

Effect of Selected Commercially Available Corrosion Inhibitors in Kenya on Bond Strength of Reinforced Concrete.

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ABSTRACT— Corrosion of reinforced concrete water structures generates tensile stress within the concrete and reinforcement interface influencing the service life of structures. This research investigated the influence of selected commercially available corrosion inhibitors in Kenya in combination of selected brands of ordinary Portland cement on the bond behavior of reinforced concrete members. To achieve the desired objective, samples in concrete of characteristic strength of 25N/mm², 9 cylinders each of 150mm diameter x 300mm long each for four corrosion inhibitors and one control experiment were cast with an embedded rebar of 10mm diameter and 110mm long. For each series 9 cubes of 150mm x 150mm and 9 cylinders of 150mm diameter x 300mm long were cast for compressive strength and split tensile strength test respectively. After 24 hours the cast specimens were demolded and immersed in curing tanks for 27 days and tested for bond strength. The physical and chemical properties of the materials were investigated for compliance to relevant applicable British and Kenyan standards for conformity to acceptable criteria. The concrete materials were batched by weight and mixed by a lab electric pan concrete mixer in batches of 0.009 m³. The concrete batches were tested for consistency by the slump and compaction factor tests. The result show that bond strength increased with all selected corrosion inhibitors in combination with each respective cement brand. A bond strength model that correlated significantly with Orangun et al and Stanish et al model has been proposed.

KEYWORDS: Reinforced concrete, Bond strength, Corrosion inhibitors

1. INTRODUCTION

Reinforced concrete is among the materials widely used in construction of water conveyance structures. Steel as a constituent material in reinforced concrete provides tensile strength while concrete, an alkalinity material provides a physical barrier, that protects the steel from corrosion. The alkalinity of the concrete with pH values of about 12 to 14 [1], provides the conditions for the formation of a passive film protecting the steel reinforcement from corrosion [2]. The protection provided by the concrete is not sufficient because the concrete is porous thus allowing the penetration of aggressive agents, such as chloride ions that lead to the corrosion of the reinforcement that subsequently affects the bond strength. The ultimate limit state design of reinforced concrete is based on the fundamental assumption that there exists an effective bond linking concrete and steel when the structural element is loaded and the behavior of the composite material depends on this bond. The strength capacity of concrete and steel is directly related with their bond strength. For a reinforced concrete member to exhibit its full design strength there must be no slipping between concrete and the steel reinforcement. The reinforcing steel must resist the tension force, and the change in

tension force in the bar is transmitted to the concrete by the bond stress. The essence of bonding in reinforced concrete member is the mechanical interlocking between concrete and reinforcement as well as the deformity characteristic in the longitudinal and transverse ribs of the reinforcement [3]. The bond of reinforcing bars to the surrounding concrete influences the behavior of reinforced concrete structures in many ways [4]. It is a major factor for the maximum load carrying capacity of reinforced concrete elements since it affects the anchorage of bars and the strength of lap slices. The deformation capacity of the reinforced concrete elements, and hence the redistribution capacity in statically indeterminate structures, is directly influenced by the bond. Consequently, a fundamental issue for reinforced concrete structures is the bond between the reinforcing bars and the concrete [5]. One drawback in reinforced concrete bond research is the absence of a generalized method for determining bond strength [6]. This leads comparisons between various researches and test results on bond difficult. Most investigators have used pull-out tests that are commonly adopted in reinforced concrete bond studies [7–10]. Use of corrosion inhibitors is among the strategies available to control reinforced concrete deterioration due to corrosion and hence the service life of the structures. The efficiency of commercially available corrosion inhibitors in Kenya varies hence the need to identify their effect on bond strength and other concrete properties. This research presents the effect of selected corrosion inhibitors commercially available in Kenya on bond strength of reinforced concrete. The validity, accuracy, and efficiency of the proposed results are established by comparing the results of the present study with the works of other researchers. The results of the analysis presented in this research indicate that all the selected corrosion inhibitors increased the bond strength of reinforced concrete.

2. BACKGROUND

When reinforcing steel corrodes a decrease in load-carrying capacity of reinforced concrete components occurs through decrease of the cross-sectional area of the steel bars as the effect of corrosion increases, and the severity of reinforcement corrosion can have a significant effect on flexural strength, deformational behavior, ductility and bond. The effect of corrosion on the bond at the interface of the steel rebar and the concrete is affected and consequently the composite action of reinforced concrete. The expansive nature of the corrosion products that build up at the interface exerts a radial pressure on the surrounding concrete, which leads to cracking and spalling. Spalling will reduce the bond by removing the concrete cover, which in turn will reduce the confinement of the steel rebar and expose the concrete to further corrosion activity. Corrosion also causes the ribs on the rebar to deteriorate, which changes the surface area of the bar and decreases bond strength. According to Shetty et al (2011) [11] bond strength is attributed to chemical adhesion of the concrete to the steel, friction at the bar-concrete interface from mill-scale, rust and other surface irregularities, bearing against the rib faces and shear acting along a cylindrical concrete surface between adjacent ribs. The chemical adhesion results from the weak bonds between the steel and the hardened hydrated cement paste of the concrete, which is lost when the applied load on the steel bar is increased. Once the embedded bar begins to slip, the friction contributes to the bond strength at the concrete-steel interface. Bond strength is primarily derived from the bearing and mechanical interlock of the ribs on the surface of the steel bar with the concrete. Owing to the angle of the ribs, a horizontal force develops between the concrete and the rib face angle, which exerts bursting forces that tend to split the concrete. The thickness of the concrete cover and the confinement of the reinforcement now limit the magnitude of the failure load. Chung et al (2004) [12] found that the level of corrosion had a significant impact on the flexural crack pattern of reinforced concrete slabs subjected to four-point loading. From their study, the reinforced concrete slabs that were tested at lower corrosion levels displayed more flexural cracks than the slabs subjected to severe corrosion. Although a greater number of cracks formed at low levels of corrosion, the cracks were distributed along the length of the slab with small crack widths and sufficient warning of impending failure. At higher corrosion levels a smaller amount of localized cracks was produced

that had much larger crack widths and propagated at a rapid pace. Thus, it can be said that a loss in bond due to corrosion will result in wider, more localized cracks, which makes the concrete more susceptible to moisture ingress and increases the rate of deterioration of the structure. Various researchers have proposed various empirical equations to calculate bond strength as a function of corrosion level. Stanish et al (1999) [13] derived equation 1 by normalizing the estimated bond strength by the square root of the 28-day compressive strength, f'_c , and performing a linear regression analysis with the available data points. When no corrosion is present, their relation corresponds to the estimated value of 0.66 given by ACI 408.1R-90. This equation indicates that there is no increase in bond strength at low corrosion levels and any corrosion would immediately result in a decrease in bond strength.

$$\frac{u_b}{\sqrt{f'_c}} = 0.77 - 0.027C_0 \quad 1)$$

Where

u_b is bond strength in N/mm^2

f'_c is the concrete cylinder strength (assumed to be $0.8 \cdot f_{cu}$) in N/mm^2

f_{cu} is the concrete compressive cube strength in N/mm^2

Cabrera (1996) [13] derived equation 2 for normal Portland cement concrete and only applies to corrosion levels greater than approximately 0.9%.

$$u_b = 23.478 - 1.313C_0 \quad 2)$$

Lee *et al* (2002) [15] proposed equation 3 and 4 by expressing bond properties of reinforcement as a function of corrosion percentage. Neither of these equations makes provision for the fact that bond strength seems to increase at low corrosion levels (for less than 2% reduction in reinforcing bar mass).

$$u_b = 5.21e^{-0.0561C_0} \text{ for } C_0 \geq C_c \quad 3)$$

$$u_b = 0.34f_{cu} - 1.93 \text{ for } C_0 \geq C_c \quad 4)$$

where

C_0 is corrosion percentage

C_c is corrosion percentage at cracking.

Orangunet al. [16] proposed the following formula for bond strength:

$$\tau_u = 0.083045 \sqrt{f'_c} \left[1.2 + 3 \left(\frac{c}{d_b} \right) + 50 \left(\frac{d_b}{L_D} \right) \right] \quad 5)$$

Where τ_u is the bond strength in N/mm^2

c is the minimum concrete cover in mm

f'_c is the cylinder compressive strength of concrete in N/mm^2

d_b is the bar diameter in mm and

L_d is the development length in mm

This research is aimed at establishing whether a selected available commercial corrosion inhibitors will have a detrimental effect on bond strength and hence the service life of reinforced concrete water conveyancing structures.

3. Methodology

This research was conducted at the University of Nairobi Concrete and Materials lab where the physical properties of the materials, sample preparation and testing was done. The chemical properties of the ordinary Portland cement and chloride content was done in State Department of Infrastructure in the Ministry of Transport, Infrastructure, Housing and Urban Development of the Government of Kenya.

3.1 Concrete samples

The constituent materials for preparing test samples consisted of Ordinary Portland cement (42.5N/mm²), clean river sand, and 20mm maximum size coarse aggregate and portable water.

3.1.1 Cement

The chemical composition of the cement used in this research was tested. Available cements in Kenya are manufactured in accordance to KS EAS 18-1: 2001, an adoption of the European Norm EN 197 cement standards [16]. The cements locally available are produced for specific uses [17]. The Cement used for this research was ordinary Portland cement type 42.5N sourced from one wholesaler.

3.1.2. Other concrete materials

Table 1 shows the description and source of other materials of concrete used in the research.

Table 1. Details of materials used in the research

SN	Description	Source	Remark
1.	Fine aggregates	Stockpile vender sourced from Machakos River	This was washed and oven dried before use.
2	Coarse aggregates	Kenya builders quarry	5-20mm uniformly graded at the source
3.	10mm ribbed bars	Local manufacturer	Factory cut to 400mm
4.	Mixing water	Portable water in the Lab	

3.2.2. Concrete Mix Design

The concrete used for this works was of characteristic strength of 25N/mm² designed in accordance with the DOE method [18-19].

3.2.3 Test on hardened concrete

To access the effect of selected corrosion inhibitors of the properties of concrete, a minimum of three specimens were cast for testing at a time for any test and the average value obtained by testing the specimens considered. A total number of 135 cubes of size 150mm for compressive strength test, 135 cylinders of 150mm diameter and 300mm long for split tensile strength test, 135 numbers of 150mm diameter and 300mm long concrete cylinders with centrally placed steel rod of diameter 10 mm and length 1010mm for bond strength. Table 2 shows the details of the specimens cast for each test.

Table 2: Number of specimen's cast

Identification	Cubes for compression test	Cylinders for split tensile test	Cylinders for bond strength
Control Concrete	27	27	27
Fly ash concrete	27	27	27
Concrete with Inhibitor X	27	27	27
Concrete with Inhibitor Y	27	27	27
Concrete with Inhibitor Z	27	27	27

Inhibitor X is an admixture with 2-dimethylaminoethanol, inhibitor Y is a 30% by mass calcium nitrite [Ca(NO₂)₂] based while inhibitor Z is 30% by mass calcium nitrate [Ca(NO₃)₂] based.

3.2.4 Testing Methodology for bond strength

Before pouring the concrete in the moulds of pull out test, the internal surfaces of these moulds were oiled and the sides tightly secured. The length of 10mm diameter reinforcing steel bars was 1010 mm factory cut. Fresh concrete was mixed by a concrete pan mixer and poured into the mould in five layers and vibrated by a vibrating table in 60 seconds. After 24 hours, the moulds were removed and the concrete specimens cured in a water tank for 27 days. Three brands of cement were used and concrete cubes and cylinders for each brand of cement were cast in 9 samples, and the compressive strength, split tensile strength and pull out strength was tested at 7, 14 and 27 days. All the tests listed below were conducted;

- a) Tests on fresh concrete
 - i) Slump test
 - ii) Compaction Factor test
- b) Strength tests
 - i) Compressive strength test
 - ii) Split tensile strength test
 - iii) Bond strength test

3.2.5 Testing of samples

- a) Compression test

The compressive strength of concrete was investigated at 7, 14 and 27 days using a digital Universal Testing Machine with a loading capacity of 2000 KN shown in figure 3.1 in accordance to BS EN 12390-3:2009.



Figure 3.1: a) Digital compression machine during cube testing for compressive strength and b) a sample during compression testing

- b) Split tensile test

A hydraulic Universal Testing machine as shown in figure 3.2 a) and b) was used to test the cylinders for tensile strength.



Figure 3.2: Sample during split tensile test

- c) Pull-out testing

A manually operated hydraulic pump with a load cell of 100 kN connected to the load detector shown in figure 3.3 was used to perform the bond tests. The load was applied with a rate of 2 kN/sec and distributed on the specimen surface by a square steel plate with size of 20 cm and a hole at the center. All

the specimens were tested at age of 28 days.

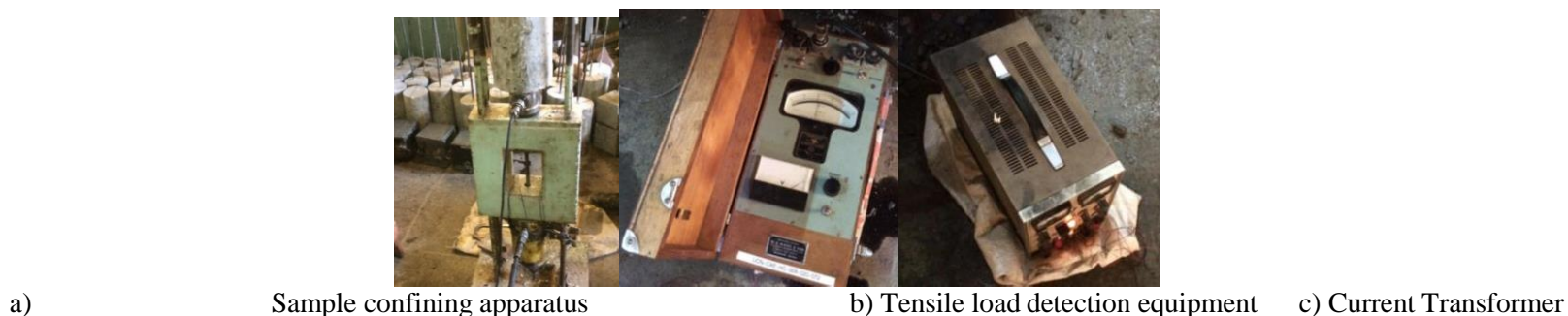


Figure 3.3 a)- c) Pull out Testing equipment used in the research

3.2.6 Bond stress calculation

Bond stress is calculated as average stress between the reinforcing bar and the surrounding concrete along the embedded length of the bar. In general, the bond stress corresponding to the maximum pull out load can be regarded as the bond strength or the ultimate bond. The criterion of ultimate bond strength is characterized by its clear definition and simplicity in bond strength interpretation. For uniform bond, the bond stress S can be expressed as:

$$S = \frac{P_{\max}}{\pi \times L \times d} \quad 5)$$

Where P_{\max} = maximum pull out load

d = diameter of the bar

L = Embedded bar length

4.0 Results of the material properties

4.1 Properties of aggregates

Various tests were carried out on the aggregates to determine their suitability for the research. Water soluble chloride ions percent were found to be zero in fine aggregates, 0.002 % in coarse aggregates all less than 0.03% acceptable in compliance with BS EN 12620: 2002. Chloride ions are the most aggressive and widest spread corrosive ion since it contributes to corrosion of steel reinforcement [19] by destroying the passivity condition when they are adsorbed. Limiting the water soluble chloride ions in the concrete constituents reduces the total amount of free chloride ions responsible for steel reinforcement corrosion [20].

Table 3: Physical properties of aggregates used in the study

Material	Specific gravity	Water Absorption %	Silt content %	Max Size
Fine aggregates	2.6	1.8	7.4	4.0
Coarse aggregates	2.6	0.3	0	20.0

The specific gravity of all the aggregates are within the limits of 2.4 – 3.0 stated in literature [21-24] and they influence the mix design of the concrete. The water absorption of the fine aggregates is within the limits of 1% – 3% stated in literature and British Standards [25-28] and therefore a low water absorption hence suitable for concrete works. The very low water absorption in the coarse aggregates need was taken

into consideration in the mix design. ASTM C117[29] give an allowable limit of 10% for silt and clay content in fine aggregates for concrete production while BS 882 give a limit of 4% [30]. As a thumb rule according to [31], the total amount of deleterious materials in aggregates should not exceed 5%. The silt content in the fine aggregate was more than the allowable percentage of silt content, it was washed and oven dried before use.

Table 4: Mechanical properties carried on coarse aggregates.

Test	Size of aggregates mm	Crushing value %	Impact Value %	Flakiness index %	Loss Angeles Abrasion Value %
Result	5-20	18	8	35	20

The mechanical properties of aggregates depend on the properties of the parent rock. The Aggregates Impact Value gives a measure of resistance to load 30% as value stated in literature and British Standards [32-33] and specified in [34]. The Aggregate Crushing Value provides resistance of the aggregates to the applied loads and for this research it was within the acceptable limit of 30% for wearing courses.

4.2 Chemical Properties of selected OPC Brands in Kenya used for the research

Table 5 shows the results of the chemical analysis of the ordinary cement brands used in this research

Table 5 Result of Chemical composition the Cement used.

SN	Test	Result			KS EAS 18-1: 2001 Requirement
		Cem A	Cem B	Cem C	
1.	CaO%	59.86	59.11	58.82	Sum \geq 50
2.	SiO ₂ %	16.56	21.56	19.47	
3.	SO ₃ %	2.02	2.78	2.03	\leq 3.5
4.	MgO%	1.76	1.04	0.57	\leq 5
5.	K ₂ O%	0.027	0.051	-	
6.	Fe ₂ O ₃ %	2.32	3.48	1.44	
7.	Al ₂ O ₃	7.61	8.09	6.85	3-8
8.	Na ₂ O ₃ %	0.054	0.018		
9.	LOI%	0.11	0.10	4.75	\leq 5
10.	Cl%	0.012	0.016	0.014	\leq 0.1
11.	IR%	2.20	0.55	1.96	\leq 5

a) *Effect of sum of lime (CaO) and silicon dioxide (SiO₂) on bond strength*

From table 5 there is a notable variation in the amounts of CaO, SiO₂ and Insoluble Residue. Cem A has the highest amount of CaO (59.86%), Cem B has the highest SiO₂ (21.56%) and Cem A has the highest Insoluble residue (2.20%). The sum of lime (CaO) and silicon dioxide (SiO₂) obtained in the chemical analysis of ordinary Portland cement should not be less than 50% [35]. All cement samples used for this work satisfied this requirement. Cement sample B has a CaO + SiO₂ value of 80.67 % and produced the highest compressive strength of 44.89 N/mm². This is consistent with the known fact that both CaO and SiO₂ give compressive strength and hence bond strength to concrete though SiO₂ has to be limited relative to CaO in order not to negatively affect setting time.

b) *Effect of CaO/SiO₂ on bond strength.*

The ratio of lime (CaO) to silicon dioxide (SiO₂) contents in ordinary Portland cement should be greater than 2. The restriction on the ratio of lime to silicon dioxide [35] is to ensure that the quantity of silicon dioxide is considerably lower than that of lime so that the setting of concrete is not inhibited. All the cement samples investigated satisfied this requirement. The lime-silicon dioxide ratio for cement samples A, B, and C were 3.61, 2.71 and 3.0 respectively. The results also indicated that the higher the ratio of (CaO/SiO₂) of a cement sample the higher the compressive strength of concrete which can be produced from it and the higher the bond strength.

c) *Effect of MgO on bond strength.*

The quantity of magnesium oxide (MgO) in ordinary Portland cement should not exceed 5% [34]. All the cement samples satisfied this requirement with 1.76%, 1.04% and 0.57% for cement samples A, B and C respectively. Magnesium oxide contributes to colour of cement and hardness of the resulting concrete. Cement sample A with the highest MgO content of 1.76 % was expected to produce concrete with the highest compressive strength since MgO contributes to hardness of concrete and highest bond strength. If the quantity of MgO is in excess of 5 percent, cracks will appear in concrete and which may reduce the bond strength by reducing the effective length.

d) *Effect of SO₃ on bond strength*

The quantity of sulphur trioxide (SO₃) content in ordinary Portland cement should be less than 3.5 %. All the samples satisfied this requirement.

e) *Effect of Chloride Content on bond strength*

The chloride content in ordinary Portland cement should be less than 0.4%. All the cement samples in this work satisfied this requirement.

f) *Effect of Al₂O₃*

Aluminium oxide (Al₂O₃) aids the quick setting of cement paste. Cement sample B contained the highest quantity of 8.09 % of Al₂O₃ resulting in the fastest initial set of the cement paste

g) *Effect of Fe₂O₃*

Iron oxide (Fe₂O₃) contributes to cement colour and helps in the fusion of the different ingredients. The Fe₂O₃ contents for the different cement samples are 2.32, 3.48 and 1.4493 for cement samples A, B, and C respectively as shown in Table 5.

h) *Effect of Residues*

British standards consider Na₂O, K₂O, TiO₂ and P₂O₅ in ordinary Portland cement as residues and limit the sum of all of them to 5%. All the cement samples investigated satisfied this requirement with cement samples A, B and C having total residue contents of 0.55, 2.2 and 1.96% respectively. If in excess of 5% efflorescence and unsightly cracking will occur and reduce the bond strength.

4.3 *Composition of corrosion inhibitors used in the research*

a) *Inhibitor Y and Inhibitor Z*

Both inhibitors are anodic and were in liquid form but inhibitor Y was a calcium nitrite [Ca(NO₂)₂] based while inhibitor Z was calcium nitrate [Ca(NO₃)₂] based. The two inhibitors increase the compressive strength of concrete with no susceptibility to alkali-aggregate reaction (AAR) [35]. The inhibitors act as accelerators of cement hydration and as a passivating inhibitor due to their oxidizing properties, which

stabilize the passive film [35].

b) Fly Ash

Table 6 shows the result of the chemical analysis of fly ash that was used in this study. Fly ash acts as an inhibitor by reducing permeability and increasing chloride resistance. From the chemical analysis result the % by volume of CaO in the fly ash used is 5.64% which is less than 8% composition by volume and this is fly ash class F as per ASTM C618. Also the sum of SiO₂, Al₂O₃ and Fe₂O₃ by composition in the sample is 71.21% which is greater than 70% as required by ASTM C618 standard for class F fly ash. The fly ash was used in the concrete mix by replacing ordinary Portland cement by 25%. This percentage has the capacity of controlling damaging alkali-silica reaction (ASR) in concrete and the effect has been ascribed to the reduced concentration of alkali hydroxides in the pore solution.

Table 6 shows the chemical analysis of the fly ash used

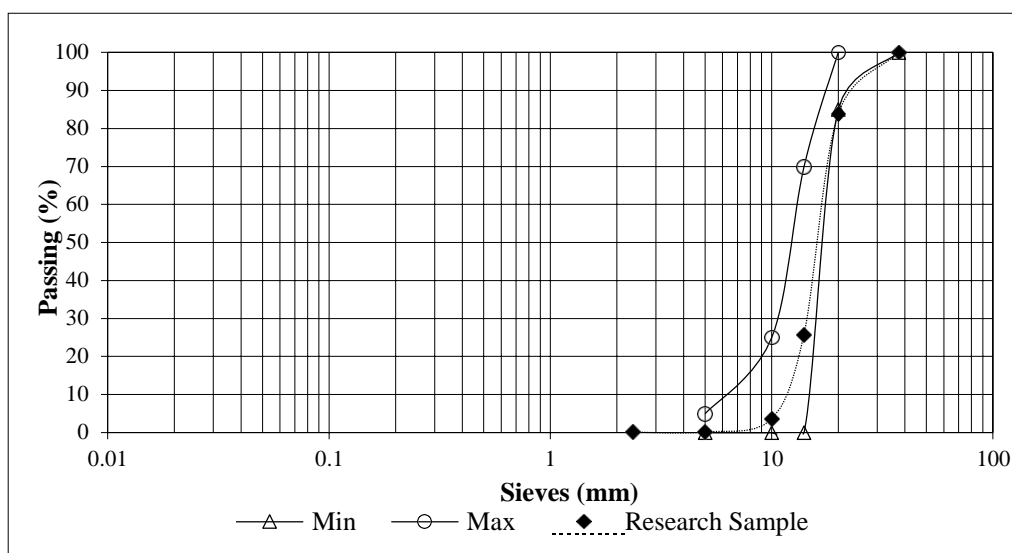
Parameter	Result	Test Standard
SiO ₃	47.18 %	ASTM C618
Al ₂ O ₃	19.87%	
Fe ₂ O ₃	10.61%	
UBC	0.99%	
Na ₂ O	0.86%	
Fineness(Residue on 45 Micron)	8.69%	
Moisture content	0.07%	
MgO	3.79%	
Cl	0.047%	
Bulk Density	1.03 Gm/cc	
TiO ₂	1.01	
CaO	5.64	
K ₂ O	1.17	
P ₂ O ₅	0.243	

c) Inhibitor X

Is an Amino alcohols based corrosion inhibitor in liquid form?

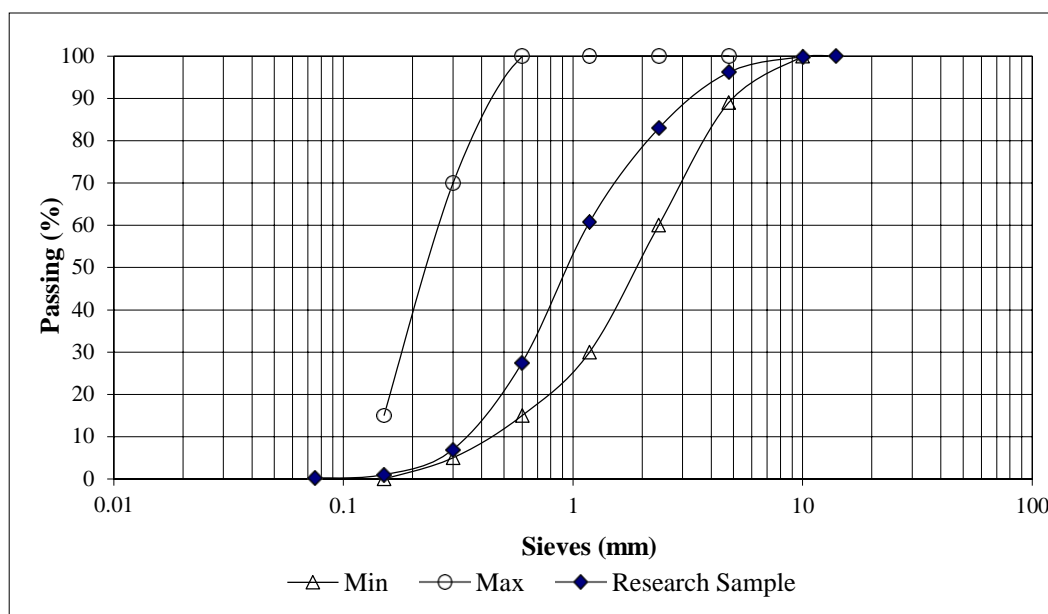
4.4 Gradation of Coarse and Fine aggregates

Particle size distribution analysis on a representative sample as shown on graph 1 of the course aggregates for the work was carried out to obtain the proportions by weight of the different sizes of coarse aggregates present. The sample is well graded with a maximum aggregate size was 20mm.



Graph 1 Gradation of Coarse aggregates

Particle size distribution analysis as shown on graph 2 on a representative sample of the fine aggregates for the research was carried out to obtain the proportions by weight of the different sizes of fine particles present according to BS 812-103 and BS 882. The proportions were expressed as percentages by weight passing various sieve sizes conforming to BS 410. As shown in graph 1 the coarse aggregates were well graded and expected to give a well interlocked composite concrete mix.



Graph 2: Gradation of fine aggregates

4.5 Results of fresh concrete tests

Table 7 shows the result of fresh concrete tests

Table 7 Results of fresh concrete test

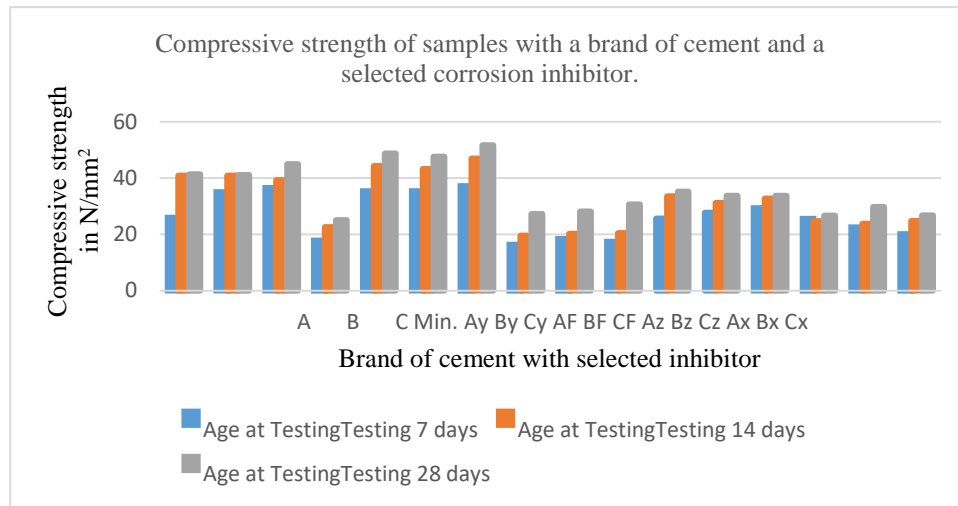
Mix with and without inhibitor	Cement Type	w/c ratio	Slump(mm)	Compaction Factor
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Control-No inhibitor	A	0.5	73.3	0.97
	B	0.5	68	0.96
	C	0.5	93	0.95
Inhibitor Y	A	0.5	60	0.95
	B	0.5	63	0.93
	C	0.5	64	0.94
Fly Ash	A	0.5	55	0.93
	B	0.5	40	0.94
	C	0.5	45	0.97
Inhibitor Z	A	0.5	66	0.95
	B	0.5	65	0.95
	C	0.5	66	0.92
Inhibitor X	A	0.5	60	0.96
	B	0.5	65	0.95
	C	0.5	64	0.96

From the results of table 7, at the same water cement ratio fly ash had the lowest slump with all cement brands and thus a reduced workability. Fly ash has spherical shaped particles that act as miniature ball bearings within the concrete mix and require less water for a lubricant effect.

4.6 Results of hardened concrete

Bar chart 1-3 shows comparative relationship of the hardened properties of concrete with selected inhibitors.



Bar Chart 1 Compressive strength in N/mm² of samples with a brand of cement and a selected corrosion inhibitor at 7,14 and 28 days

From bar chart 1, it can be noted that the corrosion inhibitor with 30% calcium nitrite in combination with selected cement brands had the highest increase in compressive strength while all the other inhibitors. The corrosion inhibitors influence in the compressive strength of concrete is most likely caused by their reaction with water and cement during the reaction of cement hydration. The compressive strength of concrete has an influence on the bond strength and their relationship is critical in bond strength modelling.

Graph 4 shows the failure mode during split tensile testing while bar chart 2 shows the relationship between the split tensile strength and the corrosion inhibitor in combination with a selected brand of cement.

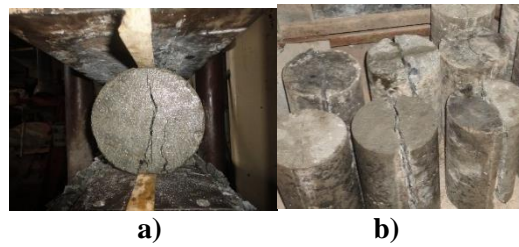
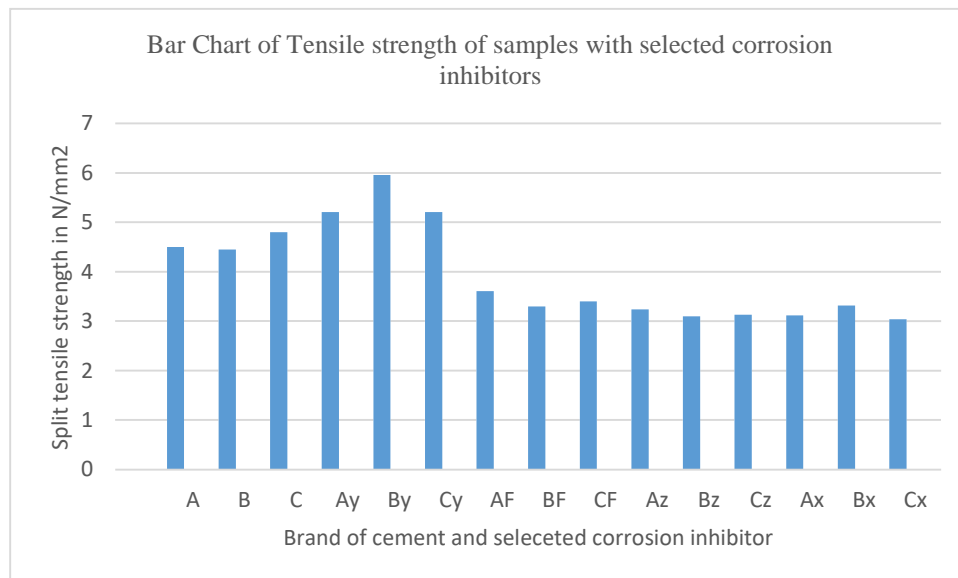
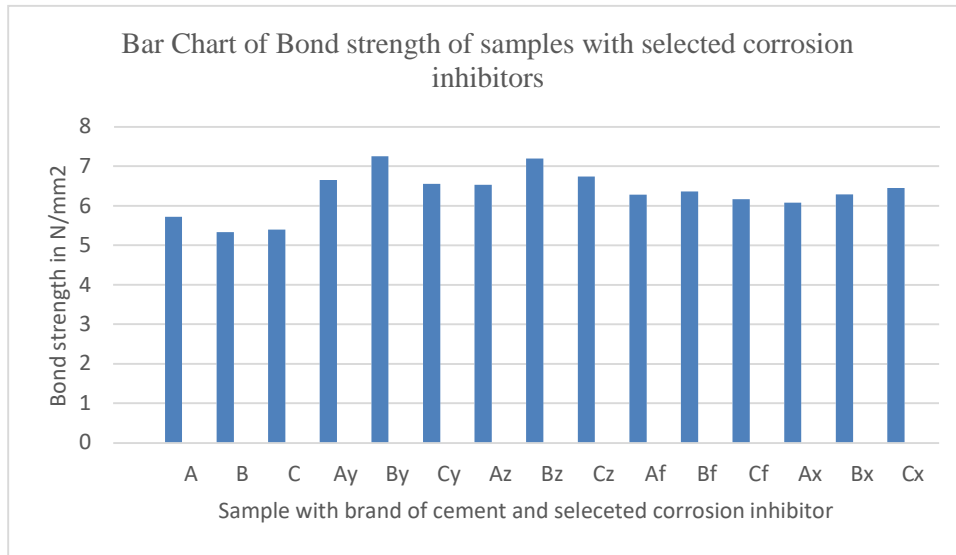


Figure 4: a) and b) Failure mode of the samples during split tensile test.



Bar Chart 2: Split tensile strength in N/mm² for samples with a brand of cement and a selected corrosion inhibitor

From bar chart 2, it can be noted that the corrosion inhibitor with 30% calcium nitrite in combination with selected cement brands had an increased split tensile strength and the converse is true for all the other corrosion inhibitors. The corrosion inhibitors influence in the split tensile strength of concrete is most likely caused by their reaction with water and cement during the reaction of cement hydration. The split tensile strength result correlation with results of existing models gives a view of the expected bond strength results.



Bar Chart 3: Bond strength for samples with a brand of cement and a selected corrosion inhibitor

From bar chart 3, all corrosion inhibitors in combination with the respective cement brand selected increased the bond strength with use of inhibitor x giving the lowest result. The corrosion inhibitors increase in bond strength of concrete is most likely caused by their reaction with water and cement during the reaction of cement hydration thus affecting the compressive strength. Most bond strength models have based their result on compressive strength and hence the need for a parametric study of the result of this research with the models of other authors.

4.7 Parametric study of the results

Table 8 gives a comparative result of the split tensile strength from works of other authors

Table 8: Comparative study of results of hardened concrete.

Selected inhibitor	Cement Brand	Bond strength	Compressive strength (N/mm²) at 28 days(f_{ck})	Split tensile strength in N/mm²						
				Measure Value	Lavanya & Jegan (2015) $f_{t1}=0.249f_{ck}^{0.772}$	ACI Committe e (2014) $f_{t2}=0.56f_{ck}^{0.5}$	Anoglu et al (2006) $f_{t3}=0.387f_{ck}^{0.63}$	CEB-FIB (1991) $f_{t4}=0.3f_{ck}^{0.6}$	Gardner (1990) $f_{t5}=0.33f_{ck}^{0.66}$	
No Inhibitor	Cem A	5.72	41.29	4.50	4.40	3.60	4.03	3.50	3.95	
	Cem B	5.33	41.09	4.45	4.39	3.59	4.02	3.48	3.93	
	Cem C	5.40	44.89	4.80	4.70	3.75	4.25	3.69	4.17	
Inhibitor Y	Cem A	6.65	48.7	5.21	5.00	3.91	4.48	3.90	4.40	
	Cem B	7.25	47.5	5.96	4.90	3.86	4.41	3.83	4.33	
	Cem C	6.56	51.6	5.21	5.23	4.02	4.64	4.05	4.58	
Inhibitor Z	Cem A	6.53	35.2	3.61	3.89	3.32	3.65	3.15	3.55	
	Cem B	7.20	33.7	3.30	3.76	3.25	3.55	3.06	3.45	
	Cem C	6.74	33.69	3.40	3.76	3.25	3.55	3.06	3.45	
Fly Ash	Cem A	6.28	27.27	3.24	3.20	2.92	6.65	2.66	3.00	

	Cem B	6.36	28.13	3.10	3.27	2.97	3.17	2.71	3.06
	Cem C	6.17	30.6	3.13	2.94	3.10	3.34	2.87	3.23
Inhibitor X	Cem A	6.08	26.6	3.12	3.13	2.89	3.06	2.62	2.94
	Cem B	6.29	29.7	3.32	3.41	3.05	3.28	2.81	3.17
	Cem C	6.45	26.7	3.04	3.14	2.89	3.06	2.62	2.95

Table 9 Correlations of Result of Split tensile strength of this work with results of other authors.

		This work	Lavanya & Jegan(2015)	ACI Committee 318(2014)	Anoglu et al(2006)	CEB-FIB(1991)	Gardner(1990)
This work	Pearson Correlation	1	.945**	.947**	.369	.948**	.948**
	Sig. (2-tailed)		.000	.000	.176	.000	.000
Lavanya & Jegan(2015)	Pearson Correlation	.945**	1	.982**	.330	.983**	.983**
	Sig. (2-tailed)	.000		.000	.230	.000	.000
ACI Committee 318(2014)	Pearson Correlation	.947**	.982**	1	.302	1.000**	1.000**
	Sig. (2-tailed)	.000	.000		.274	.000	.000
Anoglu et al(2006)	Pearson Correlation	.369	.330	.302	1	.308	.310
	Sig. (2-tailed)	.176	.230	.274		.264	.261
CEB-FIB(1991)	Pearson Correlation	.948**	.983**	1.000**	.308	1	1.000**
	Sig. (2-tailed)	.000	.000	.000	.264		.000
Gardner (1990)	Pearson Correlation	.948**	.983**	1.000**	.310	1.000**	1
	Sig. (2-tailed)	.000	.000	.000	.261	.000	

** . Correlation is significant at the 0.01 level (2-tailed).

From table 8 and 9

- It can be observed that other than their primary role of corrosion inhibiting, all the inhibitors improved the bond strength of the reinforced concrete.
- The split tensile strength results of this work significantly correlate with results of other authors. Table 10 shows a parametric study of bond stress result of this work with result of other authors.

Table 10: Parametric study of bond strength of this work with other authors.

Selected inhibitor	Cement Brand	Bond Strength (N/mm ²)	Orangun et al(Eq.5)	Bond Strength(N/mm ²) Stanish <i>et al</i> (1999) $u_b=[0.77 - 0.027C_o]\sqrt{0.8f_{cu}}$
No Inhibitor	Cem A	5.72	3.20	4.43
	Cem B	5.33	3.19	4.41
	Cem C	5.40	3.34	4.61
Inhibitor Y	Cem A	6.65	3.45	4.81
	Cem B	7.25	3.43	4.75
	Cem C	6.56	3.56	4.94
Inhibitor	Cem A	6.53	2.95	4.09

Z	Cem B	7.20	2.89	4.00
	Cem C	6.74	2.89	4.00
Fly Ash	Cem A	6.28	2.60	3.60
	Cem B	6.36	2.64	3.65
	Cem C	6.17	2.76	3.81
Inhibitor	Cem A	6.08	2.66	3.55
	Cem B	6.29	2.72	3.75
X	Cem C	6.45	2.57	3.55

Table 11 shows statistical correlation of the bond strength results.

Table 11 Correlations of results of this work with results of other researche

		This work	Orangun et al	Stanish <i>et al</i>
This work	Pearson Correlation	1	.000	.012
	Sig. (2-tailed)		.999	.967
	N	15	15	15
Orangun et al	Pearson Correlation	.000	1	.998**
	Sig. (2-tailed)	.999		.000
	N	15	15	15
Stanish <i>et al</i>	Pearson Correlation	.012	.998**	1
	Sig. (2-tailed)	.967	.000	
	N	15	15	15

** . Correlation is significant at the 0.01 level (2-tailed)

From results of table 11, the results of this work have no significant correlation with the results of Orangun et al and Stanish et al and hence the need to propose a model that will significantly correlate this works results the existing models.

4.8 Proposed Bond strength Model

Table 12 shows tests between bond stress results of this work and those of Orangun et al and Stanish et al

Table 12 Tests of Between-Subjects Effects of this research and those of Orangun et al and Stanish *et al*

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	This work	.000a	0	.	.	.
	Orangun et al	.000b	0	.	.	.
	Stanish <i>et al</i>	.000a	0	.	.	.
Intercept	This work	601.793	1	601.793	1954.346	.000
	Orangun et al	134.102	1	134.102	1141.984	.000
	Stanish <i>et al</i>	255.854	1	255.854	1063.524	.000
Error	This work	4.311	14	.308		
	Orangun et al	1.644	14	.117		
	Stanish <i>et al</i>	3.368	14	.241		
Total	This work	606.104	15			

	Orangun et al	135.746	15
	Stanish <i>et al</i>	259.222	15
Corrected	This work	4.311	14
Total			
	Orangun et al	1.644	14
	Stanish <i>et al</i>	3.368	14
a R Squared = .000 (Adjusted R Squared = .000)			
b R Squared = .000 (Adjusted R Squared = .000)			

From the table 12 and bond strength results of this work its proposed to correct the works of Orangun et al for the selected corrosion inhibitors with a new model in equation 6;

$$\tau_u = 0.136526 \sqrt{f'_c} \left[1.2 + 3 \left(\frac{c}{d_b} \right) + 50 \left(\frac{d_b}{L_d} \right) \right] \quad (6)$$

Where τ_u is the bond strength in N/mm²

C is the minimum concrete cover in mm

f'_c is the cylinder compressive strength of concrete in N/mm²

d_b is the bar diameter in mm and

L_d is the development length in mm

Table 13 shows the correlation of the proposed bond strength model from this research and the bond strength model of Orangun et al and Stanish et al

Table 13 Correlations of bond strength results of this work with the proposed model and Stanish et al bond strength model

		This work	Stanish <i>et al</i>	Proposed Model
This work	Pearson	1	.012	.008
	Correlation			
	Sig. (2-tailed)		.967	.979
	N	15	15	15
Stanish <i>et al</i>	Pearson	.012	1	1.000**
	Correlation			
	Sig. (2-tailed)	.967		.000
	N	15	15	15
Proposed Model	Pearson	.008	1.000**	1
	Correlation			
	Sig. (2-tailed)	.979	.000	
	N	15	15	15

** Correlation is significant at the 0.01 level (2-tailed).

From table 13, the proposed model strongly correlates with the results of this work and the model of Stanish et al and is applicable to the selected corrosion inhibitors for reinforced concrete of characteristic strength 25N/mm².

5. Conclusions

From the results of this research, the following conclusions can be drawn;

- At the selected dosages of the selected corrosion inhibitors in combination with all respective brands of cement increased the bond strength of reinforced concrete increased.
- The bond strength results of this research do not significantly correlate with the models of Orangun et al and Stanish et al.
- A new proposed bond strength model (a modifying the model of Orangun et al) significantly correlates with the results of this research and the Stanish et al bond strength model.

6. References

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