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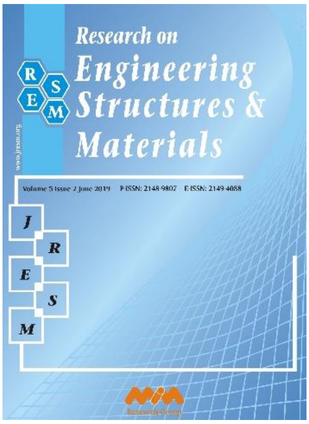

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Research Article

Prediction of chloride ingress for palm kernel shell concrete

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Abstract

Steel reinforcement corrosion emanating from ingress of chloride into concrete is the key reason for weakening of concrete structures globally. Infiltration of chloride into concrete happens by absorption and diffusion. On the other hand, reinforced concrete containing supplementary materials is more susceptible to corrosion exposure due to its high permeability. In this paper, two concentrations of sodium chloride (NaCl) were applied on concrete containing palm kernel shell as full replacement to granite. Concrete cube specimens of Grade 20 were cast into 150 mm by 150 mm by 150 mm moulds, and their workability were determined by compacting factor and slump tests. The hardened specimens were soaked in sodium chloride (NaCl) solution of 3% and 6% concentration. Spray, Absorption and Compressive strength tests were conducted at 7, 14, 21 and 28 days. Equations were generated by means of the data gotten from the laboratory tests to forecast the chloride penetration depth into the palm kernel shell concrete under the conditions considered in this work. The models generated revealed that absorption affected chloride ingress into the concrete significantly at 6% NaCl concentration. The models also reveal that the cover to reinforcements in Palm Kernel Shell Concrete subjected to chloride attack should be more than what is presently endorsed for reinforced concrete structures.

1. Introduction

A key material often utilized in the building industry is concrete [1–5]. Utilizing Palm Kernel Shells (PKS) as a substitute for coarse aggregates in concrete can reduce the rising price of materials used in construction especially in less developed nations of the world and also bring about a reduction in the overall dead weight of the building. Olutoge (2000) [6] examined the physical, compressive strength and fire resistance of concrete made with PKS and the strength fell within the range specified for lightweight concrete.

Itam et. al [7] studied the density of PKS concrete and found out that it varies in the range of 1700 to 2050 kg/m^3 based on the type of sand used and the PKS contents. Generally, when concrete's density is lower than 2000 kg/m^3, it is categorized as lightweight concrete. Thus, PKS concrete is classified as lightweight concrete [8].

Reinforced concrete (RC) is a composite in which concrete's little tensile strength and ductility are enhanced by the addition of steel reinforcements which have higher tensile

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strength [3]. The steel reinforcements are often entrenched in concrete before the setting of such concrete. The reinforcing arrangements are designed to counteract tensile stresses in regions of the concrete that might cause cracking and subsequently lead to structural failure. RC structures are intended to stay safe and functional over a long period of time. For example, bridges are generally designed to stay safe and functional for a service life of 120 years [9]. However, when these structures are constructed in environments that are high in chloride concentration, the steel reinforcements in them are prone to corrosion from the chloride ions. This poses a challenge to these structures leading to grave economic and safety implications. NaCl is an ionic compound and it is composed of the same amounts of positively and negatively charged sodium and chloride ions respectively [10].

When concrete structures are constructed in highly chloride concentrated environments, chloride ions have the capacity of penetrating through concrete cover into the reinforcing steel [9,11–14]. Corrosion is initiated on the steel at the critical concentration of the chlorides with adequate oxygen and moisture. Corrosion has two implications on the reinforcements: it results in spalling, cracking, and delamination of the concrete leading to the weakening of the bond between the concrete and the reinforcement. Also, this further makes it possible for the chloride ions to infiltrate the steel to cause further corrosion. Additionally, the area of the reinforcement reduces as they corrode, with a resulting reduction in their capacity to carry load [15–18]. Steel corrosion affects structural performance by reducing the effective cross-sectional area of reinforcements, its yield and ultimate strength, elongation rate, bond strength between the steel and concrete, thereby reducing the stiffness and bearing capacity of the structure. These have grave impact on the environment [9,19,20]. Fig. 1 shows the effect of chloride ingress on some steel samples as reported by Adeniyi et. al [11].

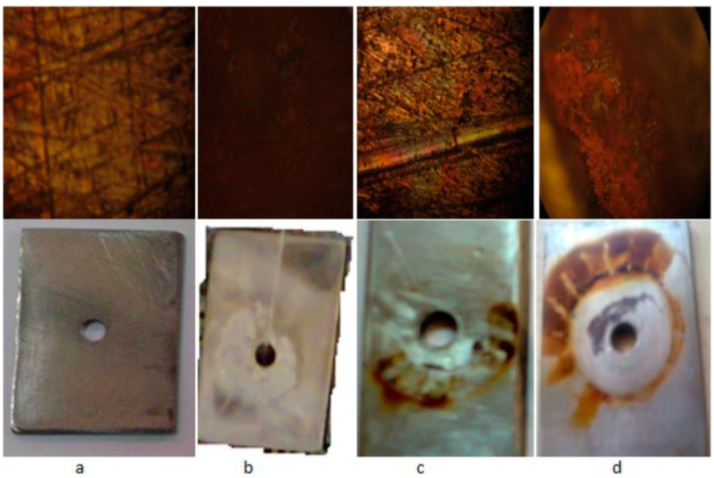

Fig. 1 Photographs and optical micrographs of SS-304 in different chloride environments, (a) as received (b) freshwater (c) brackish and (d) marine after 60 days of immersion [11]

The conveyance of chloride ions into concrete in chloride infested environments can occur by capillary absorption, diffusion and hydrostatic pressure. Absorption occurs by the rising of water in the concrete and this largely affect the level at which chloride ion is taken up. Thus, it impacts the gradient concentration in the concrete. Once there is continuous hydration of the concrete, diffusion process then increases the access of chloride ions through the cover. Permeation arises by water pressure when chloride ion solution is present under an applied hydraulic head on at least a side of the concrete structure

[17,21,22]. Consequently, movement of chloride ions via absorption and pore-liquid, when solutions with chloride ions are sucked into concrete pores, are the two major conveyance mechanisms for chloride ingress in concrete. Diffusion, which is a slow and continuous process, occurs as a result of chloride concentration gradient, once the pore liquid is not allowed evaporate [9,17].

PKS are components of oil palm tree and are predominant in western Africa especially in the riverine areas of Nigeria [23]. They are often regarded as wastes and discarded in the open consequently constituting a nuisance in the environment with little economic benefits. Odeyemi et. al (2019) [3], Dadzie and Yankah (2015) [24] and Olutoge (2010) [25] all stated that the incorporation of PKS in concrete will result in a substantial decrease in the cost of concrete production. The government of Nigeria is promoting the use of local materials in construction to lessen cost. This has resulted in the sourcing and development of substitutes such as non-conventional and agro-based construction materials to achieve the optimum benefits of agricultural wastes [26]. PKS are fibrous carbonaceous and are found in various sizes ranging from 0 – 5 mm, 5 – 10 mm, and 10 -15 mm for small, medium, and large sizes respectively [3]. Fig. 2 shows some samples of PKS.

Fig. 2 Samples of Palm Kernel Shell

The permeability of PKS concrete is high when compared to normal concrete as reported by [27–29] leading to a decline in its durability when exposed to moisture. Therefore, the use of PKS in reinforced concrete structures may lead to early reinforcement corrosion in chloride environment. Therefore, the objectives of this research are: to evaluate the compressive strengths of palm kernel shell concrete when subjected to chloride attack, to determine the consequence of chloride ingress in PKS concrete and to generate numerical models for predicting chloride penetration due to absorption on two different NaCl concentrations.

2. Research Methodology

2.1. Materials

Materials utilized for this research include Lafarge Elephant brand of Ordinary Portland Cement (Grade 42.5R), Palm Kernel Shell (PKS) obtained from local palm oil industry within Ibadan, Oyo State was used as coarse aggregate. River sand was used as the fine aggregate which conforms to BS EN 12620:2002+A1:2008 [30], potable (drinking) water of pH 7 and Sodium chloride (NaCl) solution which was utilized as the curing medium to determine the chloride ingress into the concrete. Epoxy resin was employed to coat the concrete to foil evaporation loss and to guarantee that ingress of salt solution is in a single direction. Silver Nitrate ($AgNO_3$) having a concentration of 0.1M was utilized as the colorimetric solution to estimate the chloride penetration depth.

2.2. Method

2.2.1 Laboratory Tests

Particle Size Distribution as stipulated in BS EN 933-1:2012 [31] , Specific Gravity and Aggregate Crushing Value tests were conducted on the aggregates, while Slump and Compacting factor tests, both conforming to [32] and [33] respectively, were conducted on the concrete in its fresh state. The proportion of aggregates going through the sieves was plotted against the diameter of the aggregates. Equation 1 was used to compute the Fineness modulus and the Uniformity coefficient, which expresses the grading of the aggregate, was determined from the graph by means of Equation 2.

$$Fineness\ modulus = \frac{Total\ cummulative\ percentage\ retained}{100} \quad (1)$$

$$C_u = \frac{D_{60}}{D_{10}} \quad (2)$$

where: C_u represents the Uniformity coefficient, D_{60} denotes the size of aggregates corresponding to 60% fines on the cumulative particle-size distribution curve and D_{10} denotes the size of aggregates corresponding to 10% fines on the cumulative particle-size distribution curve. If the C_u of the sample is lower than 4.0 it is inferred that the sample is uniformly graded but if the C_u of the sample is larger than 4.0, then it is inferred that the sample is well graded [15,34,35]. Also, destructive Compression test which conforms to [36] as shown in Fig. 3 and Chloride penetration evaluation were carried out on hardened concrete.

Fig. 3 Destructive Compression Test on Concrete Samples

2.2.2 Concrete Batch, Mixing and Curing

A mix ratio of 1:2:4 for a compressive strength Grade 20 was used, and batching was carried out by weight adopting a water-cement ratio of 0.5. Mixing was done manually as shown in Fig. 4. The specimens were compacted in three different layers; each layer compacted with twenty-five (25) blows with the aid of a tamping rod. The surface of each of the samples was trowel finished to be flat with the top of the concrete mould. The samples were left for 24 hours to ensure setting of the concrete cubes and they were demoulded thereafter. Three cubes from each group were randomly chosen and weighed before immersing in water. This was done to determine the weight gained by each group after each curing regime. The cubes were divided into two groups for curing, that is, curing with clean water and curing with salt water both at 3% and 6% concentration. Curing by immersion was adopted for all the concrete cubes as shown in Fig. 5. The first groups of concrete cube samples were cured in clean water for a period of 28 days so that they can attain their full compressive strength. The weight gained after this time was recorded for each group.

Fig. 4 Mixing of Palm Kernel Shell Concrete

Fig. 5 Curing of Concrete Cubes

2.2.3 Chloride Penetration Test on Concrete

The four (4) sides of the second group of samples were treated with epoxy resin. The epoxy resin was applied on the specimens to prevent the loss of water from the sides and to guarantee salt solution is one-directional. Afterwards, the samples were allowed to cure by the drying of the epoxy resin. The concrete cube specimens were then submerged in NaCl solution with a concentration of 3% and 6% NaCl respectively and left in the salt solution for 7, 14, 21 and 28 days as specified by BS 1881-122 [37] in order to generate data for the model.

After each curing time, the specimens were split vertically, and the vertical surface was sprayed with the colorimetric solution and allowed to stay for 5 minutes. This test was done to obtain the depth of chloride penetration using the colorimetric solution. The colorimetric solution used in this research is Silver Nitrate ($AgNO_3$) solution having a concentration of 0.1 M. The colour of the chloride-contaminated zone changed to light grey colour. The chloride penetration depth was gotten with the aid of a venier caliper. The colour change agrees with the submission by [38], who also discovered that the duration of colour change is a function of the reaction between chloride and $AgNO_3$ on the sprayed surface, to evaluate the depth of chloride penetration.

The model for the chloride ingress in the PKS concrete was generated based on the experimental data obtained from the tests conducted using SPSS software package. The parameters utilized for the model formulation are compressive strength (f_{cu}), time (t), absorption (i) and chloride penetration depth (d). The chloride penetration depth was then stated as a function of compressive strength, time and absorption i.e. $d = f(f_{cu}, t, i)$.

3. Results and Discussions

3.1. Properties of Aggregates

The graph of the sieve analysis conducted on the fine aggregates is presented in Fig. 6. The size of the aggregate varies from 0.10 mm to 4.75 mm signifying that the samples are within the group of fine, medium and little coarse sand [15]. This result is within the range specified for fine aggregates. The coefficient of uniformity (C_u) is 1.8 which is less than 4 indicating that the fine aggregate is uniformly graded.

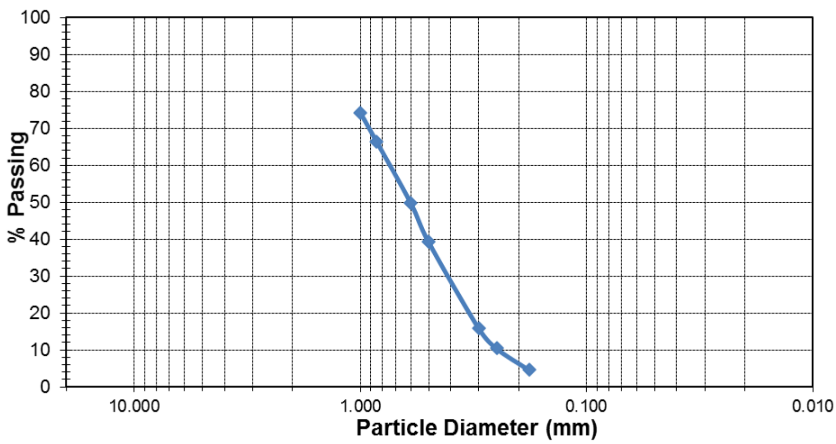

Fig. 6 Particle size distribution (PSD) curve of the fine aggregate

ACI Education Bulletin (2007) [39] specified that Specific gravity for aggregates should be within 2.30 to 2.90. The specific gravity for the fine aggregates in this study is 2.65. This signifies that the fine aggregates are suitable for construction purpose.

The ACV for the coarse aggregate used in this study is 29.8% which is in the range prescribed by BS EN 12620:2002+A1:2008 [30]. This denotes that the aggregate is fit to produce concrete.

3.2 Workability of Fresh Concrete

Compacting factor and slump test were utilized in determining the workability of the fresh concrete. From the test carried out, a compacting factor of 0.98 and slump height of 45mm was obtained. The result implies that the concrete is stiff. The results are consistent with the submission of Azunna (2019) [27], Anifowose *et. al* (2017) [40], Ede *et. al* (2016) [41] and Bamigboye *et. al* (2015) [42].

3.3 Compressive Strength

The results for the compressive strength test for the cubes cured with water, 3% NaCl, 6% NaCl for 7, 14, 21 and 28 days are presented in Fig. 7. The Figure revealed that samples cured in ordinary potable water has the maximum compressive strength at 28 days compared to the one cured in salt water. The Figure also reveals that the compressive strengths of concrete cubes cured in salt water reduced as the curing days increases. However, concrete cubes cured with 3% NaCl retained its compressive strength when exposed to the salt solution better than the samples in the 6% NaCl solution. The compressive strength results obtained in this research is in tandem with the result obtained by Azunna (2019) [27] and Odeyemi et. al (2019) [3] for PKS concrete.

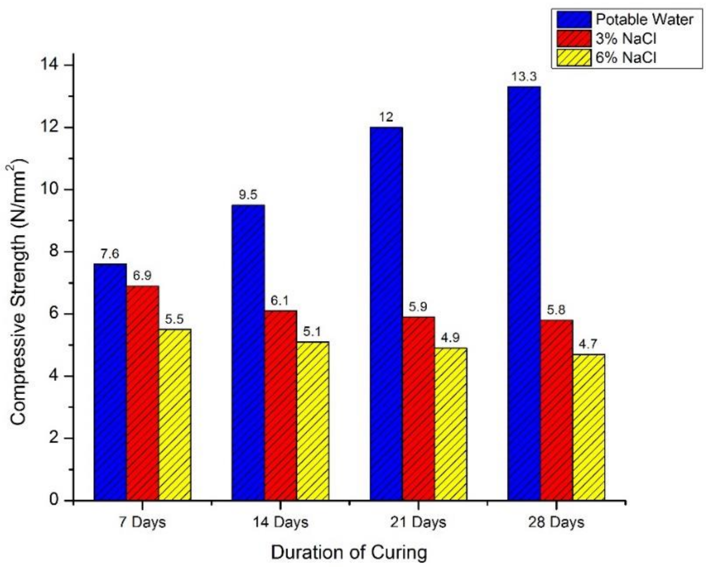

Fig. 7 Average Compressive strength of Concrete Cubes

3.4 Water Absorption

Fig. 8 is a presentation of the result of the Absorption tests conducted on concrete cubes at 7, 14, 21 and 28 days in ordinary potable water, 3% NaCl and 6% NaCl solutions. The results show that the chloride concentration of the curing medium increases the water absorption capacity of the concrete cubes. Thus, the samples cured in 6% NaCl solution absorbed more water and salt when compared with other samples. This result is consistent with the findings of Ikumapayi (2019) [9].

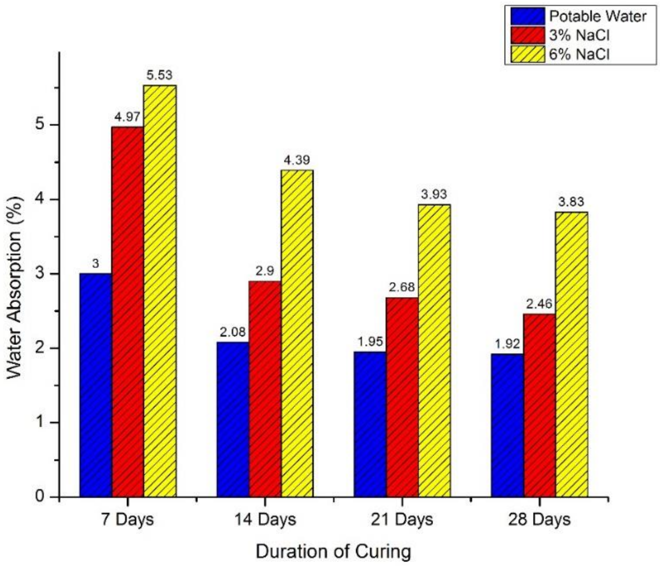

Fig. 8 Water Absorption for concrete cured with water and sodium chloride

3.5 Depth of Chloride Penetration

Fig. 9 illustrates the result of the spray test conducted to determine chloride penetration depth on the PKS concrete at 7, 14, 21 and 28 days respectively in sodium chloride solution. It was discovered that as the curing days increase, the depth of chloride penetration also increases. This happened since the depth of chloride penetration is a function of the available pore space in the sample and the concentration of the salt solution. The result shows that concrete cubes cured in 6% saltwater have the highest penetration.

3.6 Model for Chloride Penetration Depth

3.6.1 Sodium chloride (3% NaCl)

Tables 1, 2, 3 and 4 show the analysis and results of data gotten from tests conducted on the 3% NaCl solution. The regressions analysis gave an R^2 value of 0.940 which is an indication that there is a good relationship between the chloride penetration depth (d) and other parameters i.e. Absorption (i), Time (t) and Compressive strength (f_{cu}).

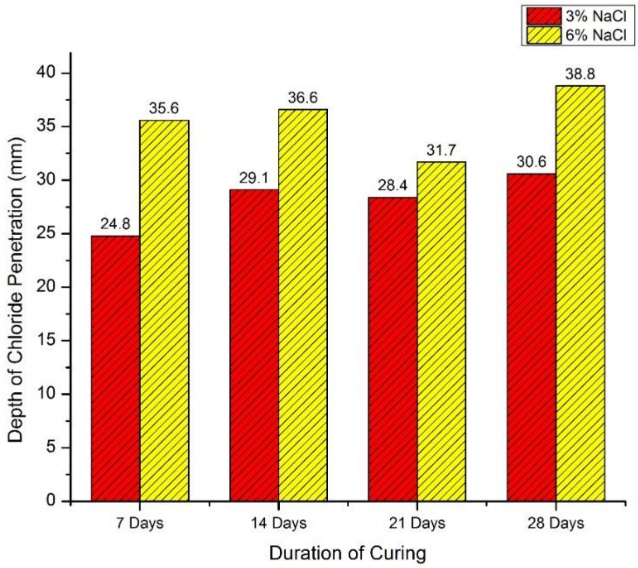

Fig. 9 Depth of chloride penetration in concrete

The level of significance of the values obtained from Table 2 is less than 0.05 which shows that the regression coefficients are statistically significant. Thus, the model for chloride penetration for concrete immersed in 3% Sodium Chloride solution is presented in Equation 3

$$d = 27.776 + 1.682t + 0.19f_{cu} - 1.036i \tag{3}$$

Where d = Chloride penetration depth (mm); f_{cu} is the characteristic strength $^{N}/_{mm^2}$; t is Time (Age of Concrete coded in multiple of 7 i.e. 7 days = 1, 14 days = 2, 21 days = 3 and 28 days = 4); i – Absorption.

Table 1 Model Summary for 3% Sodium Chloride (NaCl)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1.	0.970	0.940	0.918	0.63882

Table 2 Analysis of Variance

Model	Sum of Squares	df	Mean Square	f	Significance
Regression	51.238	3	17.079	41.852	0.000
1 Residual	3.265	8	0.408		
Total	54.503	11			

Table 3 Coefficients Summary for Sodium Chloride NaCl at 3% Model

Model		Unstandardized Coefficients		Standardized Coefficients	T	Significance
		B	Standard Error	Beta		
1	Constant	27.776	1.891		14.686	0.000
	t	1.682	0.188	0.882	8.925	0.000
	f_{cu}	0.091	0.263	0.035	0.346	0.738
	i	-1.036	0.220	-0.423	-4.698	0.002

Table 4 Regression Summary for Chloride Depth Penetration and Absorption for 3% NaCl Solution

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	29.6328	5.21786	5.67910	0.00020	18.0066	41.25894	18.00667	41.25894
Absorption (%)	1.711101	1.22513	1.39666	0.19273	-1.0187	4.440861	-1.01866	4.440861

Fig. 10 shows that there is no relationship between depths of sodium chloride penetration NaCl (3%) and Absorption for NaCl. This show an approximately constant slope and the R^2-value is very small which support the model result earlier obtained that it can only explain about 0% of the variation of the data, and also indicate that the depth penetration of sodium chloride do not really depend on the absorption of the salt solution.

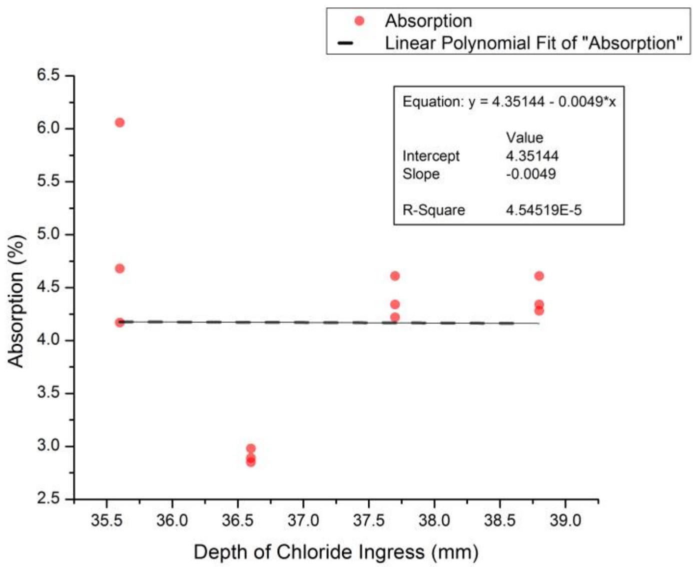

Fig. 10 Chloride Penetration depth against Absorption for 3% NaCl

3.7 6% Sodium chloride (NaCl)

Table 5 presents the regression analysis showing the coefficient of correlation R^2 value of 0.989 which implies that there is a high relationship between the chloride penetration depth (d) and other parameters considered in the model absorption i.e. (i), time (t) and compressive strength (f_{cu}). Table 6 shows that the regression coefficient is statistically significant. Also, Table 7 and 8 reveals that the significant value for the intercept and time is statistically significant while absorption and compressive strength are not. Thus, the model is presented in Equation 4

$$d = 34.462 + 1.073t + 0.19f_{cu} + 0.019i \quad (4)$$

Where d = chloride penetration depth (mm); F_{cu} is the characteristic strength $N/_{mm^2}$; t is Time (Age of Concrete coded in multiple of 7 i.e. 7 days = 1, 14 days = 2, 21 days = 3 and 28 days = 4); i – Absorption.

Table 5 Model Summary for 6% Sodium Chloride (NaCl)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
2	1.000	0.989	0.973	0.03300

Table 6 Analysis of Variance

Model	Sum of Squares	df	Mean Square	f	Sig
Regression	17.174	3	5.725	5258.253	0.000[b]
1 Residual	.009	8	0.001		
Total	17.182	11			

Table 7 Coefficients Summary for Sodium Chloride NaCl at 6% Model

Model		Unstandardized Coefficients		Standardized Coefficients	T	Significance	95.0% Confidence Interval for B	
		B	Standard Error	Beta			Lower Bound	Upper Bound
2	Constant	34.462	0.084		412.204	0.000	34.269	34.655
	t	1.073	0.010	1.002	106.451	0.000	1.049	1.096
	f_{cu}	0.005	0.008	0.002	0.186	0.857	-0.017	0.020
	i	0.019	0.010	0.005	0.509	0.624	-0.018	0.028

Table 8 Regression Coefficient for Chloride Depth Penetration and Absorption for 6% NaCl Solution

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	32.01836	3.61004	8.86923	0.0000472	23.9746	40.0620	23.974	40.005
Absorption (%)	1.98375	0.75291	-1.2933	0.2249	-2.6513	0.7038	-2.651	0.7844

Fig. 11 shows that there is a linear relationship between sodium chloride penetration depth and Absorption for 6% NaCl solution. This show an upward movement trend and the R^2 value shows that the variation in the depth of penetration of sodium chloride can be explained at about 17% of its absorption.

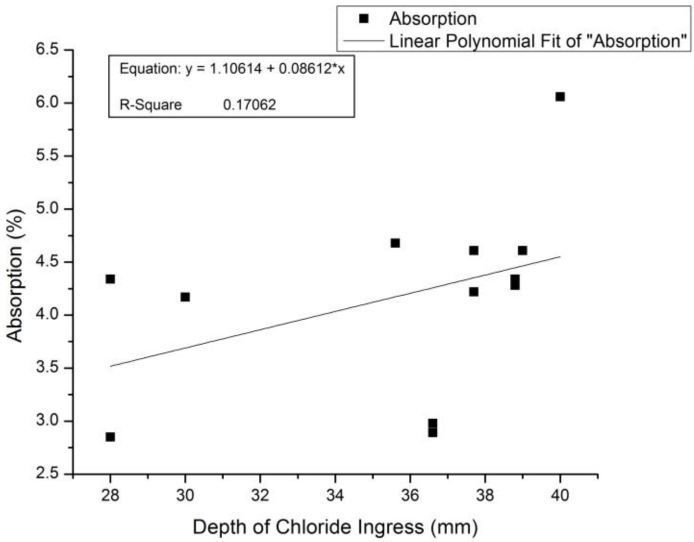

Fig. 11 Chloride Penetration depth against Absorption for 6% NaCl

4. Conclusions

Studies have shown that the corrosion of steel reinforcements resulting from chloride attack is a major cause of weakening of concrete structures globally. Chloride ingress into concrete takes place by absorption and diffusion. Researchers have also discovered that reinforced concrete containing supplementary materials are more susceptible to corrosion exposure due to their high permeability. This research investigated the effect of two concentrations of sodium chloride (NaCl) on concrete containing palm kernel shell as full replacement of granite. Grade 20 concrete were cast into 150 mm by 150 mm by 150 mm cubic moulds, and their workability were determined by compacting factor and slump tests following the relevant international standards. The hardened concrete samples were fully submerged in potable water, sodium chloride (NaCl) solution of 3% and 6% concentration, respectively. Spray, Absorption and Compressive strength tests were conducted at 7, 14, 21 and 28 days. Equations were generated by means of the data gotten from the laboratory tests to forecast the chloride penetration depth into the palm kernel shell concrete for the two (2) chloride concentrations considered in this work. The following conclusions were drawn from the study:

- The absorption of concrete cured in ordinary potable water (control) were found to be less than that of the concrete cured in salt water.
- Absorption, Time and Compressive Strength have a significant influence on the diffusion of chloride ions into the PKS concrete.
- The chloride penetration depth into the PKS concrete increases as the exposure days increases.

- Exposure of PKS concrete to Sodium chloride (NaCl) solution leads to a long-term loss in compressive strength.
- For the Grade 20 concrete utilized for this study, the relationship between chloride penetration depth, age of concrete, compressive strength and absorption is given as:

$d = 27.776 + 1.682t + 0.19f_{cu} - 1.036i$ for 3% NaCl concentration

$d = 34.462 + 1.073t + 0.19f_{cu} + 0.019i$ for 6% NaCl concentration

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