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RESEARCH ARTICLE-CIVIL ENGINEERING

Influence of Diethanolamine on the Properties of Concrete, Corrosion Rate of Rebar and Renewable Energy Generation

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Abstract

The effect of additives on the performance, durability and multi-functional service sustainability of a novel self-compacting concrete (SCC) was investigated in this research. Constant partial replacement of cement with 40% fly ash and admixture of M25 grade conplast SP 430 were used to form the SCC. This was followed with the addition of varying amount (0–4%) of diethanolamine as an organic corrosion inhibitor, while one set of concrete was made without the additive, to act as a control. The effect of the additives on the compressive strength, split tensile strength, the corrosion rate of the reinforcement steel rebar and the ability of electrical energy being harnessed from the concrete were analyzed. It was observed that the amount of diethanolamine to be added for maximum enhancement of mechanical properties and corrosion resistance of SCC was 3.2%. The mechanical properties of the SCC and its corrosion resistance were found to be better. Also, the energy that could power some DC components and devices was harvested or generated from the concrete beam. Hence, the study concluded that diethanolamine is a good corrosion inhibitor for reinforced concrete steel rebar and that the presence of fly ash and admixture of M25 grade conplast SP 430, strengthened the concrete.

Keywords Concrete · Corrosion · Organic inhibitor · Concrete · Renewable energy

1 Introduction

In recent years, improvement in performance, serviceability and durability of concrete has caught the attention of many researchers, especially with the development of its application in marine constructions such as offshore oil platforms, wharves, submarine tunnels, cross-sea bridges and building of high rising structures like skyscrapers [1–5]. With the emergence of global challenges, occasioned by urbanization, climate change and sustainability, the construction industry is expected to come up with innovations, toward addressing the challenges. Consequently, the raw material requirement for modern civil infrastructures must be put into consideration for enhanced performance, durability and sustainability [6–9]. Improvement on the strength of concrete and corrosion resistance of its reinforcement rebar is among the

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strategies that have been employed to address some of the issues of performance and durability.

The inclusion of mineral admixture and corrosion inhibitor as effective additives in the concrete mix is one of the methods that have been utilized [1, 10–13]. Electrochemical, design, pigging, coating and inhibition are the most used methods over the years for combating corrosion [14]. Presently, the combination of fly ash and mineral powder is the most common mineral admixture that has been used as an additive for concrete. It helps to form a stable condensation system, through induced activation, hydration and hardening. This, thus, takes maximum advantage of the composite effect of its multi-functional components to enhance the durability, performance and mechanical properties of the concrete [1, 15, 16].

Furthermore, most developing nations are still battling with inadequate energy supply for domestic and industrial uses [17]. Therefore, the quest for more sources of cleaner and sustainable renewable energy has resulted in many innovations in the concrete industry through adopting multi-facility applications such as the use of sensors in energy harvesting from open civil infrastructures. These novel and recent techniques are receiving global acceptance [18]. Considering this fact, this work focuses on capturing and storing wasted external energy such as mechanical, thermal and wind from open buildings. Energy harvesting is framed in such a way that ambient energy derived from concrete is converted into electrical energy [18]. The application of the piezoelectric effect is evaluated by making a composite cement mix ratio, followed by casting, curing and subjecting to mechanical deformation that generates electricity, stored in an external device. Adopting a suitable parameter for inducing the control of corrosion in concrete needs a special mechanism. Anode and cathode play a unique role that controls corrosion, based on electrochemical methods. The inclusion of suitable additives in the mixture of concrete in a standard proportion decreases corrosion rate when applied on vibrated compact surface. The organic composition of additives, applied in the mix ratio of concrete, has been found to be cost-effective and successful when implemented at various construction projects [19]. In reinforced concrete structures, added organic compounds significantly improve the effective strength of the structures and also control the rate of corrosion.

Adopting an environment-friendly component in the concrete could help militate against corrosion in a self-compacting concrete. These types of components are mostly applied on the surface of the concrete and adsorbed in the concrete to form a hair-line film, which acts as a protection enforcement using ethanolamine [20]. The organic additive gives special treatment to the dropping of carbon-based and chloride-based corrosion following sorption supported chemical reactions. With these functions, the formation of metallic coatings favoring corrosion is controlled.

Previous studies carried out on self-compacted concrete for corrosion control were mainly centered on chloride-based composition [21]. In this research, M25 grades were used for all the mix proportion, as ordinary Portland cement was replaced by constant percentage of fly ash (40%) and in addition, organic commercial corrosion inhibitor (diethanolamine) with varying percentages of 0 to 4% by weight of cement content. The admixture considered for this case is Conplast SP430 of about 0.5% [22]. The effects of the additives on the mechanical properties of concrete and corrosion rate of reinforcement steel bar were investigated. The research also studied the possibility of harvesting energy from concrete structures.

2 Methodology

In this study, attention was focused on investigating the strength of SCC, framed with special organic compounds and compared with conventional concrete. All materials used in preparing the concrete mixes and testing were calibrated based on IS 4031–1998 [23]. The SCC mixes were prepared with M25 grades superplasticizer, for all the mix proportions, as ordinary Portland cement was replaced by constant percentage of fly ash (40%) and in addition, organic commercial corrosion inhibitor (diethanolamine) with varying percentages of 0 to 4% by weight of cement content. The special admixture used to enhance the strength of the concrete in this study is Conplast SP 430 [23]. The selection of the organic inhibitor was based on attractiveness and economy, as diethanolamine leads the construction industry in vast application, both in the mixing of concrete and external application. In case of industrial application, diethanolamines are commonly used to eliminate hydrogen from sour gas that acts as water-based solution. The casting of the concrete was processed with the various composition of diethanolamine, ranging from 0 to 4%. Castings without diethanolamine (i.e., casting having 0% diethanolamine), being the conventional concrete, acted as control sample. The diethanolamine used was purchased from a known chemical shop in India. Apart from the additive replacing part of the cement, other components of the concrete mixture followed standard recommended specifications. The casting of samples for testing of mechanical properties and corrosion inhibition was made for both the conventional and self-compacting concrete mixtures. Mild steel was used as the metallic reinforcement for the concrete. Figures 1 and 2 show the framework and reinforcement of the beam, respectively.

Mechanical testing of the beam specimens was done using a universal testing machine, and the applied load

Fig. 1 Framework of beam

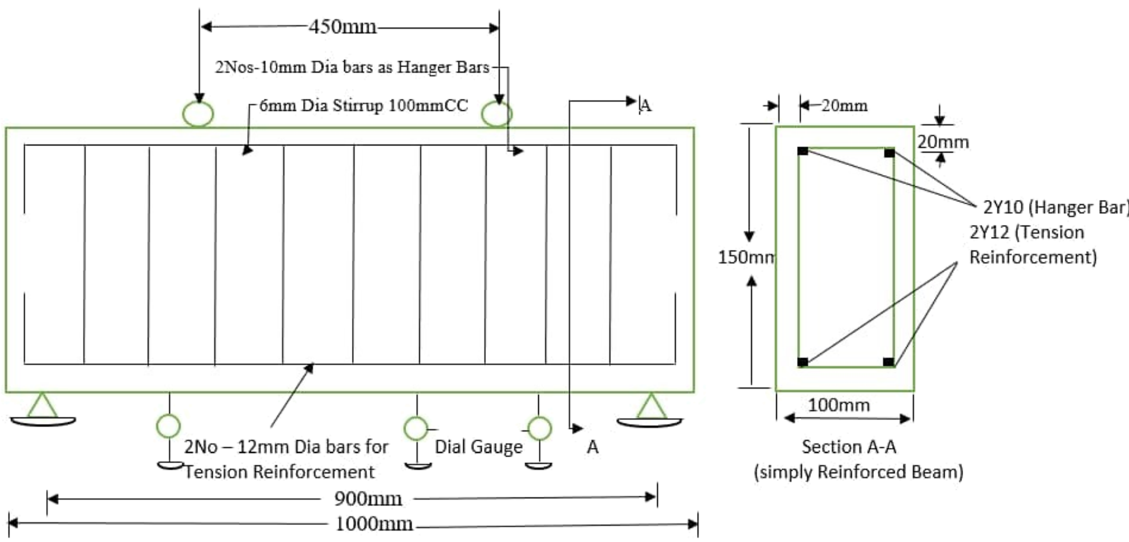

Fig. 2 Beam reinforcement

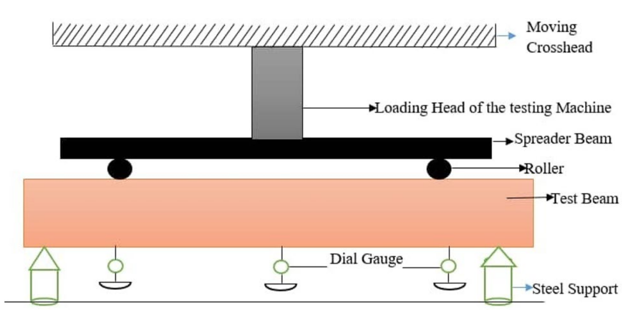

Fig. 3 Two-point loading system design diagram

Fig. 4 Experimental setup for the test specimens

from the top side continued until a complete tension among steel reinforcement was obtained [24]. The ultimate deflection gives the data on the strength of the specimen,

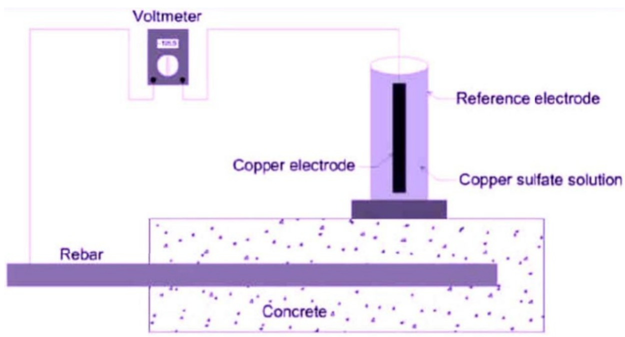

Fig. 5 Schematic experimental setup of potential measurement of corrosion rate

where the beam specimens are subjected to flexural load under a steady moment and progressed until failure [25]. The experimental evaluations of the loading system and their respective schematic views are shown in Fig. 3, while the experimental setup for the beam testing is shown in Fig. 4. Mechanical properties evaluated are compressive, split tensile and flexural strength.

2.1 Corrosion Rate Measurement

The potential measurement and gravimetric methods were utilized to evaluate the corrosion rate of the steel rebar used for reinforcement of the concrete. The composite concrete samples were immersed in sodium chloride electrolyzed water and hydrochloric acid solution, respectively, for each method.

2.1.1 Potential Measurement

Figure 5 shows a schematic representation of the potential measurement experimental setup.

The electrochemical study was conducted at room temperature (25 ±2 °C) by three electrode systems, where the reinforced steel rebar acted as a working electrode, a stainless steel wire as a counter electrode, and copper/copper sulfate as a reference electrode with stainless steel. The samples were immersed in water and electrolyzed with NaCl [1, 26]. Corrosion potentials were measured at 100 h periodic intervals for 600 h at ambient conditions, using the half-cell electrode potential measurement method as documented in ASTM C876 [6].

2.1.2 Gravimetric Method

The corrosion rate, CR_G, for the reinforced steel rods was carried out with the gravimetric method and evaluated using Eq. 1. [29].

$$CR_G = \frac{8.76 \times W}{D \times A \times T} \quad (1)$$

where weight loss, the density of steel, area of specimen and exposure time are designated by W, D, A and T, respectively [27]. The reinforced steel specimen was pickled in an aqueous solution of hydrochloric acid to remove dust and scales [28] before using them for concrete reinforcement. Further, the samples were split open for steel exposure and the parameters measured as w_1 for initial weight before exposure and w_2 for the final weight after exposure. This was done to assess the corrosion rate [29], which was determined after 50 days.

2.2 Sorptivity Assessment

Measurement of water absorption capacity of the composite concrete material by capillary action was determined. The corresponding schematic view of the experimental setup is shown in Fig. 6.

The sorptivity assessment normally gives the data on the rate of absorption of water [30]. The experimentation works were done in a container with water level maintained at 5 mm. After immersing the specimens, the capillary rise values were monitored in a time period of 35 min [30]. Simultaneously, their corresponding initial weight and final weight were measured. It was also ensured that no external moisture entered the specimen [31]. The sorptivity values are measured using Eq. 2. [31].

$$S = I\sqrt{\mathrm{t}} \quad (2)$$

i = cumulative absorption at time (t), m/s; S = Sorptivity in mm, t = elapsed time in min,

2.3 Energy Harvesting Technique

The experimental setup of the energy harvesting technique and their respective schematic views are shown in Fig. 7.

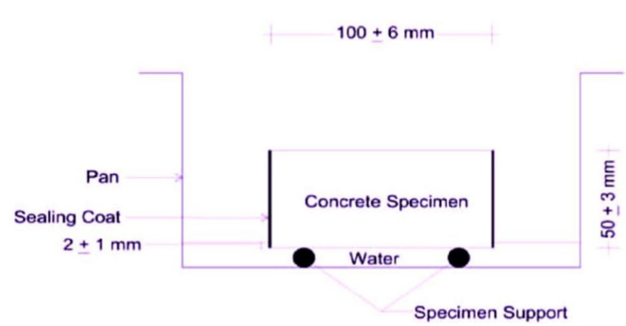

Fig. 6 Sorptivity assessment setup

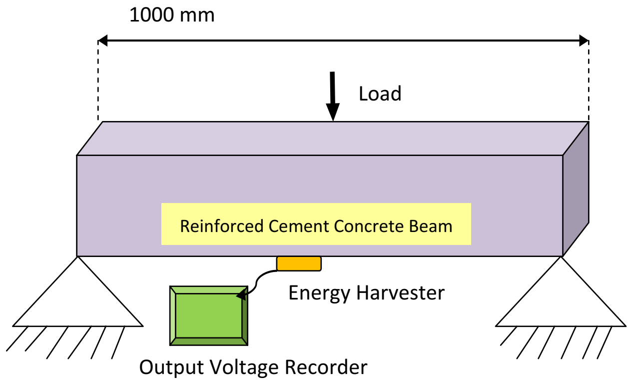

Fig. 7 Schematic view of the energy harvesting method

Applied stress or strain on the concrete makes the crystal structure deform and cause electrical energy to be generated. The charge density due to electrical thrust is proportional to the applied stress and given by Eq. (3).

$$\rho = \mathrm{d}X \tag{3}$$

ρ = charge density, d = piezoelectric coefficient, X = stress.

Also,

$$\nabla E = \frac{\rho}{\varepsilon} \tag{4}$$

∇E = divergence of the electric field, ρ = charge density, ε = permittivity.

The devices are developed by forming piezoelectric material, electrodes and external circuit that create electric potential and generate electrical energy [32].

3 Results and Discussion

3.1 Effect of the Corrosion Inhibitor on Mechanical Properties of Concrete

Figure 8 presents the effect of inhibitor on the compressive strength developed after 3, 7, 14, 28, 56 and 90 days.

Figure 8 shows that diethanolamine had a significant influence on the compressive strength of the steel reinforced concrete, as the compressive strength increased with increasing concentration of diethanolamine up to 3.2% and started decreasing with further increase in the concentration of the inhibitor. Similarly, compressive strength increased with an increase in curing time. Hence, it can be asserted that SCC had a better compressive strength than conventional concrete (CC). This finding is consistent with the report of [11] and could be attributed to the reduced water absorption capacity of the SCC, which reduced the rate of corrosion of the reinforced steel and thus maintained higher strength than the CC with higher water absorption capacity, which increases corrosion rate and reduces strength (Figs. 12, 13, 14, 15, 16, 17).

Figure 9 shows that SCC (i.e., 0.8–3.2% additive) performed better than CC (i.e., without additive) in terms of both flexural and split tensile strength. According to [26], the addition of superplastics and/or inhibitors introduced components in the concrete mix that made the concrete denser. Some of the components act by forming compounds or layers, which help to reduce the size of the pores in the concrete, thereby reducing penetration of deleterious components into the concrete and thus protect it [33]. The effect of the amount of diethanolamine addition on the split tensile strength and flexural strength of the concrete after 28 days of curing is shown in Fig. 9. A critical inspection of Fig. 9 reveals that increasing the amount of diethanolamine,

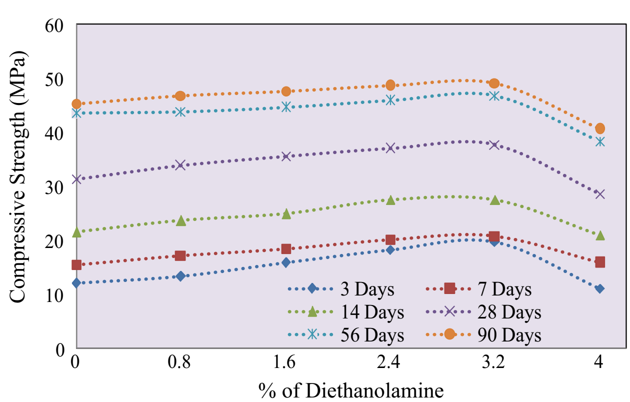

Fig. 8 Influence of diethanolamine on compressive strength

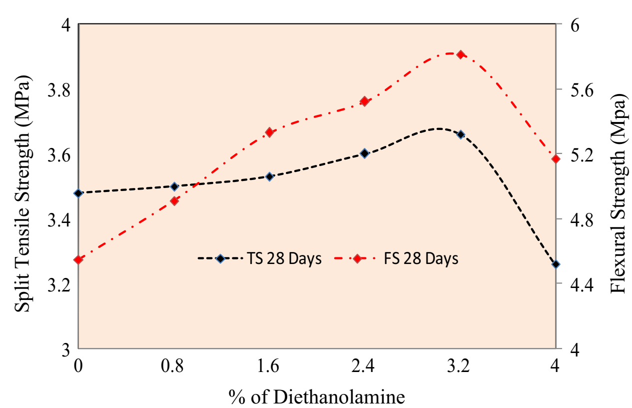

Fig. 9 Split tensile and flexural strength versus % of corrosion inhibitor

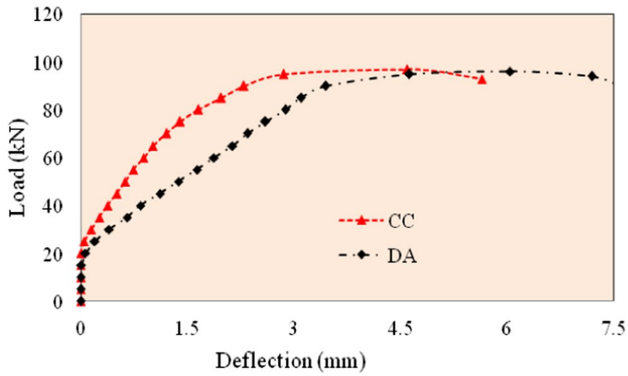

Fig. 10 Load deflection for beam of SCC with 3.2% inhibitor and CC

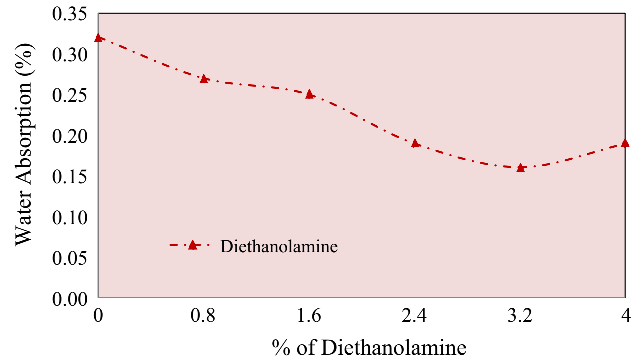

Fig. 12 Water absorption versus % corrosion inhibitor

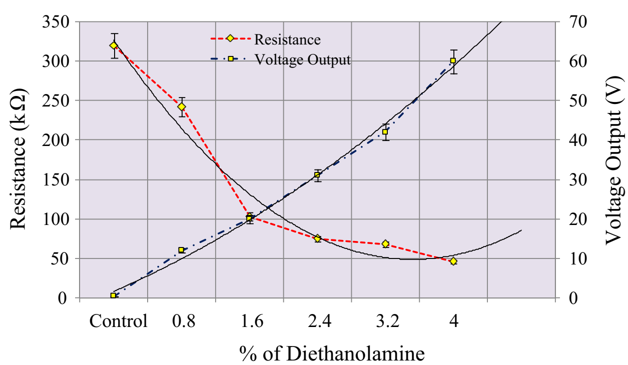

Fig. 11 Impact of flexural strength on specimen

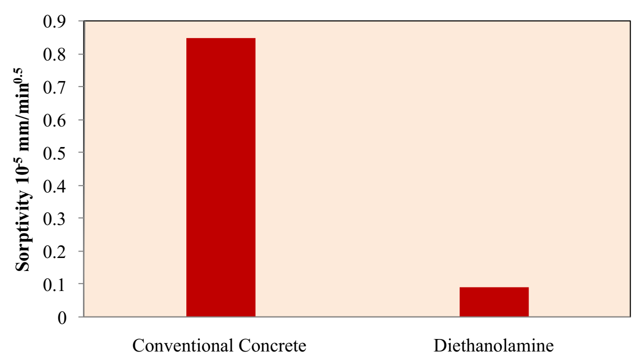

Fig. 13 CC and SCC sorptivity at optimum inhibitor concentration

improved both properties and until the maximum of 3.2% concentration was reached. However, the improvement recorded in flexural strength with the addition of diethanolamine was higher than that of split tensile strength. Increased strength with the increasing amount of diethanolamine is a clear indication that the degradation of steel rebar decreased with an increase in diethanolamine addition, up to 3.2%. This could be due to the increasing performance of the protective oxide layer, formed on the surface of the steel rebar by the inhibitor [33].

Figure 10 shows the applied load deflection for the beam of SCC with optimum amount (3.2%) of organic corrosion inhibitor, compared with that of CC. Significant difference was observed in the ultimate load of the conventional concrete and the sample specimens with 96 kN and 97 kN, respectively. This outcome is an indication that 3% diethanolamine is significant in self-compacting concrete [26].

The applied stress was driven to the projected model as a compacted load to a frequency running from 0.2–0.6 Hz. The model was tried for its detecting property, received with negligible corrosion rate proportions [27]. Typically, the debacle in common development occurs through typhoon, tempest and tremor, in which the effects were estimated in the range of 0–5.0 Hz [28]. Figure 11 describes the voltage from the composite concrete with 12 MPa practical loads [29]. Simultaneously, for the energy harvesting, the electrical resistance was higher in the control test. However, with increase in diethanoamine blend rate, which is with composite material detecting property, a decrease in resistance was noted [30]. In any case, when an outer load was applied on the skin of the basic part with higher frequency, the detecting property concerning the obstruction in a short time frame was invigorated.

From Ohm's law, $V = IR$, and also from electrical power, $P = IV = V^2/R = I^2R$, implying that the amount of power generated increased with the addition of diethanolamine and that an average of 0.0002A (2.0×10^{-4}A) or 0.2 mA of current flowed across the system, which is enough to power some DC components and devices.

3.2 Effect of Diethanolamine on Sorptivity and Corrosion Rate

Water absorption efficiencies of the samples are shown in Fig. 12. The change in water absorption was due to the addition of inhibitors. It decreased with increased concentration of inhibitor and reached a minimum at 3.2% of inhibitor's concentration. This observed trend is in agreement with

[12]. The sorptivity of the SCC sample with an optimum composition of diethanolamine and CC is shown in Fig. 13. It showed that adding 3.2% of diethanolamine to concrete reduced the water absorption capacity drastically to about 8 times that of CC. This may be due to the compact nature of the SCC and the tendency of some components of the additive to form substances, which could seal up or minimize the size and amount of pores present in it [30].

3.3 Analysis of Corrosion Potential and Corrosion Rate

Figure 14 shows that the corrosion potential shifts toward the passive region for the concrete with diethanolamine added compared to the CC, which is an indication that the oxide layers formed are more stable and more protective in SCC than CC. Hence, the rate of corrosion would be higher in CC than SCC as shown in Fig. 15. Similarly, Figs. 16 and 17 made it clear that the oxides formed on the surface of steel rebar in CC (Fig. 16) are more loosely attached to the surface compared to that of SCC (Fig. 17).

A critical and objective inspection of Fig. 15 reveals that the addition of diethanolamine drastically reduced the corrosion rate of the steel rebar in the SCC, when compared with that of CC. Degradation of reinforced concrete in a chloride environment is mainly due to the attack of chloride ion on the steel rebar, which is chloride-induced corrosion related. Fortunately, the addition of superplasticizer/ inhibitor introduces functional components in the concrete mix which makes the concrete a denser or more compact structure [15]. Some of the constituents act by forming layers or compounds which help to reduce the number and size of pores in concrete, thereby reducing penetration of both water and deleterious components (e.g., Cl^-) access into the concrete or contact with the steel rebar surface; thus, the steel rebar is preserved in its passive state [15, 33].

Table 1 presents the summary of some tested parameters. It shows the improvements recorded at the optimum concentration of the additive on the 28th day. From Table 1, sorptivity recorded the highest improvement of 90.8%, while split tensile strength had the least value of 4.31%. SCC was also found to have better performance for all parameters tested. This implies healthier and longer life span for structures made with SCC material. Since concrete is more of compressive load-bearing element, the greater improvement obtained for flexural and compressive strengths (28.89 and 16.67%, respectively) compared to 4.31% of split tensile strength is significant. The results obtained are not only consistent with findings from earlier related studies, but also better in some cases as shown in Table 2.

A critical inspection of Table 2 shows that the outcome of the present research is in line with those of related earlier studies [35]. It also reveals that the present research, comparatively, obtained better results than many of those in the previous studies. The use of diethanolamine as an additive in concrete mix for properties enhancement as well as corrosion inhibition should therefore be encouraged in engineering construction.

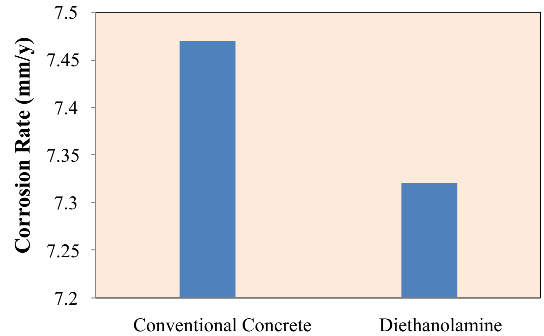

Fig. 15 CC and SCC corrosion rate at optimum inhibitor concentration

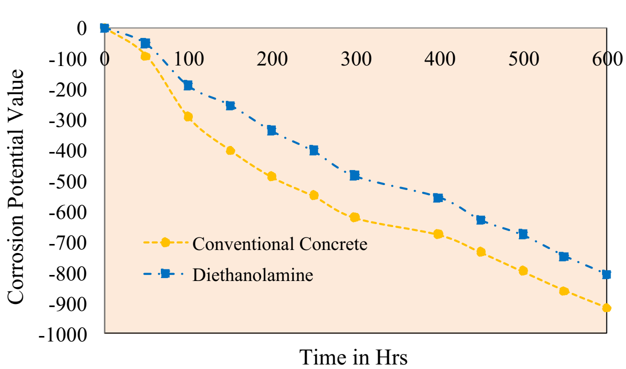

Fig. 14 Half-cell corrosion potential (mV) versus time

Fig. 16 Specimens after testing DA0 (DA0 = CC; i.e., without inhibitor addition)

Fig. 17 Specimens after testing DA3

Table 1 Summary of parameters tested

S/N	Parameter	CC	SCC	*Improvement (%)
1	Split tensile strength (MPa)	3.48	3.63	4.31
2	Flexural strength (MPa)	4.5	5.8	28.89
3	Compressive strength (MPa)	30	35	16.67
5	Sorptivity (mm/min$^{1/2}$)	0.87	0.08	90.8
6	Corrosion rate (mm/yr)	7.456	4.305	42.26

*At 28th day of test; at optimum concentration of the inhibitor

4 Conclusion

Detailed investigation on the effect of diethanolamine on the mechanical properties of steel reinforced concrete was undertaken in this study. The influence of diethanolamine on the corrosion rate of the steel used for reinforcement of the concrete was also studied. The possibility of the reinforced steel concrete with various concentration of diethanolamine to generate electricity was equally investigated. From the various investigations conducted, the outcome is summarized as follows:

i. diethanolamine reduced the rate of corrosion of the reinforced concrete steel; therefore, it is a good corrosion inhibitor of steel rebar used for concrete reinforcement. It reduced the corrosion rate of steel up to 3.2% weight of cement;
ii. diethanolamine has a great influence on the mechanical properties of reinforced concrete. It increases both compressive strength and split tensile strength of concrete as its amount in concrete mix increases, up to 3.2% weight of cement;
iii. the water absorption capacity of concrete decreased with increased concentration of diethanolamine, up to 3.2% in the concrete mix and;
iv. energy enough to power some DC components and devices could be generated from SCC made with diethanolamine addition.

Hence, it can be concluded that diethanolamine is a good corrosion inhibitor of steel used for concrete reinforcement and improves the properties of the concrete at an optimum amount of 3.2% in the concrete mix. Therefore, it is recommended for use as a superplasticizer in making self-compacting concrete (SCC).

Table 2 Comparison of improvement in properties between previous works and the present at the optimum concentration of inhibitors

S/N	Inhibitor/ Qty	Type of cement	Improvement in property (%)			References
			Split tensile strength	Flexural strength	Compressive strength	
1	Sodium nitrite (5%)	**PC	NS	4.76	*NS	[34]
	Sodium nitrite (5%)	PC	NS	13.0	NS	
	Dicyclohexyl + ammonium nitrite (5%)	PC	NS	4.23	NS	
	Dicyclohexyl + ammonium nitrite (5%)	PC	NS	11.02	NS	
	Amine based (5%)	PC	NS	3.42	NS	
	Amine based (5%)	PC	NS	13.75	NS	
2	Calcium nitrite (4%)	PC	9.2	26.51	22.58	[35]
	Sodium nitrite (3%)	PC	5.75	21.77	9.7	
	Hexamine (2%)	PC	4.31	19.83	3.2	
	Diethanolamine (3%)	PC	5.17	24.14	12.9	
3	Amino and ester based (1.3%)	PC	− 19.07	NS	− 15.85	[36]
	Nitrite based (3%)	PC	− 10.17	NS	5.25	
	Phosphate based (3%)	PC	− 11.4	NS	− 19.86	
4	Sodium nitrate (5%)	PC	0.42	NS	0.91	[37]
	Calcium nitrate (6%)	PC	1.4	NS	5.4	
5	Calcium nitrite based (5L/m^3)	PC	− 9.09	− 2.08	0.42	[38]
	Amino and ester based (5L/m^3)	PC	− 20.45	− 12.5	− 13.92	
	Aminoalcohol and organic & inorganic (12.25 kg/m^3)	PC	− 13.64	− 16.67	− 10.55	
	Organic (0.5 kg/m^3)	PC	6.82	27.08	16.67	
6	Calcium nitrite based (5L/m^3)	BFSC	5.56	5.5	− 5.61	[38]
	Amino and ester based (5L/m^3)	***BFSC	− 7.14	− 7.4	− 12.63	
	Aminoalcohol and organic & inorganic (12.25 kg/m^3)	BFSC	− 12.96	− 12.6	− 16.63	
	Organic (0.5 kg/m^3)	BFSC	3.70	3.70	− 6.41	
7	Diethanolamine (3.2%)	PC	4.31	28.89	16.67	Present work

**NS* = Not specified; ***PC* = Portland cement; ****BFSC* = Blast furnace slag cement

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