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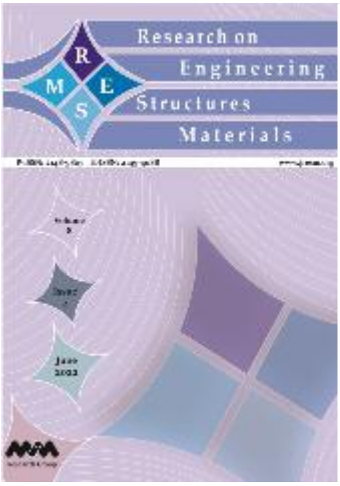

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Technical Note

Experimental investigation of behaviour of concrete mixed and cured with Nembe seawater

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Abstract

Freshwater is conventionally used to produce concrete, but freshwater scarcity has become a significant challenge worldwide. The aim of this study is to experimentally investigate the workability and strength of Portland cement concrete mixed and cured with Nembe seawater. The initial and final setting times and slump of fresh concrete mixed with freshwater and seawater were determined. Four sets of concrete specimens were produced for the compressive strength tests: concrete cast and cured with freshwater, cast with freshwater and cured with seawater, cast with seawater and cured with freshwater, and cast and cured with seawater. The use of seawater for mixing concrete decreased the initial setting time of the cement paste and the slump of concrete by approximately 36% and 54%, respectively. Concrete specimens mixed with seawater and cured with freshwater exhibited the highest compressive strengths at the 60th and 90th days of curing. Although the concrete mixed with seawater yielded slightly higher compressive strengths than concrete mixed with freshwater, the difference between using freshwater and seawater as mixing and curing water in terms of compressive strength was minimal.

1. Introduction

Concrete is a widely used construction material composed of cement, fine aggregate, coarse aggregate, and water. The demand for concrete structures has increased in recent decades because of their advantages, such as local availability of constituent materials, cost-effectiveness, and good durability. Urbanisation and globalisation have contributed to the rising demand for concrete structures. The increased use of concrete for constructing buildings and civil engineering structures indicates that more constituent materials are required to meet the current demand for concrete. Because of the enormous material and energy resources consumed during concrete production, there is a need to improve the sustainability of concrete. Sustainable construction aims at utilising recyclable materials in building new structures, minimising waste generation, and reducing energy and material consumption. Previous studies on the environmental impacts of concrete mainly focused on energy and material consumption and carbon dioxide emissions; however, little is known about its water consumption and the practical measures required to minimise such consumption [1].

Water is used for mixing concrete components and curing concrete, and it plays a significant role in determining the strength and durability of concrete. When water is mixed with cement, a paste that binds the aggregate particles together produces a stiff mass in a hardened state. Water is also used for curing, a critical process that enhances the

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strength development and durability of concrete. Conventionally, freshwater has been used to produce concrete, but freshwater scarcity is a significant challenge facing the world in the 21st century. Although water covers approximately 70% of the earth's surface, water scarcity affects every continent [2]. Water stress affects over two billion people globally, and sub-Saharan Africa has more water-stressed countries than any region [2]. The concrete industry competes for freshwater with many essential sectors, such as agriculture and food processing. With the current water scarcity in Nigeria and many other countries, there is an urgent need to seek alternative water sources for concrete production. The use of seawater instead of freshwater is justified because the construction industry annually utilises 16.6×10^9 m^3 (16.6 km^3) of water globally for concrete production (based on 2012 concrete consumption values) [1]. In some countries (for example, the United Arab Emirates), most of the water used for concrete production is obtained through seawater desalination [3], which increases production costs. The use of seawater in concrete is expected to increase globally as the freshwater supply decreases. Approximately 97% of the earth's water is found in the oceans, 2% is frozen freshwater trapped in glaciers and ice caps, and less than 1% is accessible freshwater [4]. Seawater refers to water in the seas and oceans, and it is salty. Seawater contains small amounts of salts and smaller amounts of other substances, including dissolved organic and inorganic materials. The principal ions in seawater are chloride, sodium, sulphate, calcium, magnesium, and potassium. The specific amounts of these salts in seawater vary but generally comprise approximately 99% of all sea salts. Sodium chloride is the most abundant salt in seawater, constituting over 90% of the total salt weight [5]. Freshwater includes water from ponds, lakes, streams, rivers, ice caps, glaciers, icebergs, and below the soil surface (groundwater). Freshwater generally contains lower concentrations of dissolved salts and other total dissolved solids than seawater.

Previous studies have suggested the possibility of using seawater in mixing and curing cement-based materials. Despite the wide acceptance that seawater is unsuitable for structural concrete, some structures have been successfully built using seawater concrete [6]. Recent research indicates no significant adverse effects of seawater on the mechanical properties of seawater concrete [7], and long-term exposure tests suggest high prospects of using seawater as a material in reinforced concrete [8]. Mbadike and Elinwa [9] analysed the effect of saltwater on the compressive and flexural strengths of concrete for different target strengths. They used freshwater specimens as the control and found that saltwater reduced the concrete strength by approximately 8%. Osuji and Nwankwo [10] evaluated the effect of seawater collected from the Escravos area of the Niger Delta on the compressive strength of concrete. They observed that concrete cast and cured with seawater exhibited approximately 15% higher 28-day strength than concrete cast with freshwater. Lim et al. [11] investigated the strength and corrosion behaviours of seawater-mixed and seawater-cured mortar containing fly ash in various replacement percentages. They reported that utilising seawater as the mixing water can yield comparable compressive strength as freshwater, particularly when cured for extended periods. Younis et al. [6] found that using seawater in concrete initially increased concrete strength up to the seventh day, and a decrease of approximately 7%–10% was observed for Mix B compared to those for Mix A after 28 days. Liu et al. [12] found that seawater and sea sand increased the compressive strength of concrete but decreased the compressive elastic modulus. Teng et al. [13] reported that the use of seawater and sea-sand slightly increases the early-age strength of ultra-high performance concrete but slightly decreases the strength at seven days and above. Vafaei et al. [14] investigated the mechanical properties of fibre-reinforced seawater sea-sand concrete subjected to elevated temperatures. Choi et al. [15] assessed the early-age mechanical properties and microstructures of Portland cement mortars produced with various supplementary cementitious materials exposed to seawater and found that the effect of seawater exposure was more significant on flexural strength than compressive strength. Sun et al. [16] investigated the physical degradation behaviour of cement mortars at three different relative humidity levels based on variations in the physical appearance, dynamic elastic modulus, and microstructure. Lin et al. [17] examined the combined effects of expansive agents and glass fibres on the fracture performance of seawater and sea-sand concrete and found that the optimal expansive agent content was 3%–6%, which increased with increasing glass fibre content. Bachtiar et al. [18] studied the effect of seawater as a curing/mixing constituent on high-performance concrete and observed that seawater-treated concrete contained increased hydration components (tobermorite and ettringite).

Concrete is reinforced with steel bars to improve its tensile resistance to applied loads. A significant concern in using seawater for mixing and curing concrete is the corrosion of steel reinforcement bars in structural concrete. The significant chloride ion concentration of seawater, which can range from 14,000 to 34,000 ppm [19], accelerates the corrosion process in concrete. Hence, preparing structural concrete with seawater is typically discouraged if conventional steel reinforcement is applied. Nonetheless, unreinforced concrete or concrete reinforced with non-corrosive reinforcement, such as fibre-reinforced polymers, can be mixed with seawater if potable water is scarce [20]. This is because not all types of concrete require reinforcement, depending on the intended application. The application of seawater for mixing concrete constituents might affect the durability of plain and reinforced concrete; however, understanding the durability of seawater-mixed concrete is a critical factor limiting its widespread adoption, and further research is required for clarification [21].

The justification for research on seawater in concrete stems from the fact that large volumes of freshwater are used for cement-based construction each year, and freshwater is becoming a relatively scarce resource. Some coastal areas with limited freshwater supply are abundantly surrounded by seawater. With the current water supply shortage in Nigeria and other parts of the world, there is a need to further explore seawater as an alternative water source for concrete production. The aim of this study is to experimentally investigate the workability and strength of Portland cement concrete mixed and cured with Nembe seawater. Nembe seawater was used for mixing and curing concrete, with the concrete specimens mixed with and cured in freshwater adopted as the control.

2. Materials and Methods

2.1. Materials

Cement: Grade 42.5 Portland–limestone cement manufactured according to NIS 444-1:2003 [22] specifications was purchased from a cement depot in Owerri, Imo State, Nigeria. The properties of the cement provided by the manufacturer are listed in Table 1.

Aggregates: Clean river sand dredged from Otammiri River in Ihiagwa, Owerri West Local Government Area, Imo State, was used as the fine aggregate. Crushed granite of 20 mm nominal size processed at a quarry plant in Ishiagu, Ebonyi State, Nigeria, was used as the coarse aggregate.

Water: Two sets of water were used for mixing the concrete ingredients and curing the hardened concrete samples. Freshwater was obtained from a borehole tap at the Structural Engineering Laboratory of the Department of Civil Engineering, Federal University of Technology, Owerri. The seawater was obtained from Nembe waterside, a water transportation route between Port Harcourt in Rivers State and the Nembe Kingdom in Bayelsa State. The seawater was temporarily stored in air-tight plastic containers and transported to the laboratory.

Table 1. Properties of Portland–limestone cement

Property	Value
Fineness	2%
Specific gravity	3.1
Density	1,440 kg/m^3
Initial setting time	120 min
Final setting time	300 min

2.2 Methods

2.2.1 Materials

Before the constituent materials were utilised, they were subjected to preliminary characterisation tests. The cement was in a dry state and free from lumps. The fine aggregate was free from deleterious substances and had a specific gravity of 2.63, fineness modulus of 2.92, water absorption of 1.6%, and bulk density of 1570 kg/m^3. The coarse aggregate had the following physical and mechanical properties: fineness modulus = 4.15, specific gravity = 2.73, water absorption = 1.3%, bulk density = 1520 kg/m^3, aggregate impact value = 25%, and Los Angeles abrasion value = 12%. The particle size distribution curves of the fine and coarse aggregates are shown in Figure 1. The freshwater and seawater were subjected to physiochemical tests to determine their physical and chemical compositions. Table 2 lists the physiochemical properties of the freshwater and seawater samples.

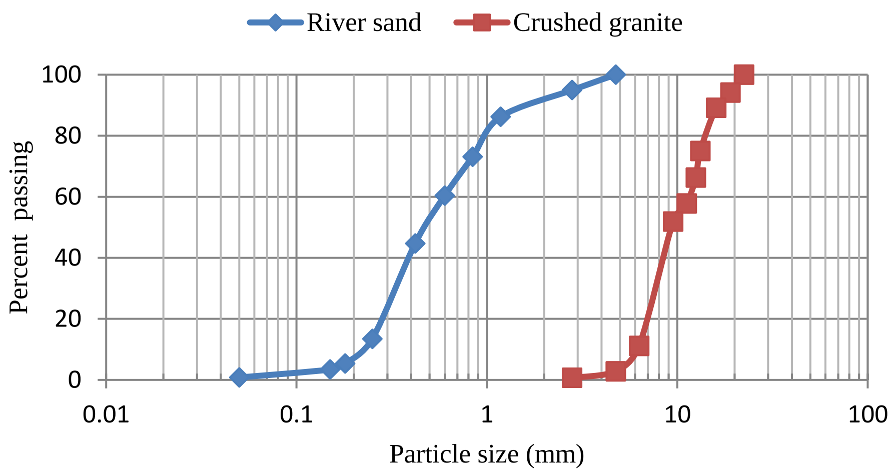

Fig. 1 Particle size distribution curves of river sand and crushed granite

The hardened concrete specimens were denoted by two letters, 'F' and 'S', representing freshwater and seawater, respectively. Each specimen was identified with two letters, such that the first letter indicated the mixing water, whereas the second letter indicated the curing water. For example, 'FS' represented a concrete specimen cast with freshwater and cured with seawater. Four sets of hardened concrete were produced, as listed in Table 3.

Table 2. Physiochemical properties of freshwater and seawater samples

Test	Freshwater	Seawater
pH	7.2	7.9
Electrical conductivity	1,053 micro s/cm	57.9 micro s/cm
Chloride	230 mg/L	19,352 mg/L
Sulphate	110 mg/L	2,649 mg/L
Nitrate	-	-
Calcium	63 mg/L	412 mg/L
Magnesium	28 mg/L	1,272 mg/L
Sodium	-	10,556 mg/L
Potassium	-	880 mg/L
Iron	-	0.14 mg/L
Chromium	-	0.03 mg/L
Phosphate	-	1.10 mg/L
Acidity	-	-
Alkalinity	-	0.8 mg/L
Salinity	-	35.7 mg/L
Total dissolved solids	1,500 mg/L	34,482 mg/L
Total suspended solids	-	-
Odour	Unobjectionable	Unobjectionable
Hardness	-	20.90 mg/L

Table 3. Details of concrete specimens

Notation	Meaning
FF	Concrete mixed and cured with freshwater
FS	Concrete mixed with freshwater and cured with seawater
SF	Concrete mixed with seawater and cured with freshwater
SS	Concrete mixed and cured with seawater

2.2.3 Tests

The setting times and slump of the fresh concrete and the compressive strength of the hardened concrete were determined. The slump of the fresh concrete was evaluated according to BS EN 12350-2:2009 [27], and the compressive strengths of the hardened concrete cubes were measured according to BS EN 12350-3:2009 [28]. The values reported in this paper were obtained as the mean of three measured values. Compressive strength is typically investigated in experimental studies because its test is relatively easy to perform, and the obtained results fairly represent an estimated measure of other mechanical properties, such as flexural strength and splitting tensile strength.

3. Results and Discussion

3.1 Properties of Constituent Materials

The specific gravity of the river sand was within the range used for normal fine aggregate. The fineness modulus of the river sand confirms that the sizes of the fine aggregate particles lie between medium and coarse sands; thus, the river sand is suitable for manufacturing normal-strength concrete. The aggregate impact and Los Angeles abrasion values of the coarse aggregate satisfied the requirements for manufacturing normal-strength concrete. According to Shetty [29], the aggregate impact value and Los Angeles abrasion value should not exceed 30% for wearing-surface concrete and 45% and 50%, respectively, for non-wearing-surface concrete.

The seawater contained significantly high amounts of chloride and sulphate ions, and sodium, magnesium, potassium, and calcium are the main constituent elements detected in the seawater. The amounts of these ions and elements in the seawater were significantly higher than those in the freshwater. Moreover, the seawater contained significantly higher amounts of total dissolved solids than the freshwater (Table 2). The chloride content of the seawater used in this study is within the typical range for seawater reported in the literature [19]. High contents of chloride and sulphate ions affect the pH of water, which significantly impacts the strength development of concrete [30]. Water with a pH ranging between 6.0 and 8.0 has no significant effect on the compressive strength of concrete [31,32]. The pH values of both water types are somewhat comparable, and the pH of Nembe seawater (7.9) is within the range obtained for different seawaters (7.4–8.4) [33].

Chemical reactions between seawater and cement occur during the diffusion of sulphate and chloride ions in the seawater in concrete. Generally, the chemical reactions of seawater on concrete are generated by sulphate attacks, and crystallisation is the primary attacking mode [34]. Sodium, potassium, and magnesium sulphates (Na_2SO_4, K_2SO_4, and $MgSO_4$) present in seawater may induce sulphate attacks in concrete because they can initially react with calcium hydroxide [$Ca(OH)_2$] present in the set cement formed via hydration of dicalcium silicate (C_2S) and tricalcium silicate (C_3S). The sulphate attacks eventually lead to the formation of gypsum. The chemical reaction of the cement paste with the high-chloride content of seawater is generally slight [34]. A possible chemical reaction between seawater and cement is as follows [35].

$$3Ca(OH)_2 + 3Na_2SO_4 \rightarrow 3CaSO_4 + 6NaOH \quad (1)$$

$$CaCl_2 + 2NaOH \rightarrow Ca(OH)_2 + 2NaCl \quad (2)$$

3.2 Setting Time and Slump

The setting time and slump values of the concrete samples mixed with freshwater and seawater are listed in Table 4. The initial setting time of the concrete specimen mixed with freshwater was significantly longer than that mixed with seawater. Compared with freshwater, the use of seawater in Portland-cement concrete decreased the initial setting time of cement by approximately 36% (Table 4). The behaviour is attributed to the high concentration of chloride ions in seawater. The sodium hydroxide produced during the formation of gypsum reacts with salts in the seawater (for example, calcium chloride), leading to the formation of sodium chloride and additional calcium hydroxide (Eq. (2)). These chlorides and chloride ions accelerate the hydration of C_3S pastes, shortening the initial setting time of the seawater-mixed concrete (Table 4). The reduced initial setting time may necessitate applying appropriate retarding admixtures when the rapid setting is undesirable. However, the final setting times of the specimens mixed with freshwater and seawater were approximately equal.

The slump of fresh concrete mixed with freshwater was higher than that of seawater; seawater decreased the slump by approximately 54%. Thus, the concrete produced with seawater was less workable and more viscous than that with freshwater. The total dissolved solids and possible suspended particles in the seawater might have likely increased the seawater viscosity (compared to the freshwater viscosity) and contributed to the decreased slump. Another probable reason for the reduced slump of the seawater concrete sample is the accelerated cement hydration owing to the presence of chloride and sulphate ions in the seawater.

Table 4. Setting times and slump values of fresh concrete

Test	CFW	CSW
Initial setting time (min)	88	56
Final setting time (min)	296	299
Slump (mm)	79	36
CFW = Concrete mixed with freshwater; CSW = Concrete mixed with seawater		

Chloride ions react with sodium hydroxide to produce additional calcium hydroxide, inducing a faster setting and quicker fluidity loss. For the adopted water–cement ratio, the fresh concrete samples containing freshwater and seawater exhibited medium workability, as their slump values ranged between 25 and 100 mm [36]. Superplasticisers may be added to concrete mixed with seawater to maintain an appreciable consistency level and, thus, improve the workability of the concrete mixture.

3.3 Compressive Strength

The compressive strengths of the test specimens cured in freshwater and seawater up to the 90th day were obtained (Figure 2). The different casting and curing conditions were analysed by comparing the parameters with the control condition, that is, the FF specimens. The rates of increase in the compressive strength of concrete specimens mixed and cured with freshwater and seawater were similar; that is, the compressive strength increased with curing age, irrespective of mixing and curing (Figure 2). The strength development rates were high within the first few days and decreased at later curing ages.

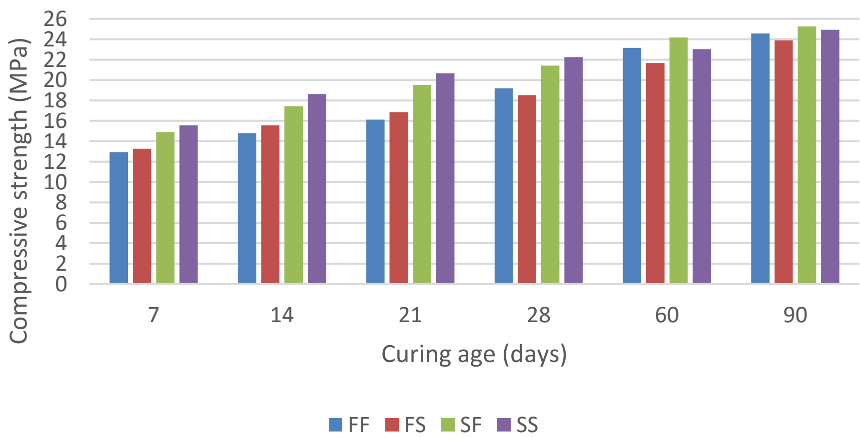

Fig. 2 Compressive strength values for FF, FS, SF, and SS specimens

On the 7th day, the FS specimens had the highest compressive strength than those of the SF, FS, and FF specimens; this trend was also observed on the 14th day. The seawater-mixed concrete underwent an earlier gain in compressive strength before 28 days than the freshwater-mixed concrete. This strength increment might be caused by the improved, densified microstructure of concrete owing to accelerated hydration in the presence of chloride ions. The FF specimens had lower compressive strength values than the FS specimens up to the 21st day, but from the 28th day, they exhibited higher strengths than the FS specimens. In addition, the SF specimens had higher compressive strength values than the FS specimens. Moreover, the FS specimens had the lowest compressive strength comparatively at the later stages. The low strength of the FS specimens could be caused by a lack of adequate hydration, which may be attributed to the thin layer of minerals covering the cement paste [11]. These minerals might have limited moisture penetration in the specimen essential for continuous hydration. By the 90th day, no significant differences between the compressive strength values for specimens subjected to different mixing and curing conditions were observed. Hence, the hydration rates of the FF and SS specimens decreased by then. The relative decrease in the rate of compressive strength gain of the SF and SS specimens after the 28th day may be attributed to the crystallisation of salt in the seawater [34].

4. Conclusions

In this study, the behaviour of concrete mixed and cured with Nembe seawater was investigated. The behaviour of concrete mixed and/or cured with seawater is somewhat linked to the chemical reactions between seawater and cement in concrete. Seawater induces the formation of gypsum and the accelerated hydration of C_3S pastes, leading to the formation of chloride and sulphate salts. The use of seawater for mixing concrete shortened the initial setting time of the cement paste and reduced the slump of the concrete. Generally, the concrete specimens mixed and cured in fresh water at the earlier curing ages (7, 14, and 21 days) had lower compressive strengths than specimens mixed and cured in seawater. Among the four groups of concrete experimentally analysed in this study, concrete specimens mixed and cured with seawater exhibited the highest compressive strengths up to the 28th day. However, concrete specimens mixed with seawater and cured with freshwater exhibited the highest compressive strengths at the 60th and 90th days of curing. From approximately the 60th day of curing, seawater curing negatively influenced the compressive strength of the concrete. Although the concrete specimens mixed with seawater yielded slightly higher compressive strength values than concrete specimens mixed with freshwater, the difference between using freshwater and seawater as mixing and curing water in terms of compressive strength is minimal.

The use of seawater for casting and curing concrete may be necessitated at construction sites close to the sea where portable freshwater is unavailable or inaccessible. Plain concrete may be mixed with seawater in locations where potable water is scarce. Such concrete may be applied to construction cases where unreinforced concrete is acceptable, such as concrete pavements and footpaths. However, adequate measures must be adopted when using seawater in producing reinforced concrete to prevent or minimize corrosion, such as painting or coating the reinforcement bars or using corrosion-resistant reinforcements (for example, fibre-reinforced polymers). Further studies should be conducted to clarify the influence of seawater on concrete properties, such as the long-term strength properties of concrete mixed or cured with seawater. In addition, the durability and microstructural characteristics of seawater concrete should be investigated in detail.

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