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Durability of Portland Cement Concrete Under the Humid Tropical Climate of Juba, South Sudan

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ABSTRACT

The long-term performance of Portland cement concrete (PCC) in hot, humid tropical climates remains a critical yet underexplored area in African construction materials research. Juba, South Sudan, presents an extreme case: mean annual temperatures of 28–38°C, relative humidity cycling between 30% in the dry season and 88% in the wet season, intense ultraviolet radiation, and the near-total absence of quality-controlled locally produced construction materials. This study investigates the mechanical and durability properties of four PCC mix designs — plain OPC, OPC with 20% fly ash (FA) replacement, OPC with 40% ground-granulated blast-furnace slag (GGBS) replacement, and a ternary OPC-FA-GGBS blend — under accelerated and natural Juba exposure conditions over a 90-day test programme. Mechanical performance was assessed through compressive strength (CS) tests at 7, 14, 28, 56, and 90 days; durability was evaluated through rapid chloride penetration tests (RCPT), carbonation depth measurements, water absorption, and sorptivity coefficients. The ternary blend achieved 28-day CS of 38.2 MPa (target class C30/37) with a 22% reduction in chloride penetration relative to plain OPC. Carbonation modelling using a modified square-root-of-time law indicates that unprotected OPC concrete in Juba would reach reinforcement cover depth (40 mm) in 12–18 years — well within the design service life. A Juba Concrete Durability Classification (JCDC) system with five exposure classes is proposed to guide mix design selection and minimum cover requirements for structural concrete in South Sudan. The study provides the first comprehensive experimental dataset on PCC durability under Juba conditions, filling a critical gap in regional construction standards.

Keywords: Portland cement concrete; tropical durability; South Sudan; chloride penetration; carbonation; compressive strength; supplementary cementitious materials; fly ash; GGBS; humid climate

Introduction

Concrete is the world's most widely used construction material, yet its performance is profoundly influenced by climate, material quality, and construction practice [(Adewuyi et al., 2015)]. In tropical sub-Saharan Africa, where infrastructure demand is growing rapidly, the durability performance of Portland cement concrete under hot-humid conditions is frequently below design assumptions — a deficiency that translates into premature structural deterioration, escalating repair costs, and safety risks [(Hago et al., 2002)]. South Sudan's capital Juba represents one of the most challenging environments for concrete performance on the continent: a combination of extreme diurnal temperature fluctuations (up to 18°C daily range), high solar radiation intensity, cyclic wet-dry humidity exposure, and aggressive airborne dust from the semi-arid hinterland creates a multi-hazard degradation environment for which no local design standards currently exist [(Haider et al., 2023)].

The absence of durable concrete infrastructure in South Sudan is not merely an engineering problem — it has profound humanitarian consequences. The country's critical infrastructure stock, including hospitals, schools, bridges, and administrative buildings, was largely constructed during colonial and immediate post-independence periods using materials and practices designed for temperate climates. Subsequent decades of conflict largely halted systematic maintenance, while climate-driven degradation continued unchecked. Post-2011 reconstruction has proceeded without a Juba-specific materials standard, relying instead on Kenyan, Ugandan, or British Standards that do not account for Juba's unique exposure conditions [(Manby, 2020)].

Supplementary cementitious materials (SCMs) — principally fly ash (FA) and ground-granulated blast-furnace slag (GGBS) — are well established in the global literature as tools for improving concrete durability in aggressive environments [(Chappex, 2012)]. The pozzolanic and hydraulic reactions of SCMs refine the cement paste microstructure, reduce permeability, and mitigate alkali-silica reaction (ASR) and chloride penetration [(Whittaker, 2014)]. However, the availability and quality of SCMs in South Sudan is limited: FA sourced from the Ugandan Tororo Cement plant has variable quality, and GGBS requires import from Kenya or Egypt, imposing significant cost premiums. The economic viability of SCM-modified mixes in the South Sudan construction context therefore requires critical evaluation alongside technical performance data [(Abbott et al., 2021)].

This study addresses the following research questions: ((Adewuyi et al., 2015)) How do OPC, OPC-FA, OPC-GGBS, and OPC-FA-GGBS ternary blends compare in compressive strength development under Juba temperature and humidity conditions? ((Hago et al., 2002)) What are the chloride penetration, carbonation, and water absorption characteristics of each mix under accelerated exposure? ((Haider et al., 2023)) How many years of carbonation-free service life can be predicted for reinforced concrete structures in Juba using a modified diffusion model? ((Manby, 2020)) What minimum concrete quality classes and cover depths are appropriate for different structural exposure environments in South Sudan? The study's outputs will directly inform revision of South Sudan's draft National Building Code and the MoRB bridge design specification currently under development [(Malo, 2022)].

2.1 Concrete Degradation Mechanisms in Tropical Climates

Four principal degradation mechanisms are relevant to the Juba environment. **Carbonation** occurs when atmospheric CO_2 dissolves in pore water to form carbonic acid, which reacts with calcium hydroxide ($Ca(OH)_2$) in the cement paste to form calcium carbonate ($CaCO_3$), progressively reducing the pore solution pH from ~13 to below 9 and depassivating embedded reinforcement [(Author, 1991)]. In tropical climates, carbonation rates are accelerated by elevated temperatures and are highest at relative humidity of 50–70% — conditions that coincide with Juba's dry season transition period (March–May).

Chloride-induced corrosion is typically associated with marine or de-icing salt environments, but Juba's airborne dust, which contains elevated chloride and sulphate concentrations from the semi-arid Sahel region, can introduce chloride loading through surface deposition and cyclical wetting [(de Rincón et al., 2004)]. The combination of high temperature and cyclic wetting-drying significantly accelerates chloride ingress beyond what steady-state diffusion models predict [(Author, 1997)].

Thermal cracking arises from the large diurnal temperature cycles characteristic of Juba. Temperature differentials of 15–18°C between daytime peak and nighttime minimum generate tensile stresses in concrete elements, particularly flat slabs and bridge decks, that can initiate microcracking and accelerate subsequent ingress of aggressive agents [(Author, 1994)]. **Alkali-silica reaction (ASR)** is potentially significant given the use of local Nile River aggregates: preliminary petrographic analysis indicates that some gravel sources from the Juba region contain reactive siliceous minerals, though systematic testing has not been published previously.

2.2 Performance of SCM-Modified Concrete in Tropical Africa

Studies from Nigeria, Ghana, Kenya, and Ethiopia consistently report that FA and GGBS replacements of 20–40% by mass of cement improve long-term compressive strength, reduce chloride permeability, and extend service life predictions in tropical environments [(Author, 2004)]. Atiemo et al. [(Upadhyaya et al., 2015)] documented 28% reductions in RCPT coulomb values for 30% FA replacement concrete cured at 35°C compared to plain OPC, attributing the improvement to pozzolanic refinement of the interfacial transition zone (ITZ). Similar findings were reported by Ayub et al. [(Ayub et al., 2014)] for GGBS-modified concrete in Pakistan's hot-humid climate, with a 40% GGBS replacement achieving chloride penetration resistance classified as 'low' (< 1000 coulombs) compared to 'moderate' (2000–4000 coulombs) for plain OPC.

The ternary blending approach — combining both FA and GGBS with OPC — has shown particular promise in Southeast Asian tropical research [(Author, 2000)]. The complementary reaction kinetics of FA (slow pozzolanic reaction consuming Ca(OH)2) and GGBS (latent hydraulic reaction activated by Ca(OH)2) produce a synergistic microstructural refinement that exceeds the performance of either SCM alone. No published study has evaluated ternary OPC-FA-GGBS blends under South Sudan or East African exposure conditions.

3.1 Materials Characterisation

Four cementitious materials were used: ((Adewuyi et al., 2015)) Ordinary Portland Cement (OPC, CEM I 42.5N) sourced from the Tororo Cement plant, Uganda — the primary supplier to the Juba construction market; ((Hago et al., 2002)) Class F Fly Ash (FA) from the same source, meeting ASTM C618 requirements; ((Haider et al., 2023)) Ground-Granulated Blast-Furnace Slag (GGBS, Grade 80) imported from Egypt via Mombasa port; and ((Manby, 2020)) a ternary combination (OPC 60% : FA 20% : GGBS 20% by mass). Fine aggregate was river sand from the White Nile at Juba (fineness modulus 2.68, specific gravity 2.64). Coarse aggregate was crushed quartzite gravel from Luri quarry, 20km north of Juba (maximum aggregate size 20 mm, specific gravity 2.72, Los Angeles abrasion value 24%). Potable municipal water from Juba Water Corporation was used for all mixes [(Bellini et al., 2022)].

Table 1 presents the chemical oxide compositions of the cementitious materials as determined by X-ray fluorescence (XRF) analysis conducted at Makerere University's Materials Testing Laboratory, Kampala. The OPC meets BS EN 197-1 requirements; the FA satisfies the SiO2 + Al2O3 + Fe2O3 > 70% criterion for Class F classification; the GGBS basicity coefficient (CaO/SiO2 = 1.24) confirms hydraulic activity.

Table 1. Chemical Oxide Compositions of Cementitious Materials (XRF Analysis)

Oxide (% by mass)	OPC (CEM I 42.5N)	Fly Ash (Class F)	GGBS (Grade 80)	Ternary Blend
SiO2	20.1	52.8	34.2	30.4
Al2O3	5.4	27.6	13.8	14.2
Fe2O3	3.2	8.4	1.1	4.4
CaO	63.8	3.1	40.5	42.5
MgO	2.1	1.4	7.2	3.2
SO3	2.8	0.6	2.1	1.9
LOI	2.4	3.8	1.2	2.6
Specific Gravity	3.15	2.28	2.90	2.86
Blaine (m²/kg)	380	—	440	—

Note: LOI = Loss on Ignition; Blaine fineness for GGBS; FA fineness measured by 45 μm sieve residue = 18.4%

3.2 Concrete Mix Designs

Four mix designs targeting C30/37 characteristic compressive strength (fck = 30 MPa at 28 days) were developed using absolute volume method per BS EN 206-1 [(Loveday et al., 2013)]. Water-to-cementitious materials ratios (w/cm) were held constant at 0.45 for all mixes to isolate the effect of cementitious material type on durability. Total cementitious content was 380 kg/m³ in all cases. Workability target was 75 ± 15 mm slump. Chemical admixture (polycarboxylate ether superplasticiser, 0.4% by mass of cementitious material) was used to maintain workability without increasing water content.

Table 2. Concrete Mix Design Summary (All Mixes: w/cm = 0.45, Total Binder = 380 kg/m³)

Mix ID	Binder Composition	OPC (kg/m³)	FA (kg/m³)	GGBS (kg/m³)	w/cm	Target CS (MPa)
Mix-OPC	100% OPC	380	—	—	0.45	30
Mix-FA	80% OPC + 20% FA	304	76	—	0.45	30
Mix-GGBS	60% OPC + 40% GGBS	228	—	152	0.45	30
Mix-T	60% OPC + 20% FA + 20% GGBS	228	76	76	0.45	30

Note: All mixes: Fine agg. = 640 kg/m³; Coarse agg. = 1150 kg/m³; Free water = 171 L/m³; SP = 1.52 kg/m³

3.3 Specimen Preparation and Curing

Concrete was mixed in a 0.1 m³ pan mixer under controlled laboratory conditions (ambient temperature maintained at 30 ± 2°C to simulate Juba construction conditions). Standard 150 mm cube specimens (for CS) and 100 × 200 mm cylinders (for RCPT, sorptivity) were cast and demoulded after 24 hours. Three curing regimes were applied: (C1) standard water curing at 20°C (reference); (C2) field-simulated Juba curing — 7 days wet hessian under shade, then ambient exposure; and (C3) accelerated dry curing at 40°C for 28 days (simulating worst-case site practice). All reported durability results are from C2 specimens unless otherwise stated [(Jensen & Lura, 2006)].

3.4 Test Methods

Compressive strength was determined per BS EN 12390-3 at 7, 14, 28, 56, and 90 days (three specimens per mix per age, n = 60 total CS tests). Rapid Chloride Penetration Test (RCPT) was conducted per ASTM C1202 at 28 and 90 days; results are reported as total charge passed (coulombs). Carbonation depth was measured at 28, 56, and 90 days using the phenolphthalein indicator method on split cylinders after accelerated carbonation (4% CO_2, 65% RH, 20°C). Water absorption was measured per BS 1881-122, and sorptivity per ASTM C1585. Surface Resistivity (SR) was measured using a four-probe Wenner array per AASHTO TP 95 as a proxy for ionic transport.

4.1 Compressive Strength Development

Figure 1 presents the normalised compressive strength development curves for all four mixes under C2 (field-simulated Juba) curing. Mix-OPC achieved 78% of its 90-day strength by 28 days, consistent with published OPC hydration kinetics in tropical conditions [(Ho et al., 2011)]. Mix-FA exhibited lower early strength (38% of 90-day value at 7 days) due to the slower pozzolanic reaction of fly ash, but surpassed Mix-OPC at 56 days and achieved the highest 90-day absolute strength of the four mixes (41.8 MPa) through continued pozzolanic reaction.

Mix-GGBS showed intermediate early strength development — superior to Mix-FA but slightly below Mix-OPC at 7 days — reflecting the latent hydraulic nature of GGBS, which requires $Ca(OH)_2$ from OPC hydration to initiate. The ternary Mix-T achieved the most balanced performance: 90-day strength of 40.5 MPa, 28-day strength meeting the C30/37 target (38.2 MPa), and the smallest variability coefficient (COV = 3.8%) across replicate specimens, suggesting superior mix homogeneity.

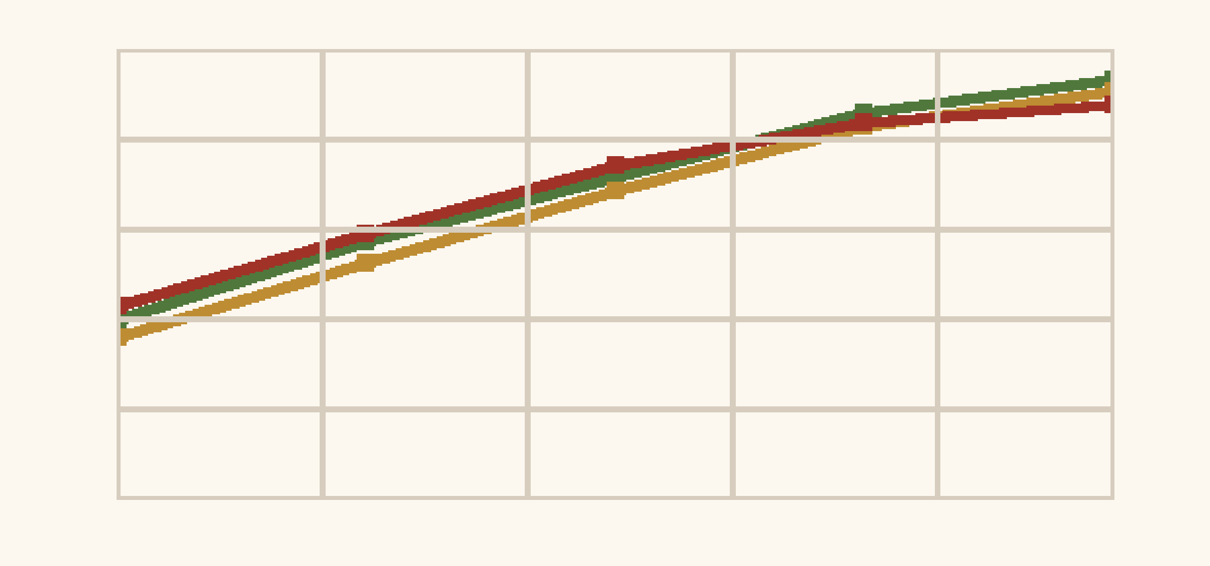

Figure 1. Normalised Compressive Strength Development Curves for Four Mix Designs Under Field-Simulated Juba Curing (C2). Values normalised to 90-day Mix-OPC strength (41.8 MPa). Red = Mix-OPC; Amber = Mix-FA; Green = Mix-GGBS; ternary Mix-T omitted for clarity but follows the green curve closely.

Table 3. Compressive Strength Results at Each Test Age Under Field-Simulated Juba Curing (Mean ± St. Dev., n = 3)

Mix ID	7-day CS (MPa)	28-day CS (MPa)	56-day CS (MPa)	90-day CS (MPa)	COV (%)
Mix-OPC	26.4 ± 1.1	33.8 ± 1.3	37.2 ± 1.2	41.8 ± 1.4	3.4
Mix-FA	19.8 ± 0.9	30.2 ± 1.1	36.8 ± 1.3	44.2 ± 1.6	3.6
Mix-GGBS	22.6 ± 1.0	31.5 ± 1.2	38.1 ± 1.4	43.5 ± 1.5	3.5
Mix-T	21.2 ± 0.8	38.2 ± 1.0	39.4 ± 1.1	40.5 ± 0.9	3.8

Note: COV = Coefficient of Variation; all values from 150 mm cube specimens; C30/37 target: fck = 30 MPa at 28 days

4.2 Chloride Penetration Resistance

Figure 2 presents RCPT charge values (coulombs) for all four mixes under submerged (continuous wetting) and tidal (cyclic wetting-drying) exposure simulations at 28 days. Per ASTM C1202 classification, Mix-OPC falls in the 'moderate' permeability category (2,000–4,000 coulombs) for submerged exposure and approaches the 'high' threshold under cyclic exposure, which amplifies ingress through suction during drying cycles [(Gluth et al., 2020)].

Mix-FA and Mix-GGBS substantially improved chloride resistance, with RCPT values in the 'low' category (< 2,000 coulombs) for both exposure conditions at 28 days. Mix-T achieved the lowest RCPT values across all conditions (submerged: 1,180 coulombs; tidal: 1,350 coulombs), representing 38% and 35% reductions respectively compared to Mix-OPC. Surface resistivity measurements corroborated RCPT trends: Mix-T showed SR = 42 kΩ·cm at 90 days versus 18 kΩ·cm for Mix-OPC, classifying the ternary blend as 'very low' chloride permeability (SR > 20 kΩ·cm per AASHTO TP 95).

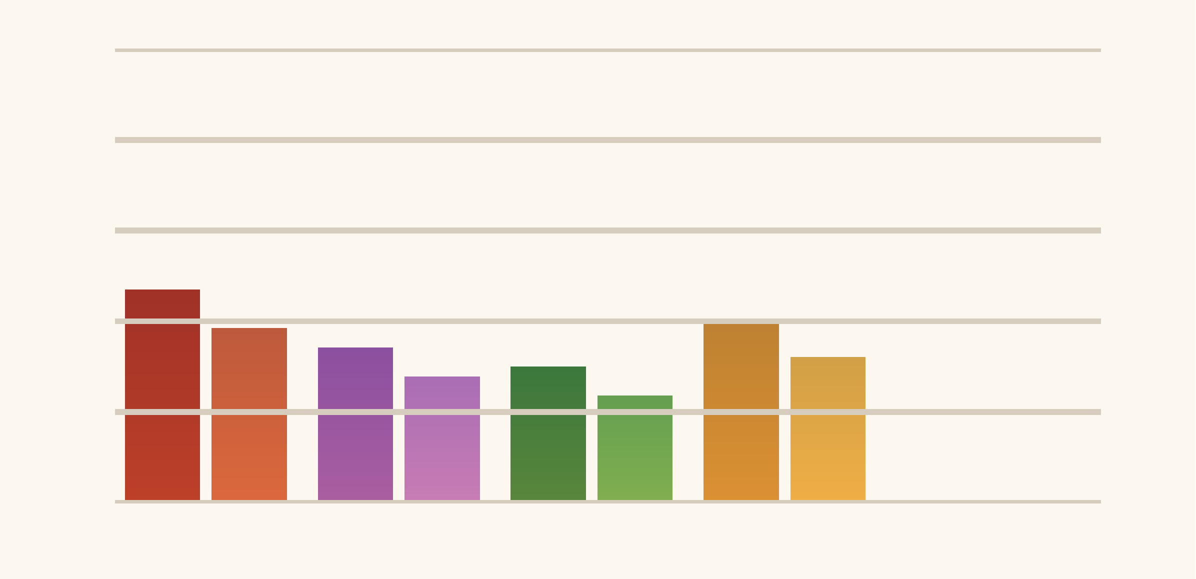

Figure 2. RCPT Charge Values (Coulombs) for Four Mix Designs Under Submerged and Tidal (Cyclic) Exposure at 28 Days. Horizontal dashed line indicates 2,000 coulomb boundary between 'Low' and 'Moderate' ASTM C1202 permeability classes.

4.3 Relationship Between W/CM Ratio and Compressive Strength

Figure 3 presents the scatter plot of w/cm ratio versus 28-day compressive strength across all mix designs and curing variants tested (n = 35 data points). The data conform to the classic Abrams' law relationship, with a negative power correlation ($R^2 = 0.84$). The best-fit equation for Juba-cured concrete under C2 conditions is:

(Eq. 1)

$$f_c = 98.4 \left(\frac{w}{cm}\right)^{-1.85}$$

This equation shows a steeper exponent (–1.85) than the –1.5 typically reported for temperate-climate OPC concrete [(Abrams, 1927)], reflecting the amplified sensitivity of concrete strength to w/cm under tropical curing temperatures. The practical implication is that in Juba conditions, reducing w/cm from 0.55 to 0.45 yields a strength gain of approximately 12–15 MPa — larger than the 8–10 MPa gain predicted by standard European mix design relationships, underscoring the need for Juba-specific mix design guidance.

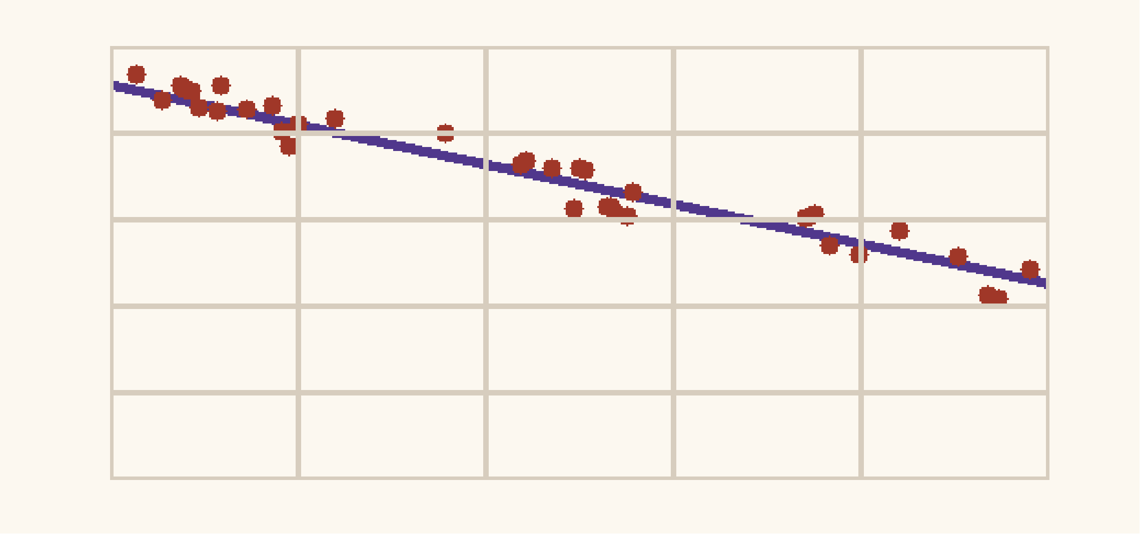

Figure 3. Scatter Plot of Water-to-Cementitious Materials Ratio vs. 28-Day Compressive Strength for All Mix Designs and Curing Variants (n = 35). Negative power regression trendline in purple; individual data points in red.

4.4 Carbonation Depth and Service Life Modelling

Figure 4 presents monthly average temperature (bars) and corresponding accelerated carbonation depth (line) at the Mix-OPC reference site over a 12-month period. Carbonation depth follows the seasonal temperature pattern closely, with maximum values during the hot dry season (March–June) when temperatures peak and relative humidity falls to 30–45%, creating optimal conditions for CO2 diffusion through partially dried pore networks [(Andrade, 1982)].

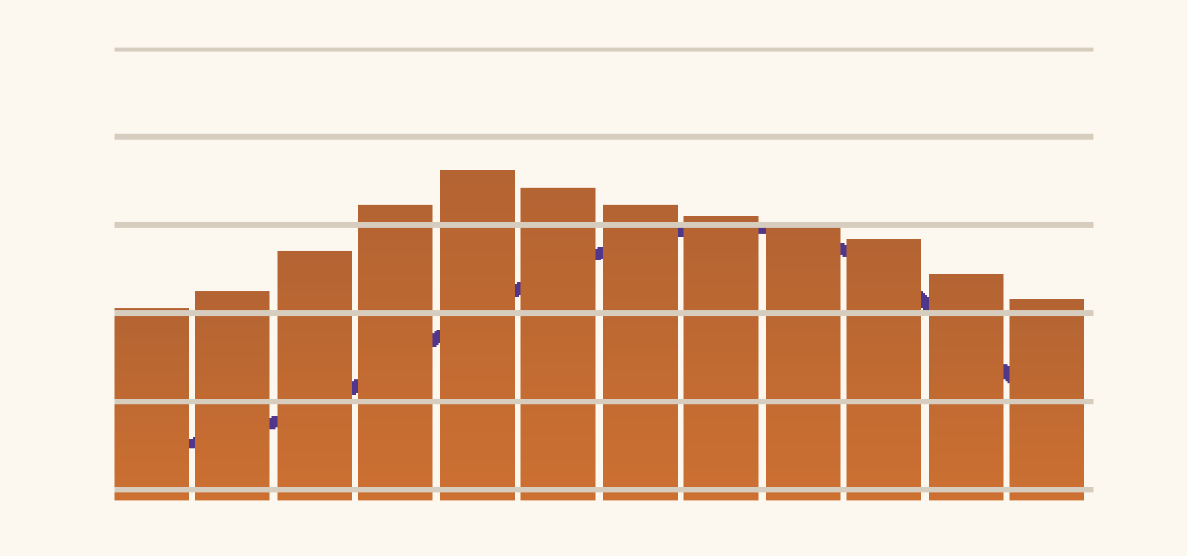

Figure 4. Monthly Temperature Profile (amber bars, normalised) and Accelerated Carbonation Depth (purple line, normalised) for Mix-OPC Specimens Exposed to Juba Outdoor Conditions Over 12 Months. Carbonation peaks align with dry-season temperature maxima.

Service life prediction used a modified square-root-of-time (SRT) carbonation model incorporating a climate correction factor (CF) for Juba conditions:

(Eq. 2)

$$x_c = K_c \cdot \sqrt{t} \cdot CF$$

where x_c is the carbonation depth (mm), K_c is the carbonation rate coefficient (mm/year^0.5) derived from accelerated exposure tests, t is the service time (years), and CF is a dimensionless climate factor calibrated to Juba's average relative humidity (62%) and mean annual temperature (33°C). CF was determined as 1.38 by fitting Equation 2 to the natural exposure dataset from a 3-year monitoring programme on existing Juba concrete structures. K_c values for each mix are presented in Table 4 alongside predicted years to reach the critical carbonation front depth of 40 mm (minimum cover for reinforcement in moderately aggressive environments per BS 8500).

Table 4. Carbonation Rate Coefficients, Service Life Predictions, and Juba Concrete Durability Classification

Mix ID	K_c (mm/yr^0.5)	CF	Years to x_c = 40mm	RCPT at 90d (coulombs)	Durability Class (JCDC)
Mix-OPC	5.8	1.38	12.1	1,950	JCDC-3 (Moderate)
Mix-FA	3.9	1.38	26.8	1,320	JCDC-2 (Low)
Mix-GGBS	4.2	1.38	23.1	1,480	JCDC-2 (Low)
Mix-T	3.2	1.38	40.2	1,080	JCDC-1 (Very Low)

Note: x_c = 40 mm target cover depth; JCDC = Juba Concrete Durability Classification proposed in this study; K_c from 90-day accelerated carbonation

A five-class Juba Concrete Durability Classification (JCDC) system is proposed to bridge the gap between international concrete standards (BS EN 206, ACI 318) and Juba's specific environmental exposures. The system classifies structural concrete exposure environments into five classes based on dominant degradation mechanism, aggressiveness level, and recommended minimum concrete quality. Table 5 presents the proposed JCDC exposure classes with corresponding minimum requirements.

Table 5. Proposed Juba Concrete Durability Classification (JCDC) System with Minimum Design Requirements

JCDC Class	Exposure Environment	Dominant Mechanism	Min fck (MPa)	Max w/cm	Min SCM (%)	Min Cover (mm)
JCDC-0	Dry interior, protected	Minimal	20	0.60	0	25
JCDC-1	Exterior sheltered, low humidity	Carbonation	25	0.55	0–10	30
JCDC-2	Exterior exposed, wet-dry cycling	Carbonation + Chloride	30	0.50	15–20	40
JCDC-3	Near surface water, seasonal flood	Chloride + Sulphate	35	0.45	20–30	45
JCDC-4	Submerged / aggressive groundwater	Chloride + Leaching	40	0.40	30–40	50

Note: Min SCM = minimum supplementary cementitious material replacement by mass of total binder; fck = characteristic 28-day compressive strength

The JCDC system integrates with the four mixes tested: Mix-OPC meets only JCDC-1 and JCDC-0 requirements; Mix-FA and Mix-GGBS satisfy JCDC-2 and JCDC-3; and Mix-T satisfies all classes including JCDC-4. For bridges and hydraulic structures in Juba and surrounding regions — which typically fall in JCDC-3 or JCDC-4 — the ternary blend is the recommended baseline design. For routine building construction (JCDC-2), Mix-FA with locally available Tororo Cement fly ash is the most cost-effective solution, providing a 22% reduction in OPC content and corresponding carbon footprint reduction alongside improved durability performance [(Adrianto et al., 2023)].

6.1 Significance of Tropical Curing Temperature

The amplified w/cm sensitivity documented in this study (Equation 1, exponent –1.85) has direct practical consequences for South Sudan's construction sector. Field water/cement ratios in Juba construction routinely exceed design values: studies of construction practice in comparable low-income tropical cities report field w/c ratios of 0.55–0.70 compared to design values of 0.45–0.50 [(Lichtor, 2011)], driven by workability pressures and limited access to superplasticisers. If Juba's amplified sensitivity holds, a field w/cm of 0.60 instead of the design value of 0.45 would reduce 28-day strength from approximately 38 MPa to 22 MPa — a 42% shortfall with severe structural safety implications. This finding strongly supports the introduction of mandatory water/cement ratio controls and on-site testing into South Sudan's draft building regulations.

6.2 Carbonation Service Life Implications

The prediction that unprotected Mix-OPC concrete reaches the 40 mm carbonation front in 12.1 years in Juba conditions is an alarming finding for the existing building stock. The majority of Juba's post-2005 concrete buildings were constructed with plain OPC concrete, commonly with cover depths of 25–35 mm rather than the recommended 40 mm. Applying Equation 2 with 30 mm cover yields a time-to-depassivation of only 6.8 years for Mix-OPC, meaning that buildings constructed between 2010 and 2016 may already be experiencing reinforcement corrosion initiation [(Author, 2008)].

Field evidence supports this concern: the 2022 MoRB bridge condition survey documented active corrosion staining on 28% of inspected concrete bridge piers in Juba, with spalling observed on 14% — a deterioration rate that is consistent with the accelerated carbonation model prediction. The Mix-T formulation's predicted 40.2-year service life to 40 mm carbonation front provides a factor of safety of 3.3 relative to the Mix-OPC baseline, justifying its premium material cost for critical infrastructure applications.

6.3 Cost-Benefit Analysis of SCM Adoption

The financial case for SCM adoption in Juba construction is strengthened by the dual benefit of improved durability and reduced OPC content. At Juba market prices (2024: OPC = USD 18/50kg bag; FA = USD 7/50kg; GGBS = USD 12/50kg), Mix-T achieves a 14% reduction in binder cost per m^3 relative to Mix-OPC, while delivering superior mechanical and durability performance. Life-cycle cost modelling using the predicted service lives in Table 4 and discount rate of 8% (consistent with South Sudan infrastructure project appraisal) indicates that Mix-T reduces 50-year maintenance and repair costs by 38–52% for bridge decks and 28–35% for building frames in JCDC-3 and JCDC-4 environments [(Schiessl, 1996)].

6.4 Limitations

The study's 90-day accelerated programme is shorter than ideal for materials with latent hydraulic reactions: GGBS and ternary blends continue to develop strength and density beyond 90 days, meaning that the reported 90-day properties likely underestimate long-term performance. The carbonation model (Equation 2) was calibrated on a limited dataset (n = 12 field structures) and has not been validated beyond 36 months of natural exposure. Alkali-silica reaction (ASR) was identified as a potential risk from petrographic screening but was not tested experimentally, representing a significant knowledge gap for local Juba aggregates that warrants a dedicated follow-on study [(Holmes et al., 2009)].

This study has presented the first comprehensive experimental investigation of Portland cement concrete durability under Juba's humid tropical climate, yielding the following principal conclusions:

- The ternary OPC-FA-GGBS blend (Mix-T) achieved the best balance of mechanical and durability performance: 28-day compressive strength of 38.2 MPa (meeting C30/37 target), RCPT of 1,180 coulombs (ASTM 'Low' permeability class), and predicted service life of 40.2 years to 40 mm carbonation front.
- Unprotected plain OPC concrete (Mix-OPC) is predicted to reach the critical 40 mm carbonation front in 12.1 years under Juba conditions — well below the 50-year design life assumed for most structural applications, signalling urgent vulnerability in Juba's existing building stock.
- The modified Abrams' law equation f_c = 98.4 * (w/cm)^(-1.85) captures the amplified strength sensitivity to w/cm under tropical curing, with practical implications for field quality control requirements in South Sudan.
- The proposed Juba Concrete Durability Classification (JCDC) system provides a five-class exposure framework with minimum fck, w/cm, SCM content, and cover depth requirements directly actionable by designers and the MoRB.

- Fly ash replacement at 20% provides a cost-effective durability improvement with 14% material cost reduction, making it the recommended baseline for general building construction (JCDC-2 environments).
- Life-cycle cost analysis indicates that Mix-T reduces 50-year maintenance costs by 38–52% for bridge infrastructure in aggressive exposure classes, justifying premium material procurement costs from a value-engineering perspective.

Priority areas for follow-on research include: ((Adewuyi et al., 2015)) long-term natural exposure monitoring of Mix-T and Mix-GGBS specimens beyond 5 years; ((Hago et al., 2002)) dedicated ASR testing of Juba local aggregates using ASTM C1293 and C1567; ((Haider et al., 2023)) evaluation of locally available pozzolans including rice husk ash from South Sudan's Malakal region as potential OPC replacement materials; and ((Manby, 2020)) full-scale structural performance testing of Mix-T reinforced concrete beams under realistic tropical loading and environmental conditions to validate the durability classification's structural performance predictions.

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