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The effect of using Ordinary Cement Brands in Kenya on Corrosion Rate of Reinforced Concrete Water Conveyancing Structures

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Abstract- In the past decade Kenya has experienced an increased demand of cement for construction of infrastructure projects including the Mega standard gauge railway and the Lamu Port South Sudan-Ethiopia Transport Corridor. The cement production and consumption increased from 154,781 tonnes per year in January 2005 to 564,000 tonnes per year in January 2017 an average of 22% increment per annum.
Attracted by this growth and to meet the demand, the existing manufacturers have expanded while new cement manufacturers have ventured into the Kenyan market bringing the total number of manufacturers to six. Each of the manufacturers produces his own brand of ordinary Portland cement with specific constituents but meeting the requirements of the Kenya Bureau of Standards. The constituents of the brands of cement react differently when mixed with other constituents of concrete resulting into varying hardened properties that affect corrosion.
In this research three brands of ordinary Portland cement in the Kenyan market: Cem A, Cem B and Cem C were used to investigate their effect on the properties of concrete that affect the rate of corrosion.
The main objective of this research was to investigate the effect of using different Kenyan brands of ordinary Portland cement of the same strength on the rate of corrosion. The physical and chemical properties of the materials were investigated for compliance to applicable British and Kenyan standards. The DOE method was used to derive the mix design for a design strength of $25N/mm^2$. Concrete materials were batched by weight and mixed by using a lab electric pan concrete mixer in batches of 0.009 $m^{3.}$ For each brand of cement 9 cubes of 150mmx 150mm x 150mm for compression test, 9 cylinders of 150mm x 300mm for tensile strength and 9 cylinders of 150mm x 300mm for accelerated corrosion test were cast. After 24 hours the cast specimens were demoulded and immersed in curing tanks for 28 days.
Specimens for compression and tensile test were tested at 7, 14 and 28 days while the specimens for impressed corrosion were immersed in a 3.5% industrial sodium chloride solution under a voltage and current of 6V and 2A respectively. The applied current and voltage were monitored on a biweekly basis until corrosion induced cracking appeared on the concrete surface. The impressed corrosion specimens were monitored visually using a 1000x optical magnification glass for onset of cracks and stopped when the crack width were approximately 0.1mm in width. The duration to approximated width of crack were 107days, 115 days and 111 days for Cem A,Cem B and Cem C respectively.From the results in the research, different Kenyan cement brands of the same compressive strength have a significant effect on the rate of corrosion of reinforced concrete structures.
ention the abstract for the article. An abstract is a brief summary of a research article, thesis, review, conference proceeding or any in-depth analysis of a particular subject or discipline, and is often used to help the reader quickly ascertain the paper's purpose. When used, an abstract always appears at the beginning of a manuscript, acting as the point-of-entry for any given scientific paper or patent application.

Index Terms- Accelerated corrosion, Cement Brand, Corrosion rate.

- **Introduction**

The rate of infrastructure development is a key indicator of the behavior of an economy[1]. For the last decade, Kenya has experienced a remarkable development of small to mega infrastructure projects attracting investors in producing construction materials including cement and steel. Cement manufacturing has attracted expansion of existing manufacturers and new ones due to existing demand in Kenya which has grown from 154,781 tons in 2005 to 564,000 in 2017 (according to Kenya bureau of statistics records) and is projected to grow steadily until 2026. Currently there are six manufacturers, each producing ordinary Portland cement with different constituent compositions under different brands to Standard Specification KS EAS 18-1[2].

The process of natural steel corrosion is very slow, requiring many years depending on environmental exposure and the properties of concrete materials to cause reasonable structural damage within the service life of the structure. Reinforced concrete has an alkaline environment that protects embedded steel from corrosion. This environment can be destroyed by carbonation or by chloride attack. It takes several years for sufficient chlorides to ingress cover concrete and destroy the passivation layer leading to corrosion of embedded steel.

François & Arliguie (1998), Castel *et al* (2003), Vidal *et al* (2007) and Zhang *et al* (2010), who allowed their laboratory specimens to corrode naturally, had to wait for four years for steel corrosion to start and an additional two years for first cracking to occur. The rate of corrosion is thus accelerated by simulating exposure environment. The objective of this research was to investigate the effect of cement brands on the rate of corrosion.

- **Literature**

Using a sensitivity analysis Li et al [3] showed that corrosion rate is one of the most important input parameters in the corrosion-induced damage models. There is a clear relationship between corrosion rate and concrete resistivity as exhibited in Alonso et al.'s [4] experimental results. From the results it was noted that accelerated corrosion tests were used without validation using natural corrosion test results. The use of small specimens (20 x 55 x 80 mm) may have a size effect on the experimental results[5].In addition to concrete resistivity, corrosion rate in concrete can be affected by other factors such as presence of cracks, concrete cover depth, among others[6].

Yalcyn and Ergun [7] developed a corrosion model by studying the effect of chloride and acetate ions on the rate of corrosion and evaluated corrosion by measuring half-cell potentials (HCP) and linear polarization potential (LPR).In their model, the rate of corrosion was taken up to a period of 90 days on cylindrical specimens of 150 mm diameter x 150 mm height using Pozzolanic cement.

The rate of Corrosion in reinforced concrete structures is affected by several factors (e.g. concentration of chlorides, concrete penetrability) that vary from time to time in a water conveyance structure. This research attempts to evaluate the effect of different chemical compositions of cement (which are exhibited on cement brands) on the rate of corrosion of reinforced concrete structures.

- **Methodology**

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

3.1 CONCRETE SAMPLES

The constituent materials for preparing test samples consisted of three brands of cement A, B, C of Ordinary Portland cement (42.5N/mm^2), clean river sand, and 20mm maximum size coarse aggregate and portable water.

3.1.1 Cement

Cement is the most commonly used binder material in concrete. It makes concrete impermeable by filling up the voids existing in the aggregates and provides strength to the composite mix upon setting and hardening. The cements properties tested during this research were the chemical composition.

Manufacturing of Cement in Kenya is in accordance to KS EAS 18-1: 2001, an adoption of the European Norm EN 197 cement standards [8]. The cements locally available are produced for specific uses [9]. Three Brands of Cement

Cem A, Cem B and Cem C of type 42.5N sourced from one wholesaler from three different manufacturers were used during the research.

3.1.2. Other concrete materials

Table 1 shows the description and source of other constituents (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 quarry graded
3.	10mm ribbed bars	Local manufacturer	Factory cut to 400mm
4.	Mixing water	Tap water in the Lab	Sourced from Nairobi Water and Sewerage Company

3.2. EXPERIMENTATION

3.2.1. Constituent Materials Characterization

The cement and aggregates chemical elemental analysis was done in accordance to the EAS 148-2:2001 CS 91.100.10. East African Standard. The physical and mechanical properties tests on aggregates were done at the university of Nairobi Concrete laboratory.

3.2.2. Concrete Mix Design

Concrete mix design is the science of correct proportioning of concrete constituent materials based on structure requirements to obtain the desired properties of concrete such as strength and practical workability [10]. The effect of the brands of cement on the rate of corrosion was evaluated using the same concrete of design strength of $25N/mm^2$ designed in accordance with the DOE method.

3.2.3 Test on hardened concrete

a) Compressive strength

The compressive strength of concrete was investigated at 7, 14 and 28 days using a digital Universal Testing Machine shown in figure 1b), with a loading capacity of 2000 KN in accordance to BS EN 12390-3:2009.

a) b) c)

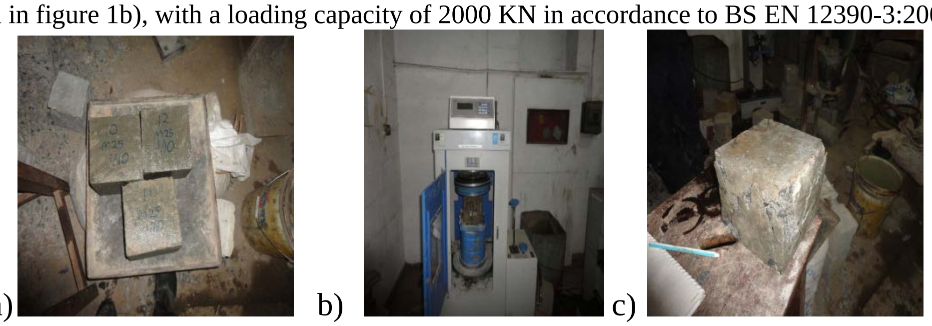


Figure 1 Concrete Samples during Compression. a) Sample after curing, b) Digital compression testing machine, c) Concrete Sample after failure.

b) Splitting tensile test

Split Tensile strength of concrete was tested on cylinders cast with Cem A,Cem B and Cem C. The strength of concrete was tested on cylinder at 7, 14 and 28 days curing. 7 days test was conducted to check the gain in initial strength of concrete. 28 days test gives the data of final strength of concrete at 28 days curing. Universal Compression testing machine is used for testing the Split Tensile strength test on concrete along with two wooden strips as shown if figure 2. At the time of testing the cylinder was taken out of water, dried and then tested.

a)  b)  c) 

Figure 2 Samples in splitting tensile test, a) and b) Concrete Sample in the Universal Testing Machine,
c) Concrete Samples at failure

3.2.4 Test on the rate of corrosion

This was done through an impressed corrosion test using the procedure below;
i)12mm x 400mm long ribbed bars were polished with abrasive papers.
ii) 120 mm of the surface length of each bar were zinga sprayed and left to naturally dry.
iii) The mixed concrete (in two batches) was poured into cylindrical moulds (150 mm in diameter and 300 mm high) where the reinforcement was placed along its longitudinal axis.
iv) The specimens were mechanically vibrated for 60s.After 24 hours, the cylindrical concrete specimens were demoulded and cured for 28days.
vi) The test specimens were dried for 24 hours and then subjected to accelerated corrosion and stored in a tank containing 3.5 % NaCl at room temperature. The experiment was run until a crack of 0.1mm was detected..

3.2.5 Test preparation and procedure

Concrete materials were batched by weight and mixed by a lab electric pan concrete mixer in batches of 0.009 m^3 . Slump and compacting test were measured for all the batches as a measure of consistency and workability. For each brand of cement 9 cubes of 150mmx 150mm x 150mm and 9 cylinders of 150mm x 300mm were cast. After casting;
a) The concrete specimens were kept in moulds at room temperature for 24 hours, then demoulded and kept in a curing tank for 28 days before testing.
b)The concrete cubes and cylinders were tested for compression and tensile strength at 7,14 and 28 days.

4 RESULTS AND DISCUSSION.

4.1 Results

i) Chemical Properties of Cements in Kenya

Three types of cements were investigated during the research and Tables 2 gives the chemical properties of the different brands Cem A, Cem B and Cem C of the grade 42.5N Cement.

Table 2 Result of Chemical composition the brands of cement tested.

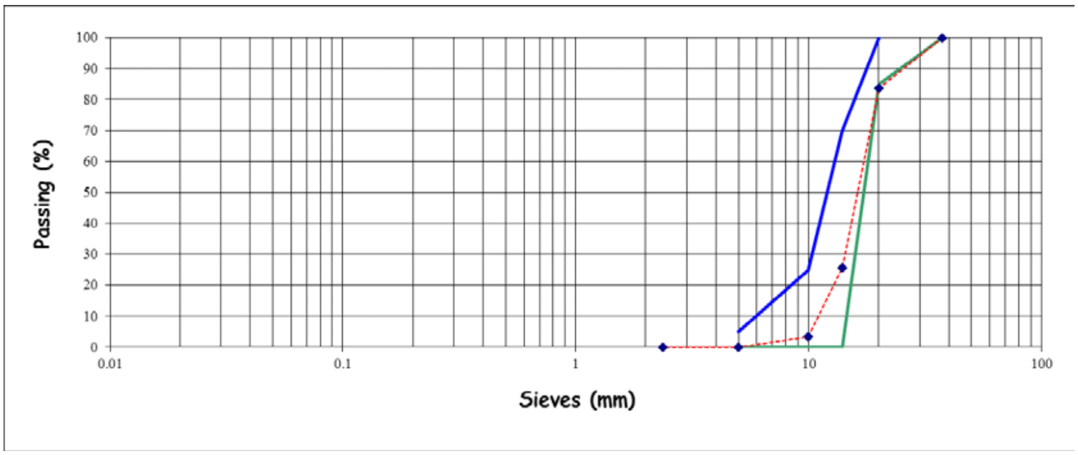
SN	Test	Result			KS EAS 18-1: 2001 Requirement
		Cem A	Cem B	Cem C	
1.	CaO%	59.86	59.11	58.82	Sum ≥ 50
2.	SiO_2%	16.56	21.56	19.47	
3.	SO_3%	2.02	2.78	2.03	≤ 3.5
4.	MgO%	1.76	1.04	0.57	≤ 5
5.	K_2O%	0.027	0.051	-	-
6.	Fe_2O_3%	2.32	3.48	1.44	-
7.	Al_2O_3	7.61	8.09	6.85	3-8
8.	Na_2O_3%	0.054	0.018		-
9.	LOI%	0.11	0.10	4.75	≤ 5
10.	Cl%	0.012	0.016	0.014	≤ 0.1
11.	IR%	2.20	0.55	1.96	≤ 5

ii) Properties of aggregates

Various tests were carried out on the aggregates to determine their suitability for the research and the results are shown in table 3 and graphs 1 and 2.Water soluble chlorides 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.

Table 3: Physical properties of aggregates used in the study

SN	Property	Test Method	Result	Limit
1.	Loss Angeles Abrasion value	BS/EN 1097-2	20%	30%
2.	Flakiness index	BS/EN 933-3	35%	<35%
3.	Aggregate Crushing Value	BS EN 1097-2	18%	<45%
4.	Aggregate Impact Value	BS EN 1097-2	8%	<45%
5.	Bulk specific gravity	ASTM C128	2.9	
6.	Water absorption capacity	ASTM C127	1.20%	



Graph 1 Gradation of Coarse aggregates

Graph 2: Gradation of fine aggregates

iii) Results of compression test

Graph 3 Compressive strength of concrete vs testing age

iv) Splitting tensile test result

Tables 4-6 shows the result of the splitting tensile test while Tables 7 and 8 shows a comparison of the result of this research with existing research.

Table 4.Result of tensile strength (f_t) of concrete samples from three cement brands

SN	Cement Brand	Strength in N/mm^2		
		7days	14 days	28 days
		f_t	f_t	f_t
1.	Cem A	2.59	2.83	3.25
2.	Cem B	2.07	2.45	3.13
3.	Cem C	1.77	2.45	2.88

Table 5.Result of relationship of compressive strength (f_{ck}) and tensile strength (f_l) of concrete samples from three cement brands

SN	Cement Brand	Strength in N/mm^2						Rate of Corrosion
		7days		14 days		28 days		
		f_{ck}	f_t	f_{ck}	f_t	f_{ck}	f_t	
1.	Cem A	25.81	3.63	40.28	3.96	41.29	4.55	2.7
2.	Cem B	36.379	2.90	39.23	3.45	44.89	4.38	2.5
3.	Cem C	34.81	2.48	36.26	3.43	41.09	4.03	2.6

Table 6 predicted splitting tensile strength of concrete from different models.

Cement brand	Compressive strength (N/mm^2) at 28 days	Split tensile strength in N/mm^2					
		Measured Value	Lavanya & Jegan(2015) $f_{t1}=0.249f_{ck}^{0.772}$	ACI Committee 318(2014) $f_{t2}=0.56f_{ck}^{0.5}$	Anoglu et al(2006) $f_{t3}=0.387f_{ck}^{0.63}$	CEB-FIB(1991) $f_{t4}=0.3f_{ck}^{0.66}$	Gardner (1990) $f_{t5}=0.33f_{ck}^{0.667}$
Cem A	41.29	4.55	4.40	3.60	4.03	3.50	3.95
Cem B	44.89	4.38	4.70	3.75	4.25	3.70	4.17
Cem C	41.09	4.03	4.39	3.59	4.02	3.48	3.93

Table 7 Checking variance and normality assumptions on the sample datasets.

SN	Sample	Variance	Test P-value	Decision
1.	Experiment	0.047	0.03	Observations in Sample have normal distribution
2.	f_{t1}	0.021	0.01	Observations in Sample have normal distribution
3.	f_{t2}	0.005	0.32	Observations in Sample have normal distribution
4.	f_{t3}	0.011	0.04	Observations in Sample have normal distribution
5.	f_{t4}	0.010	0.41	Observations in Sample have normal distribution
6.	f_{t5}	0.008	0.07	Observations in Sample have normal distribution

Table 8 Welch's 2-sample t-test.

SN	Data	t-statistics	P-Value	Decision
1.	Experiment and f_{t1}	0.40	0.06	On average samples are not significantly different
2.	Experiment and f_{t2}	0.05	0.47	On average samples are not significantly different
3.	Experiment and f_{t3}	0.29	0.07	On average samples are not significantly different
4.	Experiment and f_{t4}	0.01	0.50	On average samples are not significantly different
5.	Experiment and f_{t5}	0.18	0.11	On average samples are not significantly different

v) Rate of corrosion

Table 9 shows the properties of the rebar used in the research and the rate of corrosion.

Table 9 Physical property of the reinforcement in impressed corrosion Test

SN	Cem	Diameter	Area	Length	Initial	Average	Mass	Weght	Duration	Rate of

	Type	(mm)	mm^2	mm	Mass Kg	after corrosion Kg	Loss Kg	in Hours	Corrosion mm/yr
1.	Cem A	12	113.143	400	0.371	0.265	0.106	109 x24	0.38
2.	Cem B.	12	113.143	400	0.371	0.299	0.072	115 x 24	0.27
3.	Cem C	12	113.143	400	0.371	0.256	0.115	106 x 24	0.43

Corrosion Rate in mm/yr= 87.6 x [w/(D x A x T)]

Where W is the weight loss in milligram,

D is the density of the material used, g/cc,

A is the area of the specimen (cm^2), and

T is the duration of the test period in hours.

4.2 Discussion of results

4.2.1 Properties of aggregates and water

The fine aggregates were free of silt, clay and any other deleterious material and had a maximum aggregate size of 5 mm. This was achieved using a British standards sieve with 5 mm maximum aperture. Both the fine and coarse aggregates were suitable for concrete production. The water used for the work was potable water from Nairobi water and sewerage Company and suitable for concrete production.

4.2.2Chemical Composition of Cement Samples

The different brands however had varying properties which can be attributed to their manufacturing processes.

The difference in chemical composition of the various brands and types of cements are reflected in the difference in their mechanical properties and in the qualities of concrete produced by the different types of cements and thus it directly affects the compressive strength of concrete.

- **Effect of sum of lime (CaO) and silicon dioxide (SiO_2)**

From table 2 there is a notable variation in the amounts of CaO, SiO_2 and Insoluble Residue. Cem A has the highest amount of CaO (59.86%), Cem B has the highest SiO_2 (21.56%) and Cem A has the highest Insoluble residue (2.20%). Table 3 shows the chemical composition of the different cement samples used in this research. All the cement samples substantially complied with British Standards requirements for ordinary Portland cement.

The sum of lime (CaO) and silicon dioxide (SiO_2) obtained in the chemical analysis of ordinary Portland cement should not be less than 50% [11]. All cement samples used for this work satisfied this requirement. Cement sample B has a CaO + SiO_2 value of 80.67 % and produced the highest compressive strength of 44.89 as shown in table 5

This is consistent with the known fact that both CaO and SiO_2 give strength to concrete though SiO_2 has to be limited relative to CaO in order not to negatively affect setting time.

- **Effect of CaO/SiO_2**

The ratio of lime (CaO) to silicon dioxide (SiO_2) contents in ordinary Portland cement should be greater than 2. The restriction on the ratio of lime to silicon dioxide [11] 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 ration of (CaO/SiO_2) of a cement sample the higher the compressive strength of concrete which can be produced from it and the lower the rate of corrosion.

- **Effect of MgO**

The quantity of magnesium oxide (MgO) in ordinary Portland cement should not exceed 5% [2]. 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 lowest rate of corrosion. If the quantity of MgO is in excess of 5 percent, cracks will appear in concrete and which may affect the rate of corrosion by generating spots for penetration of chloride ions in concrete.

- **Effect of SO_3**

The quantity of sulphur trioxide (SO_3) content in ordinary Portland cement should be less than 3.5 %. All the samples satisfied this requirement.

- **Effect of Chloride Content**

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

- **Effect of Al_2O_3**

Aluminium oxide (Al_2O_3) aids the quick setting of cement paste. Cement sample B contained the highest quantity of 8.09 % of Al_2O_3 resulting in the fastest initial set of the cement paste

- **Effect of Fe_2O_3**

Iron oxide (Fe_2O_3) contributes to cement colour and helps in the fusion of the different ingredients. The Fe_2O_3 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 Table5.

h) Effect of Residues

British standards consider Na_2O, K_2O, TiO_2 and P_2O_5 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.

• CONCLUSION

The following conclusions have been reached from the outcome of this work:

i) The rate of corrosion is affected by the compressive strength of concrete which depends on the chemical properties of cement exhibited in the brand of cement with properties of the other concrete matrix material remaining the same. From the results of this research the different cement brands however had varying chemical properties. The brand with the highest lime (CaO), silicon dioxide (SiO_2) and Magnesium oxide content in cement had the highest compressive strength of concrete and the lowest rate of corrosion.

ii) Electrochemistry is a feasible method to evaluate the rate of corrosion of a steel bar embedded in concrete under accelerated corrosion.

iii) Based on the results of statistical analysis, predicted values of splitting tensile strength were not significantly different from the experimental values for the sample of cast for experiments for all the models.

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