material in the world, valued for its versatility, compressive strength, mouldability and relatively low cost (Neville, 2011; Soutsos & Domone, 2017). Its mechanical properties are, however, sensitive to temperature, and concrete structures are increasingly exposed to thermal conditions that depart from the ambient values assumed in routine design (Guo & Shi, 2011; Kodur, 2014). Such exposure may arise from accidental fires, from operational service conditions near furnaces, boilers, chimneys and generators, or from environmental causes. In tropical countries such as Nigeria, surface temperatures of exposed concrete elements can rise well above air temperature during the dry season as a result of intense solar radiation, while bush burning around built-up areas subjects boundary walls, pavements and low rise buildings to repeated episodes of mild heating. These thermal events rarely reach the temperatures associated with structural fires, but they are sustained, recurrent and largely unaccounted for in design, which raises a practical question for engineers: does exposure to mild temperatures, here taken as 40 °C to 120 °C, measurably compromise the compressive strength of the concrete grades in common use.

The physical and chemical processes through which temperature affects concrete are well established for the high temperature regime. As temperature rises, free and physically bound water evaporates, calcium silicate hydrate (C-S-H) progressively dehydrates, calcium hydroxide decomposes above about 400 °C, and differential thermal strains develop between the shrinking cement paste and the expanding aggregate, producing microcracking that concentrates at the interfacial transition zone (Khoury, 1992; Kodur, 2014; Ma *et al.*, 2015). The net effect on strength depends on the balance between these damage mechanisms and beneficial processes such as accelerated hydration and densification of the paste at moderate temperatures, and it is strongly influenced by concrete grade, aggregate mineralogy, moisture state, heating rate, exposure duration and cooling regime (Arioz, 2007; Ballim & Otieno, 2021; Husem, 2006). Cooling conditions are particularly important: quenching in water, as occurs during firefighting, induces thermal shock and consistently produces larger strength losses than gradual cooling in air (Husem, 2006).

A substantial body of experimental work exists on concrete at elevated temperature, but its coverage is uneven. Most studies have addressed fire scenarios involving temperatures of 200 °C to 1200 °C, often on medium and high strength concretes. Arioz (2007) exposed ordinary Portland cement concretes with crushed limestone and river gravel aggregates to 200 °C to 1200 °C and reported progressive losses of weight and strength, with sharp degradation beyond 800 °C. Chan *et al.* (1999) compared normal strength and high strength concretes up to 1200 °C and found that losses below 400 °C were comparatively small, while high strength mixes suffered disproportionately at higher temperatures because their dense pore structure traps water vapour. Phan and Carino (1998), reviewing high strength concrete data, similarly identified pore pressure build up and paste densification as the controlling factors that distinguish high strength from normal strength behaviour. Husem (2006) showed that both ordinary and high-performance concretes lose strength with temperature and that water cooling aggravates the loss relative to air cooling. El-Zohairy *et al.* (2020) reported that plain hardened concrete lost 10 to 20 % of its original strength when heated to 100 °C and 30 to 40 % at 260 °C and proposed constitutive relationships for the heated material.

Work within or near the mild range relevant to tropical service conditions is far more limited and has concentrated on higher grades. Osuji and Ukeme (2015) investigated Grade 40 concrete produced with Benin City aggregates at 100 °C to 300 °C and recorded compressive strength reductions of 14.5 % at 100 °C rising to 53.5 % at 300 °C. Venkateswara Rao and Achyutha Kumar Reddy (2021) exposed M45 concrete to 50 °C to 300 °C for one to three hours and observed strength gains up to about 250 °C followed by decline, together with moisture losses of 0.43 to 4.67 %. Umasabor and Osaigbovo (2021), applying response surface methodology to Grade 30 concrete heated to 62.5 °C and 100 °C, found strength increases of 11.8 to 12.1 %, which they attributed to accelerated hydration reactions under mild heating. Farzampour (2019) demonstrated the sensitivity of concrete strength to environmental variables more broadly, reporting that even modest changes in curing temperature and humidity alter strength development appreciably. Collectively these studies confirm a transition behaviour, in which mild heating may initially benefit strength before damage mechanisms dominate, but they leave the position of that transition for low grade concrete unresolved (Kodur, 2014; Ma *et al.*, 2015).

Three gaps in the literature motivate the present study. First, Grade 20 concrete has been largely overlooked. Research attention has concentrated on grades 30 to 60 and on high performance mixes, yet Grade 20 is the workhorse of residential buildings, boundary walls, pavements and other low-rise construction across developing countries, precisely the structures most often exposed to solar heating and bush fires. Its higher porosity and leaner paste content give it a different thermal response from denser mixes, since open pore structures relieve vapour pressure and accommodate thermal strain (Chan *et al.*, 1999; Soutsos & Domone, 2017), so results from higher grades cannot simply be extrapolated downwards. Second, the mild temperature band of 40 °C to 120 °C is itself underrepresented; most test programmes begin at 100 °C or 200 °C, leaving the temperatures actually experienced in tropical service largely uncharacterised. Third, the interaction between curing age and thermal exposure has received little systematic attention. Most investigations heat specimens only at 28 days (Osuji & Ukeme, 2015; Umasabor & Osaigbovo, 2021), yet real structures may experience thermal events at any age, and the maturity literature indicates that the effect of temperature on strength is strongly age dependent (Carino & Lew, 2001; Neville, 2011). Design guidance reflects these gaps: codes such as BS 8110 (British Standards Institution, 1997) address fire resistance through prescriptive cover provisions (Mosley & Bungey, 1990) but offer no basis for assessing sustained mild heating.

The present study addresses these gaps through a factorial laboratory investigation of Grade 20 concrete exposed to mild temperatures at four curing ages. The specific objectives were: (1) to determine the effect of one hour exposures at 40 °C, 60 °C, 80 °C, 100 °C and 120 °C on the compressive strength of Grade 20 concrete cured for 7, 14, 21 and 28 days; (2) to quantify the percentage change in strength relative to unheated control specimens; and (3) to characterise the relationship between exposure temperature, curing age and residual strength, including the associated changes in specimen mass and density. Air cooling was adopted after heating to represent the gradual cooling that follows solar heating, equipment shutdown or a burnt-out bush fire (Husem, 2006).

The approach is deliberately simple, and code based, using standard cube specimens, standard curing and standard testing procedures (British Standards Institution, 1983a, 1983b), so that the resulting database can be applied directly in practice. The study builds on the regional work of Osuji and Ukeme (2015) and Umasabor and Osaigbovo (2021) by extending the investigation to a lower grade, a finer temperature resolution within the mild band, and multiple curing ages, and it differs from the bulk of the international literature by targeting service relevant rather than fire relevant temperatures. The findings provide engineers in warm climates with quantitative evidence on whether Grade 20 concrete remains structurally adequate after mild thermal exposure, and they supply baseline data against which maturity based and damage-based models of low-grade concrete can be calibrated (Carino & Lew, 2001; Guo & Shi, 2011).

II. MATERIALS AND METHODS

2.1 Study Design and Research Setting

The investigation was designed as a controlled laboratory experiment with a two-factor factorial layout. The first factor was exposure temperature at six levels (20 °C control, 40 °C, 60 °C, 80 °C, 100 °C and 120 °C) and the second was curing age at four levels (7, 14, 21 and 28 days), giving 24 treatment combinations. Three replicate cubes were tested for each combination in accordance with BS 1881: Part 116 (British Standards Institution, 1983b), giving 24 treatment combinations. Three replicate cubes were tested for each combination in accordance with BS 1881: Part 116 (British Standards Institution, 1983b), giving a total of 72 specimens. The dependent variables were residual compressive strength, specimen mass and hardened density. The work was carried out in the Civil Engineering Laboratory of the University of Benin, Benin City, Nigeria, between January and May 2026.

A factorial design was chosen because the study objectives concern not only the main effect of temperature but also its interaction with curing age, that is, whether a thermal exposure that is harmless or beneficial at one age becomes damaging at another. A one factor at a time approach would not resolve this interaction, whereas the factorial layout allows the strength versus temperature relationship to be traced separately at each age using the same materials, mix and procedures (Guo & Shi, 2011). Residual strength testing, in which specimens are heated, cooled and then loaded, was adopted in preference to hot testing because it represents the condition of practical interest, namely the assessment of a structure after a thermal event has passed, and because it follows the recommendations of RILEM TC 129-MHT (2000) for post exposure property determination.

2.2 Materials

Ordinary Portland cement of strength class 42.5 (Dangote brand) conforming to BS EN 197-1 (British Standards Institution, 2011) was used as the binder. Its specific gravity was 3.15, consistent with the typical range for Portland cements (Neville, 2011). The fine aggregate was natural river sand obtained from Isior in Benin City, with a maximum particle size of 4.75 mm and a specific gravity of 2.60. The sand was visibly free of organic impurities and clay lumps. The coarse aggregate was crushed granite of 12.5 mm maximum size from a quarry at Isior, Benin City, with a specific gravity of 2.71 and a rough, angular surface texture favourable to paste aggregate bond (Jackson & Dhir, 1992). Potable borehole water from the laboratory premises, satisfying BS 3148 (British Standards Institution, 1980), was used for both mixing and curing. No chemical or mineral admixtures were used, so that the measured response reflects plain Grade 20 concrete as commonly produced in the region.

2.3 Sampling and Aggregate Characterisation

Aggregate samples were reduced to test size by riffling in accordance with BS 812: Part 102 (British Standards Institution, 1989) to ensure representative portions. Sieve analysis of the fine aggregate was performed on a standard stack of BS sieves (10 mm, 5 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm and 150 µm) and the resulting grading curve was compared with the grading limits of BS 882 (British Standards Institution, 1992). Specific gravity tests were conducted on both aggregates using standard gravimetric procedures (Jackson & Dhir, 1992).

2.4 Concrete Design Mix and Proportioning

The concrete was proportioned for Grade 20 using a nominal mix ratio of 1:2:4 by weight (cement : fine aggregate : coarse aggregate) with a water/cement ratio of 0.6. The adequacy of the nominal mix was checked against the Department of Environment (DoE) mix-design method (Jackson & Dhir, 1992) to confirm that a target mean strength of 25 N/mm² at 28 days was attainable; this target was obtained by adding a margin of 5 N/mm² to the characteristic strength of 20 N/mm², in line with the design-margin philosophy of BS 8110 (British Standards Institution, 1997). This grade and ratio were selected because they represent the concrete most widely batched on small and medium construction sites in Nigeria, the population of structures the study is intended to inform.

2.5 Casting, Compaction and Curing

Concrete was mixed in batches sufficient for twelve cubes per temperature group, using a laboratory pan mixer, with hand mixing on a non-absorbent platform when electrical power was unavailable. Cubes of 100 mm × 100 mm × 100 mm were cast in oiled steel moulds in accordance with BS 1881: Part 108 (British Standards Institution, 1983a). Each mould was filled in three layers, each layer receiving 25 strokes of a standard tamping rod, after which the filled moulds were vibrated briefly on a vibrating table to expel entrapped air. Specimens were covered and left in the moulds for 24 hours, then demoulded, labelled and fully immersed in a water-curing tank until their scheduled age of 7, 14, 21 or 28 days (Neville, 2011). The curing water was at the ambient laboratory temperature of 25 ± 2 °C; this is slightly above the 20 ± 2 °C specified in BS 1881 and is reported here for transparency, reflecting typical unconditioned-laboratory practice in the tropical setting under investigation.

2.6 Workability

The workability of each fresh batch was assessed with the slump test in accordance with BS EN 12350-2 (British Standards Institution, 2000), using a standard cone of 100 mm top diameter, 200 mm bottom diameter and 300 mm height filled in three rodded layers. The slump was recorded as the vertical settlement of the concrete relative to the cone height.

2.7 Temperature exposure and cooling regime

At the end of each curing period the cubes were removed from the tank, surface dried with a cloth and weighed. Heated specimens were then placed in an electric furnace of 1200 °C capacity that had been preheated to the target temperature of 40 °C, 60 °C, 80 °C, 100 °C or 120 °C. Once the set point was re-established with the specimens inside, the cubes were held at the target temperature for one hour, a steady state duration consistent with the residual strength procedure of RILEM TC 129-MHT (2000) and short enough to represent a transient service event rather than prolonged industrial exposure. After heating, the cubes were withdrawn and allowed to cool in still laboratory air for 24 hours before testing. Air cooling was selected to simulate the gradual cooling that follows solar heating, plant shutdown or a self-extinguishing bush fire, in contrast to the thermal shock of water quenching, which is known to cause additional damage (Husem, 2006). Control specimens remained at the ambient reference condition of 20 °C. After cooling, each cube was reweighed so that the mass loss associated with moisture evaporation could be computed (Venkateswara Rao & Achyutha Kumar Reddy, 2021).

2.8 Compressive strength testing

Compressive strength was determined with a 2000 kN universal compression testing machine in accordance with BS 1881: Part 116 (British Standards Institution, 1983b). Each cube was placed with the cast faces perpendicular to the loading platens and loaded steadily at approximately 140 kg/cm² per minute until failure. The compressive strength was calculated as the failure load divided by the loaded cross-sectional area (10,000 mm²). Hardened density was computed from the measured mass and nominal volume of each cube.

2.9 Data analysis

For every temperature–age combination the mean and standard deviation of the three replicate strengths were computed, and results are reported as mean ± SD (El-Zohairy *et al.*, 2020). The percentage change in strength relative to the control was calculated as the heated mean minus the control mean, divided by the control mean, and expressed as a percentage, so that positive values denote a strength gain and negative values a loss. Strength–temperature and strength–age relationships were plotted to visualise the trends. For every temperature–age combination the mean and standard deviation of the three replicate strengths were computed, and results are reported as mean ± SD (El-Zohairy *et al.*, 2020). The percentage change in strength relative to the control was calculated as the heated mean minus the control mean, divided by the control mean, and expressed as a percentage, so that positive values denote a strength gain and negative values a loss. The effects of the two factors were then tested by a two-way analysis of variance (ANOVA), with exposure temperature (six levels) and curing age (four levels) as fixed factors and residual compressive strength as the response. Where a factor or the interaction was significant, Tukey's honestly significant difference (HSD) test was used for multiple comparisons; because the interaction was significant, each heated condition was compared with the 20 °C control separately within each curing age. All inferential tests were performed at the 5 % significance level. Strength–temperature and strength–age relationships were plotted to visualise the trends. Statistical analyses were carried out in IBM SPSS Statistics v2.9.

III. RESULTS AND DISCUSSION

3.1 Material Characterisation and Workability

The grading of the fine aggregate fell within Zone 2 of BS 882 (British Standards Institution, 1992), classifying it as a medium sand suitable for general structural concrete (Jackson & Dhir, 1992). The specific gravities of the sand, granite and cement were 2.60, 2.71 and 3.15 respectively, all within normal ranges (Neville, 2011). The slump of the fresh concrete was 60 mm, corresponding to medium workability appropriate for conventionally compacted reinforced concrete work. Table 1 summarises the constituent material properties.

Table 1. Properties of constituent materials.

Constituent	Description / standard	Key property
Cement	OPC 42.5 (BS EN 197-1)	Specific gravity 3.15
Fine aggregate	River sand, Zone 2 (BS 882), max. size 4.75 mm	Specific gravity 2.60
Coarse aggregate	Crushed granite, max. size 12.5 mm, angular	Specific gravity 2.71
Water	Potable borehole water (BS 3148)	w/c ratio 0.6
Fresh concrete	Mix 1:2:4 by weight, slump test (BS EN 12350-2)	Slump 60 mm

3.2 Compressive Strength of Control Specimens

Control specimens tested at ambient temperature developed mean compressive strengths of 22.3 ± 0.6, 23.2 ± 0.8, 25.0 ± 0.5 and 31.5 ± 1.8 N/mm² at 7, 14, 21 and 28 days respectively (Table 2). The 28-day strength exceeded both the characteristic strength of 20 N/mm² and the target mean of 25 N/mm², confirming a sound mix design, adequate compaction and effective water curing (Neville, 2011). The 7-day strength was about 71% of the 28-day value, consistent with the normal strength development of plain OPC concrete.

3.3 Effect of mild temperature at each curing age

Table 2 presents the residual compressive strengths for all temperature and age combinations, and Table 3 gives the corresponding percentage changes relative to control. Coefficients of variation ranged from about 1 to 7 %, indicating good repeatability for a three-replicate cube programme.

Table 2. Residual compressive strength of Grade 20 concrete after one hour exposure to mild temperature (mean ± SD, N/mm², n = 3).

Temp.	7 days	14 days	21 days	28 days
20 °C (control)	22.3 ± 0.6	23.2 ± 0.8	25.0 ± 0.5	31.5 ± 1.8
40 °C	24.3 ± 0.3	26.3 ± 0.6	24.7 ± 0.3	31.0 ± 2.0
60 °C	25.3 ± 0.6	26.0 ± 1.0	23.2 ± 0.8	29.0 ± 1.0
80 °C	24.0 ± 1.0	24.0 ± 1.0	21.7 ± 0.6	28.3 ± 1.5
100 °C	26.0 ± 1.0	21.8 ± 0.3	20.3 ± 0.6	28.0 ± 1.0
120 °C	21.7 ± 0.6	19.7 ± 1.2	19.2 ± 0.8	26.3 ± 0.6

Table 3. Percentage change in compressive strength relative to the control (positive values denote a gain, negative values a loss).

Temp.	7 days (%)	14 days (%)	21 days (%)	28 days (%)
40 °C	+9.0	+13.7	-1.3	-1.6
60 °C	+13.5	+12.2	-7.3	-7.9
80 °C	+7.5	+3.6	-13.3	-10.1
100 °C	+16.4	-5.8	-18.7	-11.1
120 °C	-3.0	-15.1	-23.3	-16.4

At 7 days, all exposures from 40 °C to 100 °C raised strength above the control, with the largest gain (16.4 %) at 100 °C, and only the 120 °C exposure produced a small loss of 3.0 %. At 14 days the same general pattern persisted but the turning point shifted downwards: gains of 13.7 and 12.2 % occurred at 40 °C and 60 °C, the gain at 80 °C had shrunk to 3.6 %, and 100 °C and 120 °C produced losses of 5.8 and 15.1 %. By 21 days the behaviour had changed qualitatively. No temperature produced a gain; strength fell monotonically with temperature, from a negligible 1.3% loss at 40 °C to the largest reduction recorded in the whole programme, 23.3 %, at 120 °C. The 28-day results followed the same monotonic pattern with somewhat smaller losses of 1.6, 7.9, 10.1, 11.1 and 16.4 % at 40 °C to 120 °C respectively, leaving a residual strength of 26.3 ± 0.6 N/mm² even after the most severe exposure.

3.4 Statistical Analysis

The two-way ANOVA (Table 4) showed that residual compressive strength was significantly affected by exposure temperature [$F(5, 48) = 39.16$, $p < 0.001$], by curing age [$F(3, 48) = 172.25$, $p < 0.001$] and, critically, by their interaction [$F(15, 48) = 7.24$, $p < 0.001$]. The significant interaction provides formal statistical support for the central finding of this study that the influence of a given temperature depends on the age at which it is applied and justifies interpreting the temperature effect separately within each curing age rather than from the pooled main effect.

Tukey HSD comparisons of each heated condition with the 20 °C control within each age (Table 5; critical difference 2.31 N/mm²) refine the descriptive trends of Section 3.3. At 7 days the gains were statistically significant only at 60 °C ($p = 0.005$) and 100 °C ($p < 0.001$); the apparent gains at 40 and 80 °C and the small loss at 120 °C lay within experimental scatter ($p > 0.05$). At 14 days significant gains persisted at 40 °C ($p = 0.003$) and 60 °C ($p = 0.010$), 120 °C produced a significant loss ($p < 0.001$), and the intermediate temperatures did not differ significantly from the control. By 21 days the gains had disappeared, and strength was significantly reduced at 80, 100 and 120 °C (all $p \leq 0.001$), although the smaller reductions at 40 and 60 °C were not significant. At the design age of 28 days every exposure from 60 °C upward gave a significant loss ($p < 0.05$ to < 0.001), whereas the 1.6 % reduction at 40 °C was not statistically significant ($p = 0.99$), indicating that mild heating to 40 °C leaves the 28-day strength of Grade 20 concrete essentially unchanged.

These tests place the gain-to-loss transition on a firmer footing: the early-age enhancement is real but confined to moderate temperatures (about 40–100 °C) at early ages (7–14 days), whereas from 21 days onward the damage mechanisms dominate and produce statistically significant losses that increase with temperature. They also caution against over-interpreting the non-monotonic features of the early-age curves, such as the dip at 80 °C at 7 days, which is not statistically significant.

Table 4. Two-way analysis of variance for residual compressive strength (factors: exposure temperature and curing age).

Source	SS	df	MS	F	p
Temperature	178.59	5	35.72	39.16	< 0.00
Curing age	471.31	3	157.10	172.25	< 0.00
Temperature × Age	99.02	15	6.60	7.24	< 0.00
Error	43.78	48	0.91	—	—
Total	792.70	71			

Table 5. Tukey HSD comparison of each heated condition with the 20 °C control within each curing age (difference = heated mean − control, N/mm²).

Temp.	7 days	14 days	21 days	28 days
40 °C	+2.0 ns	+3.1 **	−0.3 ns	−0.5 ns
60 °C	+3.0 **	+2.8 **	−1.8 ns	−2.5 *
80 °C	+1.7 ns	+0.8 ns	−3.3 **	−3.2 **
100 °C	+3.7 ***	−1.4 ns	−4.7 ***	−3.5 ***
120 °C	−0.6 ns	−3.5 ***	−5.8 ***	−5.2 ***

** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant; HSD critical difference = 2.31 N/mm².*

3.5 Density and Moisture loss

Average hardened densities decreased systematically with exposure temperature at every age, for example from 2405 kg/m³ (control) to 2223 kg/m³ (120 °C) at 28 days, reflecting the progressive evaporation of free and physically held water. Mass measurements before and after heating showed moisture losses rising from about 0.5 % at 40 °C to 4.5 % at 120 °C, with older specimens losing slightly less mass than younger ones because their higher degree of hydration leaves less free water available for evaporation. These values are consistent with the 0.43 to 4.67 % range reported by Venkateswara Rao and Achyutha Kumar Reddy (2021) for M45 concrete heated to 50 °C to 300 °C, the somewhat lower losses here reflecting the shorter one-hour exposure.

3.6 Mechanisms underlying the age dependent response.

The results reveal a clear interaction between curing age and thermal exposure. At early ages, mild heating acted predominantly as an accelerant of strength development. Two mechanisms plausibly contribute. First, elevated temperature increases the rate of cement hydration, so a one hour exposure followed by 24 hours of cooling effectively delivers a brief episode of warm curing to a paste that still contains abundant unhydrated cement and free water; this is the same principle exploited deliberately in steam curing (Neville, 2011) and is consistent with the maturity concept, in which strength development is governed by the combined time and temperature history (Carino & Lew, 2001). Second, the evaporation of free water from the relatively coarse capillary network of a Grade 20 paste reduces internal moisture without generating damaging pore pressures, and partially dried specimens commonly test stronger than saturated ones because pore water pressure during loading is relieved (Farzampour, 2019; Kodur, 2014). The undulating shape of the early age curves, with a local dip at 80 °C between gains at 60 °C and 100 °C, most likely reflects the competing and oppositely signed effects of accelerated hydration, moisture state and incipient microcracking acting simultaneously, together with normal batch variability.

In mature concrete the balance shifts decisively. By 21 days most of the cement that will hydrate has already done so, so the accelerating mechanism has little material left to act upon, while the damaging mechanisms remain fully available: differential thermal strain between the shrinking paste and the expanding granite aggregate generates microcracks concentrated at the interfacial transition zone, and the onset of C-S-H dehydration around 100 °C to 120 °C removes binding water from the gel itself (Khoury, 1992; Ma *et al.*, 2015). The monotonic strength loss observed at 21 and 28 days, growing with temperature, is exactly the signature expected of this damage dominated regime (Guo & Shi, 2011). The slightly smaller losses at 28 days than at 21 days (16.4 versus 23.3 % at 120 °C) are attributable to the denser, stronger and better cured matrix at 28 days, which tolerates a given thermal strain with less relative damage, and to the higher absolute strength of the control baseline.

3.7 Comparison with previous studies

The findings agree with the broad consensus that concrete strength may increase under mild heating before declining at higher temperatures (El-Zohairy *et al.*, 2020; Kodur, 2014; Ma *et al.*, 2015), but they locate the gain to loss transition for Grade 20 concrete in terms of age as well as temperature, a distinction most prior studies could not draw because they tested at a single age. The early age gains of up to 16.4 % are of the same order as the 11.8 to 12.1 % increases reported by Umasabor and Osaigbovo (2021) for Grade 30 concrete at 62.5 °C and 100 °C, and the strength enhancement below about 250 °C observed by Venkateswara Rao and Achyutha Kumar Reddy (2021) in M45 concrete, indicating that the accelerated hydration mechanism operates across grades. At the design age of 28 days, the 11.1 % loss at 100 °C found here is somewhat smaller than the 14.5 % loss reported for Grade 40 concrete at the same temperature by Osuji and Ukeme (2015) using comparable Benin City materials, and the 16.4 % loss at 120 °C sits at the lower end of the 10 to 20 % band that El-Zohairy *et al.* (2020) measured at 100 °C.

This relatively favourable performance of the lower grade is mechanistically coherent. Higher grade concretes possess denser microstructures and finer pore systems that obstruct moisture migration, so heating generates internal vapour pressure and steeper moisture gradients, while their stiffer pastes accumulate larger thermal mismatch stresses; both effects amplify damage (Chan *et al.*, 1999; Phan & Carino, 1998). The leaner, more porous Grade 20 matrix vents moisture readily and accommodates thermal strain, so within the mild range its percentage losses remain modest (Soutsos & Domone, 2017). The present data therefore extend to Grade 20 the inverse relationship between grade and relative thermal tolerance documented at higher temperatures by Chan *et al.* (1999) and Arioz (2007). One apparent disagreement deserves note: the monotonic loss observed here at 21- and 28-days contrasts with reports of net gains at 28 days under comparable temperatures (Umasabor & Osaigbovo, 2021). The most likely explanations are differences in heating duration, moisture condition at test and grade, and the fact that strength gains driven by drying are partly reversible upon moisture re-equilibration, underlining the sensitivity of mild temperature behaviour to test protocol (Kodur, 2014).

3.8 Implications for Theory and Practice

Theoretically, the age dependence documented here has two implications. First, it supports maturity-based descriptions of early age behaviour, since the early gains scale broadly with the additional equivalent age conferred by heating and suggests that functions of the Nurse Saul type could be calibrated for low grade tropical concretes (Carino & Lew, 2001). Second, it shows that any predictive model spanning the full-service life must couple a maturity term with an irreversible damage term that activates once hydration is substantially complete; a single monotonic strength temperature relationship of the kind embedded in fire design curves cannot reproduce the observed sign reversal between 14 and 21 days (Guo & Shi, 2011; Ma *et al.*, 2015). Practically, the results indicate that Grade 20 concrete retains a comfortable margin after mild thermal events: even the worst-case residual strength of 26.3 N/mm² at 28 days exceeds the characteristic strength of 20 N/mm² assumed in design to BS 8110 (British Standards Institution, 1997). Residential buildings, pavements and boundary walls in tropical regions should therefore remain structurally serviceable after exposures of the order studied, although the 23.3 % loss recorded at 21 days cautions that concrete heated before full maturity warrants closer assessment.

3.9 Limitations

Several limitations qualify these conclusions and indicate how the findings may have been shaped by the experimental choices made. Only one mix (1:2:4, w/c 0.6) with granite aggregate was tested, so the results may not transfer directly to mixes with calcareous or gravel aggregates, whose thermal expansion behaviour differs (Arioz, 2007; Ballim & Otieno, 2021). The single one-hour steady state exposure does not capture prolonged heating, thermal cycling or realistic heating rates, all of which influence damage accumulation (Kodur, 2014), and the exclusive use of air cooling means the more damaging water quenched condition associated with firefighting remains uncharacterised for this grade (Husem, 2006). The sample of three cubes per condition, while standard, limits statistical power, and some of the non-monotonic early age behaviour may partly reflect replicate variability. Only compressive strength was measured; tensile strength, elastic modulus and durability indicators may degrade differently (El-Zohairy *et al.*, 2020). Finally, no microstructural examination (such as SEM or thermogravimetry) was undertaken, so the proposed mechanisms, while consistent with the literature, are inferred rather than directly observed (Venkateswara Rao & Achyutha Kumar Reddy, 2021).

IV. CONCLUSION

This study set out to determine how mild temperature exposure affects the compressive strength of Grade 20 concrete, the grade most widely used in low rise tropical construction, by heating water cured cubes to 40 °C, 60 °C, 80 °C, 100 °C and 120 °C for one hour at curing ages of 7, 14, 21 and 28 days, air cooling them and testing them against unheated controls. Three principal findings emerged. First, the response is strongly age dependent: at 7 and 14 days, exposures up to 100 °C increased strength by as much as 16.4 % through accelerated hydration and free water loss, whereas at 21 and 28 days every exposure from 60 °C upward produced a statistically significant reduction that grew with temperature, while heating to 40 °C left the mature-age strength essentially unchanged. Second, at the design age of 28 days the losses were modest, ranging from 1.6 % at 40 °C to 16.4 % at 120 °C, and the worst case residual strength of 26.3 N/mm² still exceeded the characteristic strength of 20 N/mm²; the largest loss in the programme, 23.3 %, occurred at 21 days and 120 °C. Third, the percentage losses are smaller than those reported for higher grade concretes under comparable conditions, confirming that the porous, lean microstructure of low grade concrete confers relative tolerance to mild heating.

The broader significance of these results is twofold. For practice, they provide quantitative assurance that Grade 20 concrete in tropical environments remains structurally adequate after the mild thermal events it routinely experiences, supporting rational post event assessment in place of either unwarranted condemnation or unexamined acceptance. For theory, the documented sign reversal between early age gain and mature age loss demonstrates that models of thermal effects on low grade concrete must combine a maturity component with an age activated damage component rather than rely on a single strength temperature curve.

The limitations of the study chart the agenda for future work. The single mix, aggregate type and exposure protocol should be broadened to multiple water to cement ratios, calcareous and gravel aggregates, longer and cyclic exposures, and water cooling, which is expected to be more damaging than the air cooling used here. The sample of three cubes per condition, while standard, limits statistical power; the two-way ANOVA and Tukey HSD analysis (Section 3.4) confirms the principal temperature and age effects and their interaction, but shows that several of the smaller differences which are notably the changes at 40 °C and the non-monotonic features of the early-age curves are not statistically significant and should not be over-interpreted. A larger number of replicates would allow these finer effects to be resolved. Larger replicate numbers would strengthen the statistical basis, particularly for resolving the non-monotonic early age behaviour, and complementary measurements of tensile strength, elastic modulus and durability indicators would complete the mechanical picture. Microstructural studies using SEM, XRD and thermogravimetric analysis are recommended to verify directly the hydration and microcracking mechanisms inferred here, and the combined action of mild temperature with aggressive agents such as chlorides and sulfates deserves attention given the coastal location of many tropical cities. Subject to these extensions, the present database offers a practical baseline for the design and assessment of Grade 20 concrete structures in warm climates

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