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# CORROSION CHARACTERISTICS OF REBAR AND FIBRE REINFORCED CONCRETES IN SELECTED ENVIRONMENTS

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## ABSTRACT

*The corrosion characteristics of rebar and fibres reinforced concretes in selected aggressive environments were investigated. Steel rebar and different fibre materials consisting of steel fibre, coconut fibre, glass fibre, and polymer fibre were used as reinforcements. Corrosion characteristics of these reinforced concretes were evaluated using visual inspection, compressive strength test and accelerated impressed current technique in 3.5wt% NaCl. Analysis of the results indicated that concrete reinforced with polymer and steel fibres after corrosion exposure exhibited lower reduction in compressive strength at 10%, 17%, respectively compared to conventional rebar concrete which had a loss of about 20% across the selected environments; whereas strength loss averaged 44% and 28% in concretes reinforced with coconut and glass fibres, respectively. The findings from this investigation suggested that steel and/or polymer fibres are suitable substitute for rebar in reinforcing concrete.*

**Keywords**: Accelerated corrosion, aggressive environments, compressive strengths, dissolved chlorides, fibre reinforced concretes.

## INTRODUCTION

The infrastructure community has benefitted from the tremendous improvements associated with the strengthening of conventional concrete with reinforcing materials such as steels and glass either as macro constituent or fibrous constituent. Such improvements have expanded the horizon of infrastructural project to hitherto impossible areas including skyscrapers, bridges, aircraft landing port, etc (Rizk, 2010; Ali, 2001). Reinforcement of concrete with rebar counteracts the low tensile strength and ductility of conventional concrete. This is because conventional concrete is quite brittle though it is very strong in compression (Banthia *et al*., 2012; Hasan *et al*., 2011). The brittleness of conventional concrete is a major drawback because it facilitates sudden and catastrophic failure, especially in structures which experienced earthquakes, blast or suddenly applied loads. This drawback can be overcome by the incorporation of reinforcement, especially steel, to carry the tensile loads and prevent any cracking or by pre-stressing the concrete so that it remains largely in compression under load (Rai and Joshi, 2014; Kandasamy and Murugesan, 2011; Hasan *et al*., 2011; Clarke *et al*., 2007).

Reinforced concrete is one of the most widely used construction materials in the world. It is a versatile and economical material that generally performs its intended use well over its service life. On the other hand, rebar reinforced concrete is a common building material for construction of facilities and structures; and has historically been deployed for effective and cost efficient concrete reinforcement. However, concrete reinforcement with hand tied rebar comes with its challenges such as cost, absence of complete bonding between the concrete and the rebar, and structural environmental degradation (Mehta and Monteiro, 2015; Rai and Joshi, 2014). Kanalli *et al*. (2014) reported that fibre reinforcement of concrete provides economic strategy for resolving the challenges identified with rebar reinforced concrete. For instance, Wafa (1990) established that concrete reinforced with steel, glass or plastic fibres is less expensive relative to rebar concrete with comparative or even higher yield strength. Fibres assist to lower the permeability of concrete and thus reduce bleeding of water. Some types of fibres produce greater impact, abrasion and shatter resistance in concrete. Fibre reinforcement also reduces cracking tendency during stiffening of the concrete. Generally, fibres do not increase the flexural strength of concrete, so it cannot replace moment resisting or structural steel reinforcement. Some fibres reduce the strength of concrete.

Fibre reinforced concrete (FRC) is concrete containing fibrous material which enhances the structural integrity of the concrete. It contains short discrete fibres that are uniformly distributed and randomly oriented; and they include steel fibres, glass fibres, synthetic fibres, and natural fibres. The character of FRC changes with different concretes, fibre materials, geometries, distribution, orientation and densities (Parveen and Sharma, 2013). Fibre-reinforcement finds application in shotcrete and normal concrete. Specifically, such concretes are typically used for on-ground floors and pavements, but can be extended to a wide range of structural parts like beams, pliers, foundations, etc. either alone or with hand-tied rebars (Van Chanh, 2004; Vandewalle, 1998). The use of FRC has passed from experimental small-scale applications to routine factory and field applications involving the placement of many hundreds of thousands of cubic yards annually throughout the world. This has made many researchers to develop enthusiastic interest in FRC (American Concrete Institute (ACI), 1999). The use of fibres is anticipated to save time, thus, reducing the overall cost of the project. It is also possible to save money on the material cost, especially if the cost of steel rises to levels that are currently being experienced in most of the developing countries particularly in sub-Saharan Africa like Nigeria. The various fibres impact different property features onto concretes including increased energy dissipated by concrete under impact loading (Mindess and Vondran, 1988). For instance, synthetic fibre (e.g., polypropylene, polyethylene, polyester, acrylic, aramid, carbon etc) or natural fibre (e.g., fly ash, cellulose or grass, coconut fibre, akwara,) could be a better option to enhanced performance than traditional steel-fibre reinforced concrete (Banthia and Bindiganavile, 2002; Banthia *et al.*, 2012). Fibre Reinforced Polymer (FRP) bars are immune to chloride-induced corrosion, and have higher tensile strength compared to steel bars. The noncorrosive FRP bar provides a viable alternative to steel as reinforcement for concrete bridge decks under severe corrosion conditions. Glass Fibre Reinforced Polymer (GFRP) is more economical compared to Carbon Fibre Reinforced Polymer (CFRP) or Aramid Fibre Reinforced Polymer (AFRP), and is generally used in bridge decks as an alternative to steel reinforcement (Pantelides and Liu, 2011). According to ACI Report 544, "fibres may also enhance the properties of concrete including the tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance" (Ryan Barborak, 2011).

The most important and costly deterioration mechanism affecting the rebar concrete structures is the corrosion of steel reinforcement (Elsener, 2002; Elsener *et al.*, 1990).Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete structure worldwide, especially of the structures located in the coastal marine environment. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. The corrosion products (iron oxides and hydroxides) formed within the restricted space in the concrete set up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete (Song and Saraswathy, 2007). Corrosion causes cross sectional loss of the steel which results in a loss of structural strength). The expansion of steel reinforcement due to corrosion causes the concrete bridge deck to experience cracking and spalling; this results in major rehabilitation costs and traffic disruption (Song and Saraswathy, 2007; Yunovich and Thompson, 2003). External factors equally influence concrete durability and deterioration of concrete. Such factors are environmental factors like: the penetration and subsequent movement of water, air, or other fluids which are transporting aggressive agents into concrete pore system (Bryant *et al.*, 2009). Environmental damaging factors can be categorized as external factors that attack concrete chemically (e.g. sulphate, chloride ion and carbon (IV) oxide penetration into the pore structure of the concrete.), or attack concrete physically (e.g. freeze-thaw damage): the most important physical environmental factors are temperature and humidity. Thus, this present work made attempt to investigate the influence of physical environmental factors on the stability of concretes reinforced with different types of fibrous materials. This was done by conducting a comparative characterization of the corrosion behavior of rebar concrete and other fibre reinforced concretes in selected environments like lagoon, sea water and swamp.

## 2.0 MATERIALS AND METHODS

### 2.1 Preliminary Resistivity Test of Fibre Materials

The electrical resistance of each of the fibre was measured using two probe technique of fibre resistance measurement reported by Safarova and Gregr (2010) and Rebouillat and Lyons (2011). The fibre materials are: (1) coconut fibre, (2) alkaline resistant fibre glass (AR Glass fibre), recycled polyethylene terephthalate (PET) fibre and steel fibre. The chemical compositions of the fibres are presented in Table 1. The resistance of the fibre was measured as a function of distance x along the fibre which represented the distance between the two probes; one was fixed and served as zero reference point and the other moveable. The resistance R was determined using the expression combining density (ρ) and size of the fibre (d) as given in Eq. (1).

$$R = \left( \frac{4\rho}{\pi d^2} \right) x \qquad (1)$$

Hence a plot of R versus x gave a linear graph with a slope yielding the resistivity (S) of the fibre given by Eq. (2).

$$S = \left( \frac{4\rho}{\pi d^2} \right) \qquad (2)$$

**Table 1 Chemical composition of the fibres**

| Fibre Material | Composition (wt. %) | |
|---|---|---|
| AR Glass Fibre | $SiO_2$ | 59.46 |
| | $Al_2O_3$ | 4.52 |
| | $ZrO_2$ | 15.02 |
| | CaO | 3.61 |
| | $B_2O_3$ | 7.38 |
| | $TiO_2$ | 5.14 |
| | $Fe_2O_3$ | 2. 98 |
| | $Na_2O$ | 0.75 |
| | $K_2O$ | 1.14 |
| Steel Fibre SW35/1.0 (straight shaped bars) | C | 0.17 |
| | Mn | 0.85 |
| | Cr | 0.13 |
| | Ni | 0.17 |
| | P | 0.04 |
| | S | 0.03 |
| | Fe | 98.61 |
| Coconut Fibre (Coir)* | Lignin | 45.84 |
| | Cellulose | 43.44 |
| | Hemi-Cellulose | 0.25 |
| | Pectin/related compound | 3.00 |
| | Water Soluble | 5.25 |
| | Ash | 2.22 |
| Recycled PET Polymer | - | - |

*http://textilelearner.blogspot.com.ng/2014/01/properties-of-coconutcoir-fiber.html

## 2.2 Formulation of Concrete Mix

### 2.2.1 Concrete

The mix proportion of cement, sand and granite was 1: 2: 4 (see Table 2) with water cement ratio of 0.5. The average weight of fibre was about 200 g at about 0.5% proportion of the concrete mix. The cement used was Dangote Ordinary Portland Cement (OPC) conforming to IS 12269-1987 with 43 grade. The fine aggregate used was natural river sand conforming to zone III of IS 383-1970. The fine aggregates were washed clean from clay so as not to cause expansion and contraction when the water dries up in the concrete. The fine aggregates were then spread under the sun for twenty-four hours. The fine aggregates passed through 20 mm sieve and retained on 4.75 mm sieve size. The coarse aggregate used was crushed granite of 4 mm diameter. The fibre materials used in the concrete mixing and casting were the predetermined fibres of coconut, glass, polyethene and steel, and steel rod at less than 1% ration of the mix.  Standard cube mould of 150 mm x 150 mm x 150 mm made of cast iron was used for the casting of the standard cubes. The standard moulds were fitted such that there were no gaps between the plates of the mold. The mold was then oiled and kept ready for casting.

**Table 2: Concrete mix formulation**

| Materials | Ratio | Weight(Kg) | % |
|---|---|---|---|
| Cement | 1 | 5.20 | 14.28 |
| Silica sand | 2 | 10.40 | 28.43 |
| Coarse aggregates | 4 | 20.80 | 56.73 |
| Fibre | <1% | 0.200 | 0.500 |

### 2.2.2 Mixing Proportion

The M 25 mix design was used in the concrete preparation. A horizontal rotating cum flow-pan type 150 L capacity EIRICH model EAG21 mixer was used for preparing concrete mixes. The concrete was mixed in a rotary mixer so as to ensure better mixing and to avoid any loss of materials. All materials were mixed in the EIRICH mechanical mixer in accordance with the ASTM C192-07 standard procedure. The mixer was hand-loaded with coarse aggregate first, followed with fine aggregate, cement and then water for that standard concrete cube. For the fibre reinforced concrete cubes, the procedure for the standard concrete cube was repeated with the introduction of the respective fibres or steel rod for rebar concrete. The various reinforcement fibres are shown in Fig. 1. The rotation was continued up to 2 minutes afterwhich the concrete was discharged on a clean platform. Dark brown low pour fuel oil (LPFO-VD6) was applied sparingly to the inside faces of the molds to avoid any sticking of concrete to the walls. After 24 hours of casting, the specimens were stripped and transferred to 100 L capacity curing tank wherein they were immersed in water for 21 days for complete curing at ambient condition.

(a) (b)

(c) (d)

**Fig. 1: Fibres used as reinforcement: (a) polymeric fibre, (b) coconut fibre, (c) glass fibre, and (d) steel fibre**

15 concrete cube samples were cast for the three selected environments at 5 cubes per environment. Each set consisted of one rebar reinforced concrete and four fibre reinforced concretes (see Fig. 2) and compressive strength test was carried out on a set. The remaining sets were inserted in lagoon, swamp, seawater for 75 days; and in accelerated corrosion solution which consists of 3% NaCl saline solution.

**Fig. 2: Image acquisitions of cast rebar and FRC cubes after curing**

## 2.3 Characterization of Compressive Strength

Compressive strength test procedure was carried out in accordance to BSI EN 12390 (2009). 5 concrete cube samples were tested in Avery Denison testing machine, and the maximum crushing load was measured. Compressive strength was then calculated using Eq. (3)

$$f_{cu} = \frac{P}{ab} \qquad (3)$$

where, $f_{cu}$was the compressive strength (KPa), P was the maximum crushing load resisted by the specimen before failure (KN), a and b were width and length of the cube (mm). The remaining cubes (corroded concrete) that were inserted in selected environments of lagoon, sea, swamp and simulated chemical environment were also subjected to compressive strength.

## 2.4 Concrete Cubes in Selected Natural Corrosive Environment

2 sets of 5 concrete cubes were immersed in the lagoon and swampy environments in the University of Lagos, Akoka Campus, for a period of two and half months to determine the effects of corrosion (Fig. 3), while a set was immersed in sea water in the laboratory. At the end of this period, the concrete samples were recovered and inspected for signs of corrosion and their compressive strengths were determined (Fig. 4). Prior to immersion, physico-chemical analysis of the sea water, lagoon and swamp water was conducted in accordance with procedures described in the America Public Health Association (APHA) standards (APHA, 1998).

**Fig. 3: Concrete samples: (a) campus lagoon (b) swamp environment**

## 2.5 Accelerated Corrosion Test

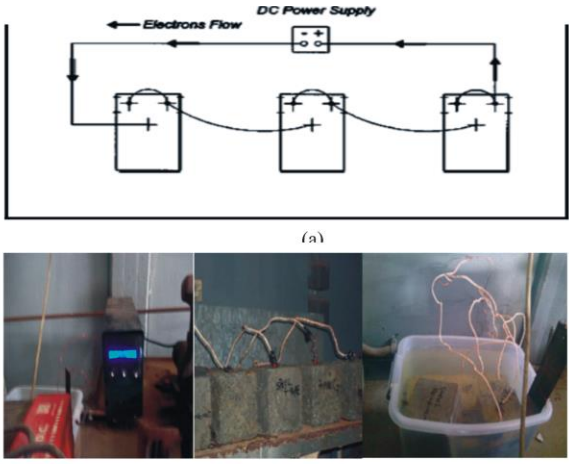
Various techniques are available in the literature for accelerated corrosion in reinforced concrete (Ahmad, 2009). These techniques include impressed voltage, macrocell, artificial climate environment, accelerated AC impedance, accelerated chloride migration test and impressed current. Among these techniques, the impressed current offers ability to control the rate of corrosion, which usually varies due to changes in the resistivity, oxygen concentration, and temperature and difficult in other techniques. It is flexible and equally offers savings in both time and money. In this work, the impressed current technique was deployed. The technique involved passing electric current from a fabricated D.C power source through the concrete samples immersed in electrolyte solution of NaCl. All concrete samples were placed in the electrolyte solution tank and connected to the positive end of the power supply at the protruding titanium/steel rods using copper core cables. The negative connection of the circuit was provided using a piece of bare steel electrode partially submerged in the solution. A constant 3A current was passed through the electrolyte solution where the concrete samples were placed for a period of 10 hours a day for 28 days.

(a)

(b)

**Fig. 4: Concrete cubes after immersion in natural Corrosive environment: (a) sets of corroded cubes and (b) typical corroded rebar concrete cube with scales**

Fig. 5 represents both the schematic illustration and the real time set-up for the accelerated corrosion test. At the end of each test, the concrete samples were subjected to visual examination and compressive strength test.



(a)

(b)

**Fig. 5 illustration of set-up for accelerated corrosion test: (a) schematic set-up, and (b) real time set-up of accelerated corrosion set-up**

## 3.0 RESULTS AND DISCUSSION

### 3.1 Physico-chemical Analysis of Selected Environments

The physico-chemical analysis of the selected environments presented in Table 3 shows the distribution of dissolved chlorides, nitrate, nitrite, sulphates, total acidity, and total alkalinity in the various environments. The pH of the environment indicates that the Sea water is significantly alkaline while Swamp and Lagoon waters are moderately acidic with acidity concentration of about 1020 mg/l and 1006 mg/l in both Swamp and Lagoon waters, respectively. Dissolved chlorides in the environment are 7.2 x $10^4$ mg/l in Sea water, 3.5 x $10^2$ mg/l in Swamp, and 1.27 x $10^2$ mg/l in Lagoon water; in these environments, dissolved oxygen 8.47 mg/l, 1.55 mg/l and 0.79 mg/l in Sea, Swamp and Lagoon water, respectively. Literature revealed that chloride radicals are the main constituent driving reinforced concrete which is further facilitated by the presence of dissolved oxygen; but a global critical value is not available for the concentration of chloride in environments that can sustain passivity in the reinforced concrete. Notwithstanding, it is postulated that, with the very high concentration of dissolved chlorides and oxygen in sea water relative to the other two environments, corrosion of reinforced concrete is most likely to be severe in sea water environment relative to the other two environments. This is validated by the work of Angst (2011) which reported that corrosion in reinforced concrete is significantly facilitated by the presence and concentration of dissolved chloride.

**Table 3: Physico-chemical test of selected environments**

| TEST | Sea | Swamp | Lagoon |
|---|---|---|---|
| PH Value | 8.43 | 5.02 | 6.02 |
| Total dissolved solid (mg/l) | 321964.00 | 191.94 | 342.66 |
| Total alkalinity (mg/l) | 160 | 30 | 40 |
| Total acidity (mg/l) | 100.00 | 1020.00 | 1006.00 |
| Total Dissolved oxygen (mg/l) | 8.47 | 1.55 | 0.79 |
| Total dissolved chlorides (mg/l) | 71552.80 | 354.50 | 127.62 |
| Total dissolved nitrate (mg/l) | 29.0 | 62.0 | 76.0 |
| Total dissolved nitrites (mg/l) | 11.20 | 29.20 | 39.43 |
| Total dissolved sulphate (mg/l) | 76.00 | 102.00 | 298.00 |

**Table 4: Resistivity values for the various fibre materials**

| Fibre | Average Length(m) | Diameter (m) | Cross sectional area ($m^2$) | Resistance (ohms) | Resistivity $\rho = \frac{RA}{x}$ (ohm .m) |
|---|---|---|---|---|---|
| **coconut** | 0.005 | 0.0010 | 7.85E-7 | 120E6 | 18840 |
| **AR glass** | 0.005 | 0.0005 | 1.96E-7 | ∞ | ∞ |
| **Pet** | 0.005 | 0.0005 | 1.96E-7 | ∞ | ∞ |
| **Steel** | 0.005 | 0.0020 | 3.14E-4 | 0.06E0 | 0.003768 |

## 3.3 Analysis of Corrosion Characteristics of Rebar and Fibre Reinforced Concrete

### 3.3.1 Visual Examination and Accelerated Corrosion of Reinforced Concrete Post Immersion in Selected Environments

Retrieved concrete cubes from the selected environments were visually inspected for signs of corrosion. The visual inspection revealed the following (see Fig. 4a):

1. Formation of scale on steel rods used in the rebar concrete which readily spalled off and apparently led to a lower compressive strength in the concrete due to reduced cross section.
2. The steel fibre reinforced concrete showed little signs of physical degradation. There were also signs of scale formation on the surface of the steel fibre reinforced concrete but at a lesser severity unlike in the rebar concrete. This could mean that corrosion was restricted to the steel fibre close the concrete surfaces but was minimal on steel fibre embedded deep within the concrete.
3. The polymer fibre reinforced concretes were obviously not affected by their host environments over a period of two and half months of the tests. This was attributed to the chemical resistance of polymeric materials like polyethylene to aggressive chloride radicals and dissolved oxygen in their host environments. This was also observed in glass fibre reinforced concrete immersed in the same environments.
4. Finally, the coconut fibre reinforced concrete showed adverse effects of wear and abrasion. This could mean that coconut as reinforcement fared poorly in marine environments. Coconut fibre, being a bio- degradable material, must have suffered adverse effects of microbial attack from marine organisms.

The effects of accelerated corrosion on the concrete cubes were a bit similar to those of natural environments but with a few differences; and these include: more pronounced formation of scales on steel rod reinforcement, indicating the aggressiveness of the test condition, pronounced evidence of spalling or loss of concrete surfaces on the cubes (see Fig. 4b). This effect was more pronounced in coconut reinforced concrete followed by steel fibre reinforcement. Glass fibre and polymer fibre reinforcements showed greater resistance to this phenomenon. This suggests that their higher resistance to current flow was a sign of resistance to corrosion which is illustrated from their very high resistivity values.

### 3.3.2 Compressive Strength of Reinforced Concrete Cubes in Selected Environments

The trends of changes in compressive strength of reinforced concrete cubes after immersion in the selected environments are shown in Fig. 6-8. Before immersion in the selected environments, rebar reinforced concrete compressive strength was about 1800 KPa whereas those of Recycled PET fibre, steel fibre, AR glass fibre, coconut fibre were 1450KPa, 1240 KPa, 1034 KPa, and 621 KPa, respectively. The compressive strength values for the variously reinforced concretes, consequent upon immersion in lagoon environment, reduced by about 9.5%, 15.4%, 16.7%, 20% and 44%, for polymer fibre reinforced concrete, rebar concrete, steel fibre reinforced concrete, AR glass fibre reinforced concrete and coconut fibre reinforced concrete, respectively. Though, in absolute terms, rebar concrete has the highest compressive strength but its corrosion resistance in these environment is less noble relative to polymer fibre reinforced concrete. Similar trend was obtained in the other two environments but that of the sea water was more severe apparently because of the higher levels of both dissolved chlorides and oxygen in sea water compared to either swamp or lagoon water. This is because corrosion of reinforced concrete is mostly influenced by the concentration of both dissolved chlorides and oxygen which acts to depassivate the reinforced concrete thus accelerating corrosion (Angst, 2011). Again, the trend in these environments is in agreement with the results from resistivity measurement.

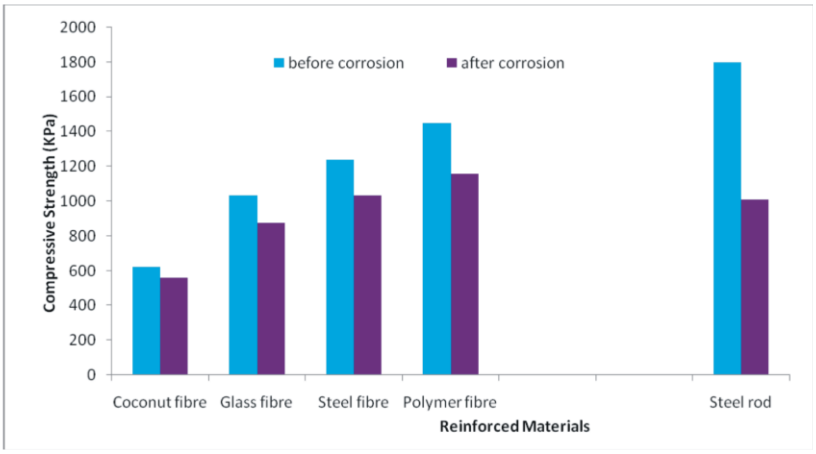


**Fig. 6: Influence of corrosion on compressive strength of reinforced concrete in sea water**

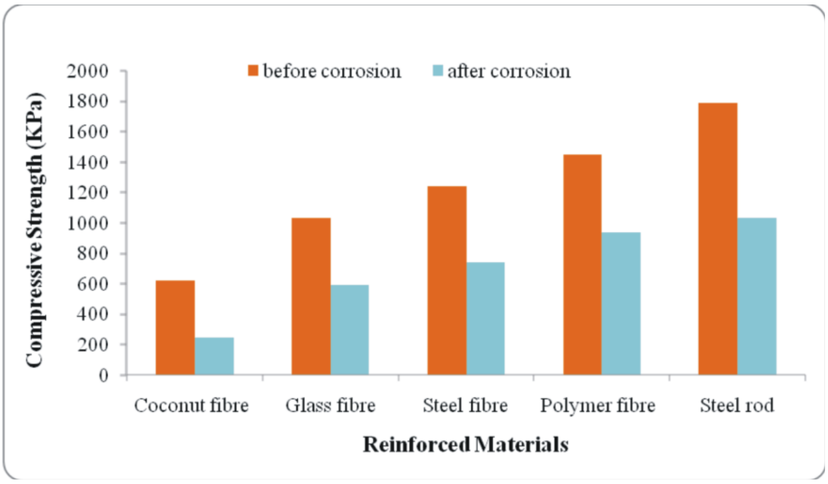


**Fig. 7: Influence of corrosion on compressive strength of reinforced concrete in swamp environment**

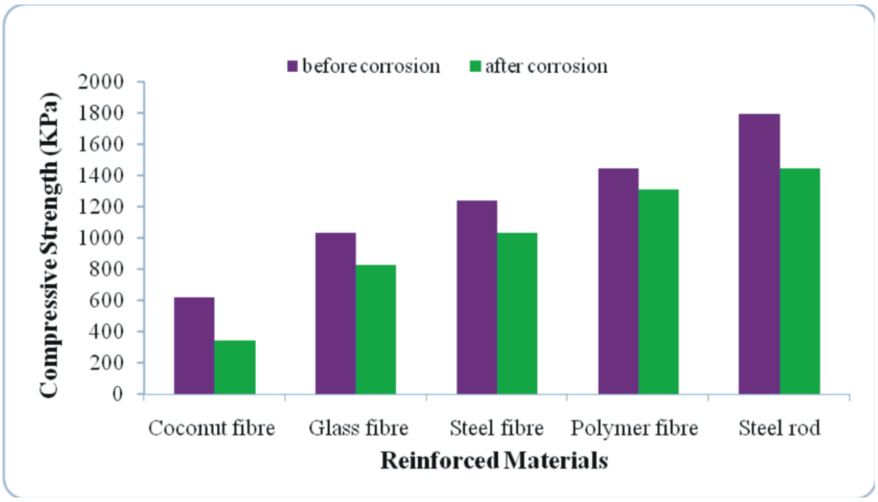


**Fig.8:** **Influence of corrosion on compressive strength of reinforced concrete in lagoon environment**

## 4.0 CONCLUSSION

Reinforced concrete samples with various fibres as reinforcements and placed in various aggressive environments have been investigated for corrosion characteristics. The followings emerged from the investigation:

i. Concrete bearing conventional steel rods reinforcement showed great strength and minimal losses of strength after exposure to various aggressive environments though the inherent problem of scale formation still persists. However, polymer fibre reinforced concrete offered the least loss in compressive strength after immersion,; and as such offers potential for improving the corrosion resistance of rebar concrete by pre-wrapping or coating steel rods with polymeric materials. In the alternative, steel fibre reinforced concrete may be considered in the place of rebar concrete.

ii. Polymer and glass fibres reinforced concretes offered lower loss in compressive strength after immersion in the selected environments relative to both steel fibre and coconut fibre reinforcement; and present themselves as competitive alternative to rebar reinforcement in concrete.

iii. Coconut fibre reinforced concretes are not suited for any of sea water, swamp, and lagoon environments considered in this investigation.

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