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RESEARCH TITLE:

ASSESSEMENT OF THE IMPACT OF SAWDUST ASH ON THE SULPHATE RESISTANCE OF CONCRETE DURING EARLY STRENGTH DEVELOPMENT

BY

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Certification

The undersigned certify that they have read and hereby recommend for acceptance by Kyambogo University a dissertation entitled: Assessment of the impact of sawdust ash on the sulphate resistance of concrete during early strength development

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Declaration

I, **Patrick Basajjansolo Kabiito,** hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and reference list

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ABSTRACT

Sulfates are detrimental to the structural integrity of concrete throughout its service life. In the project for the construction of the overhead transmission line grid for power evacuation from the Karuma Hydro Power plant, aggressive levels of sulfates were encountered along Karuma – Lira 132kV Transmission Line. This necessitated use of Sulfate Resisting Cement (SRC) in foundations to counter sulfate attack. Sulfate Resisting Cement is twice as expensive as Ordinary Portland Cement (OPC) in Uganda and may only be available on a minimum special order of 200 tons. Based on the above the study was therefore aimed at evaluating the impact of sawdust ash on the sulphate resistance of concrete during early strength development. A total of 384 concrete cubes of 4 designed mixes were used in two different sulphuric acid solutions of differing concentrations to simulate sulphate attack on concrete. Cubes were exposed to sulfate attack for 28 days in sulphuric acid solutions in the early stages of hardening (i.e., at the age of 6, 24 and 72 hours) and in the later stage of hardening (i.e., aged 28 days). SDA dosages used to replace part of the OPC were 0%, 5%, 10% and 15%. It was observed that concrete in the early stages of hardening (i.e., age of 6, 24 and 72 hours) exhibited improved resistance to sulfate attack compared to that in the later stage of hardening (i.e., aged 28 days). Moderate strength concrete grades (i.e., C16/20, C20/25) with design cement content less than 18.1% performed better than the higher strength concrete (i.e., C25/30 and C30/37). The ingress of SO_4^{2-} ions into C20/25-5% SDA concrete followed a decreasing linear function for concrete cured for 72 hours before exposure to sulfate attack. A maximum cement replacement of 10% with SDA as well as partial back filling of foundation concrete after 72 hours of casting is

recommended. There is need to extend the study beyond 28 days of sulfate attack on concrete during early strength development.

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List of Acronyms

ACI - American Concrete Institute

ASR- Alkali Silica Reaction

ASTM - American Standard for Testing and Materials

BSI – British Standards Institute

BS - British Standard

BIS – Bureau of Indian Standard

C16/20 or C20/25 or C25/30 or C30/37- Concrete Strength Class C16 or C20 or C25 or C30

C_2A – Dicalcium Aluminate

C_2S – Dicalcium Silicate

C_3A - Tricalcium Aluminate

CA- Course Aggregate

CIPS – Concrete in Plastic Stage

DOE – Department of Environment

EN - European Standard

ESCH-Early Stage of Concrete Hardening

FA- Fine Aggregate

HCM - Hardened Concrete Matrix

HCS – Hardening Concrete Stage

KHPP- Karuma Hydropower Project

KIP - Karuma Interconnection Project

kV – Kilo Volt

LSCH- Later Stage of Concrete Hardening

NR – Not Relevant

NWSC- National Water and Sewerage Corporation

OPC- Ordinary Portland Cement

PAI – Pozzolanic Activity Index

PC- Portland cement

SA – Sulfate Attack

SDA- Sawdust Ash

SR – Sulfate Resistance

SRC- Sulfate Resisting Cement

TL - Transmission Line

UGX – Uganda Shillings

WA – Wood Ash

XA1- Slightly aggressive environment

XA2 – Moderately aggressive environment

XA3 – Highly aggressive environment

XRF – X-Ray Fluorescence

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Chemically aggressive environment to concrete foundations in sub-soils (especially to the foundation structures) is a worldwide challenge. Euro code 2 provides three classes of aggressive environment namely; XA1(slightly aggressive environment), XA2 (moderately aggressive environment) and XA3 (highly aggressive environment in relation to chemical attack) (BS EN1992, 2004; BS EN206, 2013). The Structural Engineer uses this guide to deal with the challenge of chemical attack on concrete during design.

One of the important cases of chemical attack of foundations in Uganda was observed on the Karuma Interconnection Project. This project involved construction of the overhead power transmission line grids and associated substations for the Karuma Hydro Power Project. During implementation of this project, it was found that, of the 75 Km Karuma-Lira Transmission Line, 90% of all concrete foundations were to be exposed to slightly aggressive environment. The exposure condition was observed for a total distance of 67.5 Km along the Corner Kamdin-Lira highway. Since the area has community built human settlements who use the readily available Ordinary Portland cement, these domestic houses could as well be prone to sulfate attack.

Sulphate attack (SA) on hardened concrete targets a key cement constituent compound known as Tri-calcium Aluminate ($3CaO.Al_2O_3$ - C_3A). The expansive nature of the resultant compounds creates internal stresses within the concrete matrix thereby initiating cracks in the concrete (Dhir, et al., 1996). The fundamental difference between Portland Cement and Sulphate Resisting Cement (BS, 1996) is that Sulfate

Resisting Cement has low (up to 3.5%) content of C_3A as compared to Portland cement (maximum 8%) for all Normal and Rapid hardening cements.

Ground water that has aggressive elements to concrete can be identified as having dark coloured, rotten odour with emerging gas bubbles (Kaintzyk, et al., 2003). Concrete can be attacked by sulphates and sulphuric acid occurring naturally in soils, by corrosive chemicals which may be present in industrial waste in fill materials, and by organic acids and carbon dioxide present in groundwater as a result of decaying vegetable matter. Ammonium sulphate, which attacks Portland cement very severely, does not occur naturally. However, it is used as a fertilizer and may enter the ground in quite significant concentrations, particularly in storage areas on farms or in the factories producing the fertilizer. Ammonium sulphate is also a by-product of coal-gas production and it can be found on sites of abandoned gasworks. Because calcium sulphate is relatively insoluble in water, it cannot be present in sufficiently high concentrations to cause severe attack, while other soluble sulphates can exist in concentrations that are much higher than that possible with calcium sulphate. This is particularly the case where there is a fluctuating water table or flow of groundwater across a sloping site. The flow of groundwater brings fresh sulphates to continue and accelerate the chemical reaction. High concentrations of sulphates can occur in some peats and within the root mass of well-grown trees and hedgerows due to the movement and subsequent evaporation of sulphate-bearing ground-water drawn from the surrounding ground by root-action (Tomlinson & John Woodward, 2008). A chemical test (BS, 1990) on the subsoil and ground water samples picked from proposed sites is necessary to ascertain the presence of active chemical compounds (Cl^-, SO_3^{2-} and SO_4^{2-}). Sulfate Resisting Cement is recommended for use in chemically aggressive environment to concrete (BS EN206, 2013).

While Sulfate Resisting Cement is twice as expensive as Ordinary Portland Cement it is only available on a minimum special order of 200 tonnes on the local market in Uganda. As noted, the transmission line passes through settlement areas which were built using Ordinary Portland Cement without adequate precautions to guard against Sulfate attack. Hence, there exists a danger of Sulfate attack to the foundation of the buildings and a life-threatening risk in case the buildings collapse. However, the communities cannot afford Sulfate Resisting Cement. Thus, a cheaper alternative has to be found.

1.2 Problem statement

Water and soils containing undesirable substances such as free acids, sulphides, sulphates, magnesium salt, ammonium salt or grease and oil can lead to unwanted reactions in concrete. During construction of Karuma – Lira 132kV Transmission Line, aggressive levels of sulfates were found, which necessitated the use of Sulfate Resisting Cement (SRC) to counter this attack. Besides Sulfate Resisting Cement (SRC) being twice as expensive as Ordinary Portland cement (OPC) in Uganda, it is only available on a minimum special order of 200 tonnes. It cannot be afforded by the local community and yet the areas through which the transmission line passed were found to have slightly aggressive environment to concrete. There is therefore a need to find a cheaper alternative by using the readily available Ordinary Portland cement (OPC) mixed with Sawdust Ash to counter sulfate attack on concrete.

1.3 Research Objectives

1.3.1 Main Objective

To assess the impact of addition of sawdust ash on the sulphate resistance of freshly cast and hardened Portland cement concrete.

1.3.2 Specific Objectives

The specific objectives of the research work were;

1. To establish the chemical reaction between fresh Ordinary Portland cement concrete and sawdust ash.
2. To establish the effect of varying quantities of sawdust ash in quantities of 0%, 5%, 10% and 15% on the compressive strength and ingress of sulfate ions into concrete.
3. To determine the effect of sawdust ash on Ordinary Portland cement concrete in relation to the age of exposure to sulfate attack (6 hours, 24 hours, 3 days and 28 days) of concrete.
4. To carry out a cost analysis between the use of SRC and OPC mixed with SDA as an alternative for dealing with chemical sulphate attack on concrete.

1.4 Research question

These were;

a. What is the chemical reaction between fresh ordinary Portland cement concrete and Sawdust ash?
b. How does varying the quantities of sawdust ash as 0%, 5%, 10% and 15% affect the compressive strength of concrete exposed to sulfate attack?
c. What is the effect of sawdust ash on Ordinary Portland cement concrete in relation to the age of exposure to sulfate attack?
d. How does the cost of SRC compare with OPC mixed with SDA when used to counter chemical sulfate attack?

1.5 Research Justification

Water and soils containing free acids, sulphides, sulphates, magnesium salt, and ammonium salt or grease and oil attacks concrete (Kaintzyk, et al., 2003). The cost of Sulfate Resisting Cement is twice that of Ordinary Portland cement, it is neither affordable nor available to the local consumers in Uganda. During the construction of Karuma – Lira TL, 90% of the entire 75 Km was discovered as slightly aggressive to concrete foundations. Use of readily available Ordinary Portland cement concrete mixed with sawdust ash will enhance its resistance to sulphate attack. This will make structures affordable and safe for the local communities.

1.6 Significance

The use of Sawdust ash as an admixture in ordinary Portland cement concrete to obtain similar results as those for Sulfate Resisting Cement would provide a hands-on solution for the expensive and often scarce Sulfate Resisting Cement on the local market in Uganda. Besides concrete structures becoming more durable and safer throughout their design life, the cost of construction will greatly reduce by using this technology.

1.7 Scope of the Research

This research included but not limited to the following;

1.7.1 Geographic scope

This research was conducted at Kyambogo University Department of Building and Civil Engineering Structure Laboratory on an idea conceived from the 132kV Karuma – Lira power Transmission Line project in northern Uganda along the corner Kamdin – Lira highway.

1.7.2 Content scope

The content involved production of sawdust ash from timber sawdust. Investigation of its chemical composition using XRF technology. Carried out concrete mix design of four grades of concrete. 384 concrete cubes were cast for which part of the ordinary Portland cement was replaced with Sawdust ash in quantities of 0%, 5%, 10% and 15%, their durability and compressive strength were determined. Determination of the relationship between age of concrete at exposure to sulfate attack (6 hours, 24 hours, 72 hours and 28 days) and their resistance to sulfate attack. Microscopic images of concrete cubes were taken before and after exposure to sulfate attack.

1.7.3 Time scope

The research work lasted for eight (8) months, May to December 2020. Please refer to Appendix A.1

1.8 Conceptual Frame Work

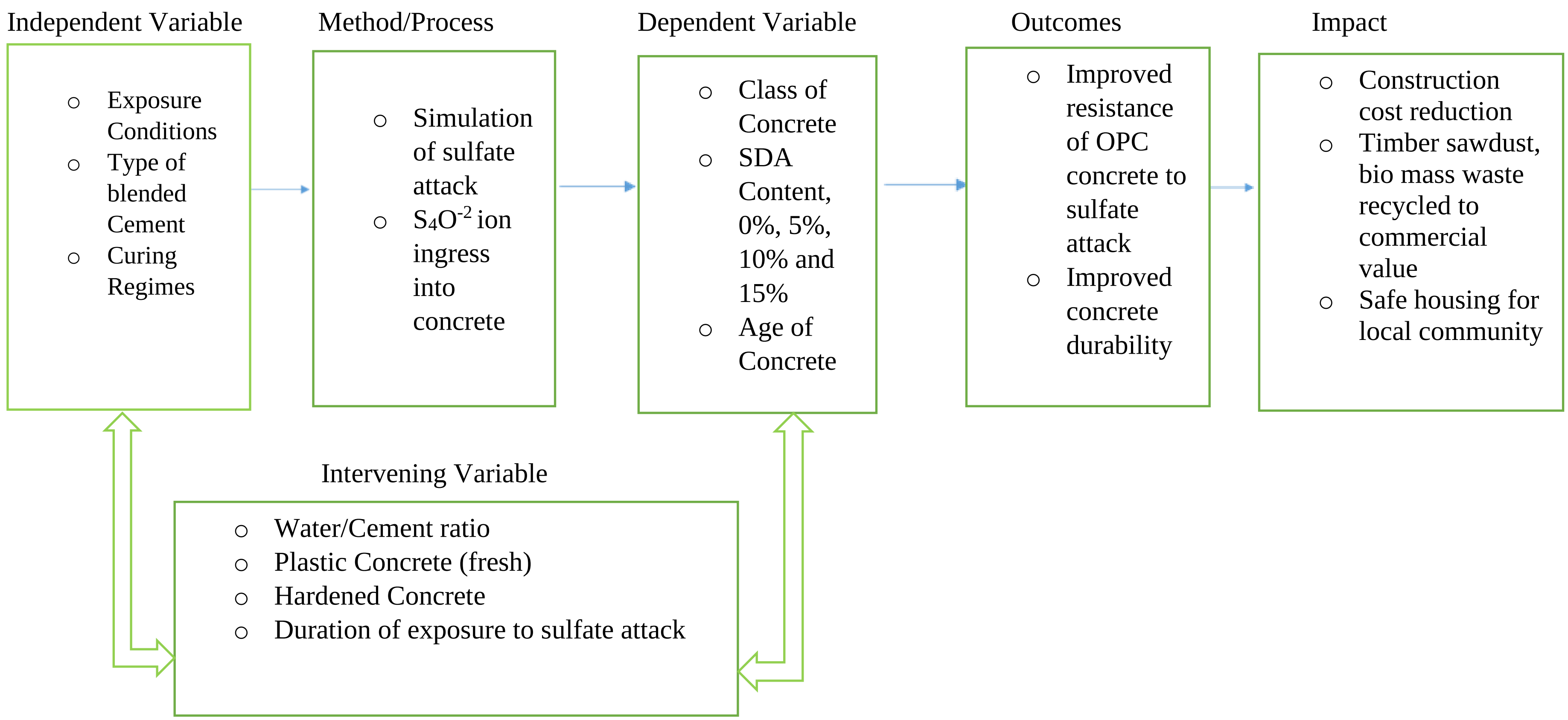


Figure 1. 1: Conceptual Frame Work

CHAPTER TWO: LITERACTURE REVIEW

2.1 Introduction

Fresh concrete is a mixture of water, cement, aggregate and or admixtures, which may be used in certain cases to control rheology, rate of setting and hardening and durability. Due to its capability to adopt to any shape in its plastic state, concrete is widely used in the construction industry in various parts of the world. After mixing of these materials to produce a uniform blend, operations such as transportation, placing, compacting and finishing of fresh concrete can all considerably affect the properties of hardened concrete. Admixtures are substances introduced into a batch of concrete, during or immediately before its mixing, in order to alter or improve the properties of fresh or hardened concrete or both. Although certain finely divided solids, such as pozzolans and slags, fall within the above broad definition of admixtures they are distinctly different from what is commonly regarded as the main stream of admixtures and therefore should be treated separately (Dhir, et al., 1996). A certificate issued by a civil engineering supervising or-ganisation or, at least by the supplier, is a precondition for their application. Concrete plasticizers improve consistence and workability without modifying the water-cement ratio. Retarding or accelerating admixtures control the setting time. For overhead lines, retarding admixtures are frequently necessary to place the concrete before initial setting in case of long transport distances or warm weather. Admixtures for water and damp proofing should avoid the ingress of water into the concrete. However, expedient concrete composition and compaction achieve the same density in the most cases. The application of concrete admixtures assumes the verification of the suitability of a concrete mixture (Kaintzyk, et al., 2003).

In his work, Ayuba (2014) reported that the addition of SDA in cement decreased drying shrinkage but increased consistency, initial and final setting times and could be used as a retarder.

Other concrete admixture includes, superplasticizers, pore fillers, pigments and water-repelling agents. Portioning of concrete constituent materials may be guided by prescriptive mixes or designed mixes which target the desired properties of the concrete in both the plastic and hardened states taking account of its design life. On large infrastructure projects in Uganda, Contractors often adopt designed mix procedures for concrete production on site. The quantities of the concrete constituent materials are predetermined by calculations per unit volume of concrete. International Standards like the American Standard for Testing and Materials for Structural Concrete (ASTM, 2004) may be used as a procedure for concrete mix design. Another widely applied concrete mix design standard is based on the British Standard, BRE (1988a)

The ground or ground water may contain chemicals capable of causing damage to concrete or steel. These chemicals may emanate from nearby industrial processing or may occur naturally. The principal constituents that cause concrete to deteriorate are sulphates, which are most common in clay soils and acidic waters (Transport Research Laboratories, 2000) The reinforcements are selected from a wide range of available materials which include; Iron steel bars (BS, 1997), Glass fiber, Carbon steel, Polypropylene fiber, Asbestos fiber among others.

Several other undesired chemical reactions may be initiated in the concrete microstructure owing to its constituent materials or the serviceability conditions. Some aggregates containing particular forms of silica may be susceptible to attack by alkalis originating from the cement or other sources, producing an expansive reaction which can cause cracking and disruption of concrete. Damage to concrete from alkali silica reaction will normally occur only when all the following are present (BS, 1997):

a) there is a high moisture level within the concrete;

b) the concrete has a high reactive alkali content, or there is another source of reactive alkali;

c) the aggregate contains an alkali reactive constituent.

In polluted ground areas such as old sanitary landfills, shorelines near sewer outfall lines from older industrial plants, or backwater areas where water stands over dead vegetation, there can be corrosion problems with metal foundation members as well as with concrete. Concrete is normally resistant to corrosion; however, if sulfates are present, it may be necessary to use sulfate-resistant concrete (Bowles, 1997). Naturally occurring sulphate in soils are those of calcium, magnesium, sodium and potassium. High concentrations of sulphate can occur in some peats and within the root mass of well-grown trees and hedgerows due to the movement and subsequent evaporation of sulphate-bearing ground-water drawn from the surrounding ground by root-action. The basic mechanism of attack by sulphate in the ground is a reaction with hydrated calcium aluminate in the cement paste to form calcium sulphoaluminate. The reaction is accompanied by an increase in molecular volume of the minerals, resulting in the expansion and finally the disintegration of the hardened concrete. The severity of attack by soluble sulphates must be assessed by determining the soluble sulphate content and the proportions of the various cations present in an aqueous extract of the soil. These determinations must be made in all cases where the concentration of sulphate in a soil sample exceeds 0.5% (Tomlinson & John Woodward, 2008). Care should be taken during design to protect the concrete against carbonation, chloride ingress, sulfate attack, Sea water attack, Alkali–aggregate reactions, Alkali-Silica Reaction (ASR) among others (BS, 1997). The structural designer is guided by the above information, material test results, prevailing service conditions of the concrete and relevant structural concrete codes of practice in order to design an appropriate concrete mix that will serve the intended purpose during its design life. For chemically aggressive environment XA2, sulphate resisting cement is recommended for use in grade C30/37 concrete with a minimum cement content of 320 Kg/m^3 and a maximum Water/Cement ration of 0.55 (BS EN206, 2013).

Siliceous fly ash is a fine powder of mostly spherical particles having Pozzolanic properties. It consists essentially of reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The remainder contains iron oxide (Fe_2O_3) and other compounds. The proportion of reactive calcium oxide shall be less than 10.0 % by mass; the content of free calcium oxide, as determined by the method described in standard shall not exceed 1.0 % by mass (ASTM, 2018). Fly ash having a free calcium oxide content higher than 1.0 % by, mass but less than 2.5 % by mass is also acceptable provided that the requirement on expansion (soundness) does not exceed 10 mm when tested in accordance with EAS 148-3 using a mixture of 30 % by mass of siliceous fly ash and 70 % by mass of a CEM I cement conforming to EAS 18-1 (see Clause 6). The reactive silicon dioxide content shall not be less than 25.0 % by mass (East African Standard, 2017)

Table 2. 1: Chemical Requirements

Parameter	Siliceous fly ash
Silicon dioxide (SiO_2), min, %	25.0
Aluminum (Al_2O_3) %	-
Iron oxide (Fe_2O_3) %	-
Calcium Oxide (CaO) max %	10.0

2.2 Materials Characteristics

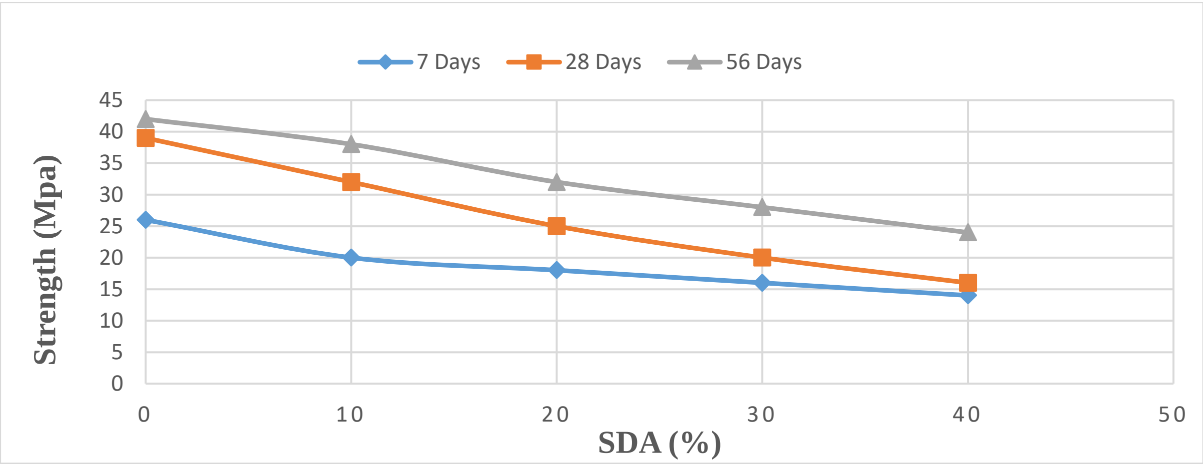
2.2.1 Cement

The different cements used for making concrete are finely ground powders and all have the important property that when mixed with water a chemical reaction (hydration) takes place which, in time, produces a very hard and strong binding medium for the aggregate particles. In the early stages of hydration, while in its plastic stage, cement mortar gives to the fresh concrete its cohesive properties (Dhir, et al., 1996). The hydration of Tricalcium aluminate is extremely exothermic and takes place very quickly, producing little increase in strength after about 24 hours.

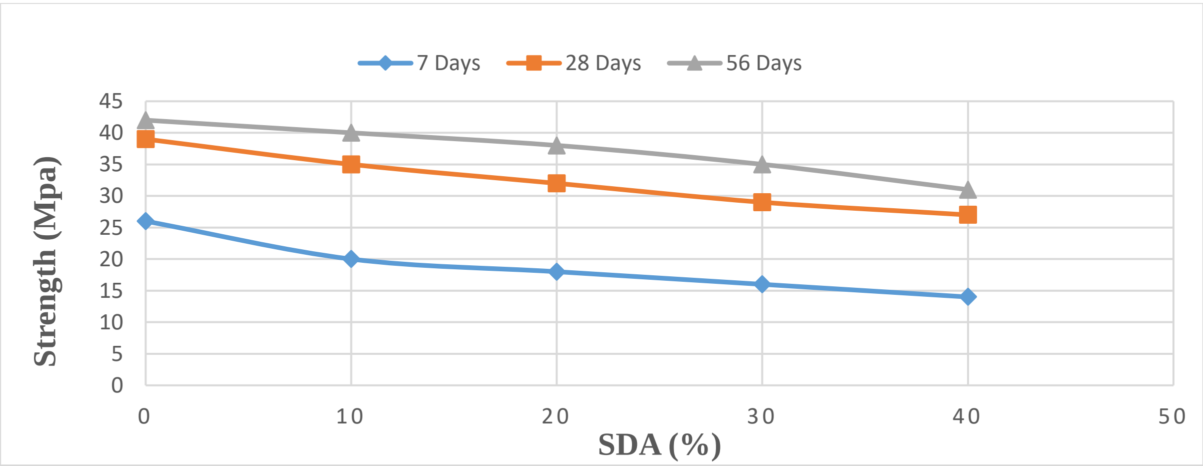
Table 2. 2: Main chemical compounds of Portland cement (Dhir, et al., 1996)

Name of Compounds	Chemical composition	Usual abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetra calcium aluminoferrite	$4CaO. Al_2O_3. Fe_2O_3$	C_4AF

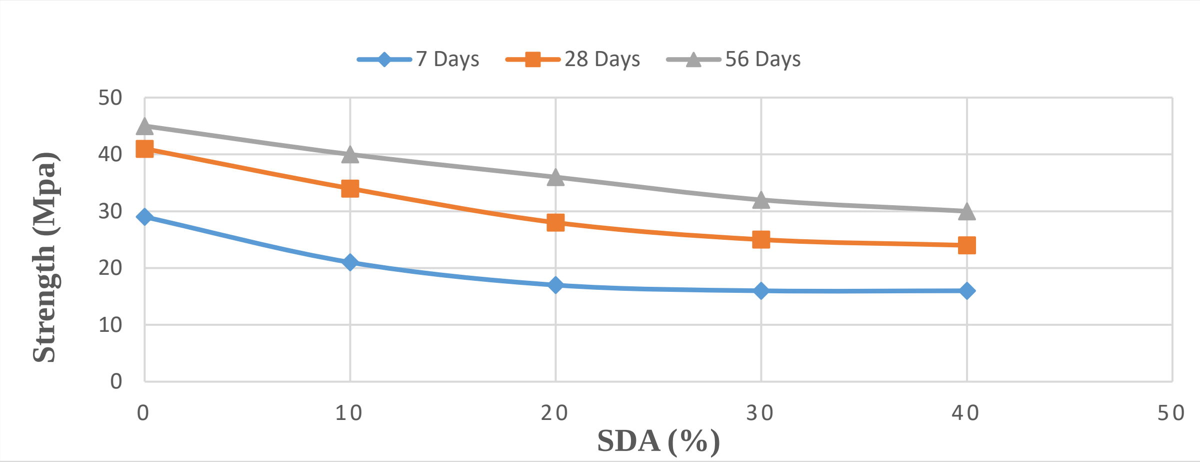
Of the four principal compounds Tricalcium aluminate is the least stable and cements containing more than 10 percent of this compound produce concretes which are particularly susceptible to sulfate attack. Sulphate attack on hardened concrete targets a key cement constituent compound known as Tricalcium Aluminate ($3CaO.Al_2O_3$ - C_3A). The expansive nature of the resultant compounds creates internal stresses within the concrete matrix thereby initiating cracks in the concrete (Dhir, et al., 1996). The fundamental difference between Portland Cement and Sulphate Resisting Cement (British Standards Institute, 1996) is that SRC has low (up to 3.5%) content of C_3A as compared to Portland cement (maximum 8%) for all Normal and Rapid hardening cements. The low rate of strength development of low-heat Portland cement is due to its relatively high C_2S content and low C_2A and C_3S contents. An exceptionally low C_3A content contributes to the increased resistance to sulfate attack of sulfate–resisting cement. In his study, Marthong (2012) used various grades of ordinary Portland cement (OPC) classified by Bureau of Indian Standard namely: 33N, 43N and 53N conforming to standard code provision. Fly ash was added as percentage by weight of total cementitious material replacing cement by various percentages. The Variation of cubes strength at different ages of 7, 28, 56 and 90 days with different grades of OPC and various percentage of SDA contents are shown in Figure. 2.1 (a), (b) and (c). The figures indicate that compressive strength of concrete in all grades of OPC at early age was significantly higher than that of concrete produced with SDA. It was reported that compressive strength continued to increase with age but decreased with SDA contents in all grades of OPC. The reduction in strength at the initial stages of hydration may have been due to SDA acting as a retarder. The initial processes of hydration get retarded, which invariably may affect the initial process of strength development. The strength reduction was found to be lower for higher grade OPC. It was observed that attaining of strength at 28 days with SDA, grades 43 and 53 OPC attained about 60% of strength as compared to normal concrete, while SDA with 33 grades OPC could attain only 50% of its strength. This comparison shows that SDA with grade 43 and 53 OPC with medium workability concrete compared favorably with OPC concrete in terms of early strength development. In long term strength gain (at 90 days), SDA with grade 43 and 53 OPC attained about 80% strength as compared to concrete with 0% SDA replacement, while SDA 33 grades OPC the strength gain was about 58% only.



a) 33 grade OPC



a) 43 grade OPC



b) 53 grade OPC

Figure 2. 1: Compressive strength of different grades of OPC (Marthong, 2012)

Hardik (2017) used Ordinary Portland Cement of grade 43 (Jaypee cement), with the following physical properties;

Table 2. 3: Physical Properties of Ordinary Portland cement of grade 43 was used (Jaypee cement) (Hardik & Dhull, 2017)

Characteristics	Value
Specific Gravity	3.15
Consistency	33%
I.S. Time	105 (min
F.S. Time	260 (min)

Ayuba (2014) used Ordinary Portland cement manufactured in Nigeria as Dangote brand, with a specific gravity of 3.14, moisture content of 0.63 % and bulk density of 1164 Kg/m^3 for the study.

2.2.2 Sawdust Ash/Pozzolana

A pozzolan is defined as a siliceous material which, in itself possesses little or no cementitious value but will, in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (ASTM, 2015).

Different researchers have studied the use of saw dust ash in concrete, Ayuba (2014) used sawdust obtained from Yola timber shed in Adamawa State, Nigeria. The Sawdust Ash (SDA) was obtained by incineration of sawdust at a temperature between 600 – 630ºC under a controled burning system for 2 hours 25 minutes and the ash was allowed to cool before sieving through 75 µm sieve. The SDA had specific gravity of 2.27, bulk density of 595 Kg/m^3 and moisture content of 3.53 %. The oxide composition of SDA was conducted using X-Ray Fluorescence (XRF) and results are shown in Table 2.4

Table 2. 4: Oxide composition of OPC (Dangote Brand) and SDA (Ayuba, et al., 2014)

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	TiO_2
OPC	14.89	5.70	4.10	68.30	1.69	0.1	0.71	2.67	0.22
SDA	7.52	3.50	1.47	50.64	5.02	19.93	3.61	1.2	0.34
Oxide (%)	MnO	BaO	V_2O_5	P_2O_5	ZnO	Cr_2O_3	NiO	CuO	L.o.I
OPC	0.04	0.15	0.02	-	-	0.01	< 1	-	1.33
SDA	0.35	0.54	0.01	1.64	0.03	<0.01	<0.01	<0.01	4.20

From Table 2.4 above, it was observed that the oxide content of both SDA and OPC compared favourably, suggesting that SDA can be used to replace part of cement in concrete with no adverse effects. The combined total content of SiO_2, Al_2O_3 and Fe_2O_3 is 12.49% which was less that the minimum 70% recommended for class N pozzolana (ASTM, 2018).

Hardik (2017) defined sawdust ash as a waste material from timber industry having following characteristics.

Table 2. 5: Characteristics of sawdust ash (Hardik & Dhull, 2017)

Oxide	% (by wt.)
SiO_2	68.30
Al_2O_3	3.50
Fe_2O_3	2.23
MgO	5.40
CaO	5.00

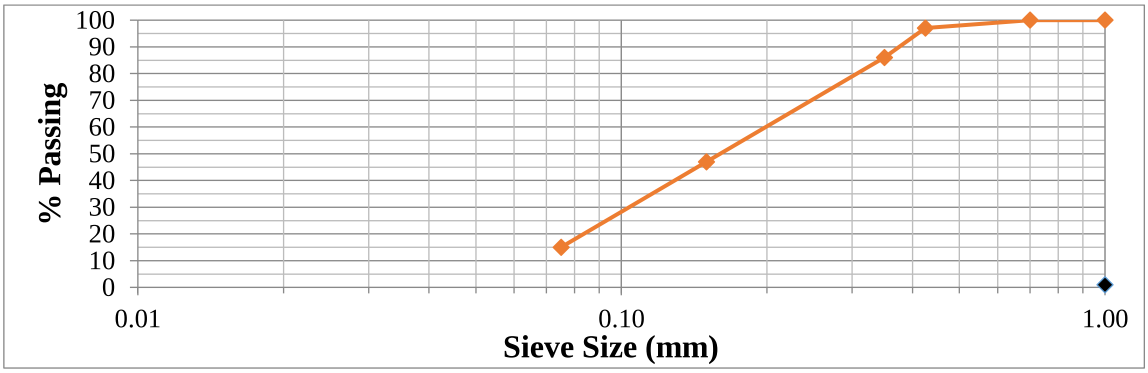
In his study, Marthong (2012) collected sawdust from local saw mill in Meghalaya, India and openly heated to about the temperature of 600 ºC. The ash was then grounded after cooling and graded in accordance with (BS, 1967). Chemical properties of SDA and their comparison with OPC are presented in Table 2.3

Table 2. 6: Physical and Chemical Properties of SDA and OPC (Marthong, 2012)

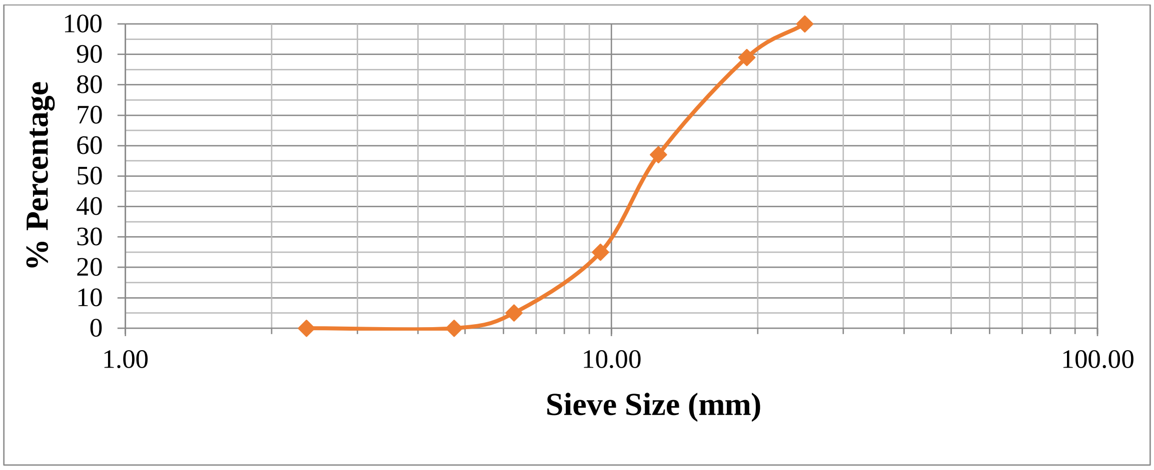
Element	**SDA % by weight**	**OPC % by weight**
Specific gravity	2.51	3.14 (33 OPC) 3.15 (43 OPC)
Moisture contents (% by weight)	2.16	0.344
Loss on ignition (g/cm3)	3.67	1.05
pH	11.12	12
SiO_2	50.20	20.70
Al_2O_3	1.02	5.75
Fe_2O_3	14.23	2.50
CaO	5.45	64.00
MgO	0.09	1.00
MnO	5.60	0.05
Na_2O	0.07	0.02
K_2O	9.57	0.06
P_2O_5	0.56	0.15
SO_3	0.58	2.75

2.2.3 Aggregates

The particle size distribution of aggregates is characterized by grading curves. The pro-portion in mass of the individual particle sizes can be determined as a percentage of the total mass with sieves of varying mash or hole widths (Kaintzyk, et al., 2003). Raheem (2012) used Sharp sand as fine aggregates and granite with maximum size of 20 mm as coarse aggregates. The fine and coarse aggregates used were obtained from a local supplier in Ogbomoso, Nigeria. The grading details were as represented in Figure 2.2 (a) and (b).



a) Fine aggregates



b) Course aggregates

Figure 2. 2: Particle size distribution curve for aggregates (Raheem, et al., 2012)

Chowdhury (2015) reported that normal weight graded natural sand having a maximum particle size of 4.75 mm and specific gravity of 2.6 were used as fine aggregate. Properties of sand are presented in Table 2.7 and its size distribution is according to requirements of concrete aggregates (ASTM, 2018). The coarse aggregate used were crushed gravel with mean size of 10 mm and having bulk specific gravity 2.6.

2.2.4 Water for mixing and Curing purposes

Mixing water is added to the concrete during the mixing procedure. Drinking water and water from any other source not adversely affecting the essential properties of the concrete can be used. Water containing oil, grease, sugar, dust, humus or peat is not suited as water from mineral sources (BS EN1008, 2002).

Table 2. 7: Grading and properties of fine aggregates (Chowdhury, et al., 2015)

Sieve size (mm)	% Passing	Limits of specifications ASTM C33/C33M-08
9.5	100	100
4.75	98	95-100
2.36	92	80-100
1.18	84	50-85
0.60	57	25-60
0.30	23	5-30
0.15	3	0-10
Properties	Results	
Bulk specific gravity	2.62	
Absorption (%)	0.70	

Table 2. 8: Consistency and setting time of SDA-cement pastes (Elinwa & Mahmood, 2002)

Ash (%)	W/C	Soundness (mm)	Initial setting time (min)	Final setting time (min)
0	0.32	0.70	116	241
5	0.32	0.75	118	247
10	0.34	1.00	128	267
15	0.35	1.15	135	283
20	0.37	1.25	160	298
25	0.39	1.30	170	318
30	0.42	1.45	190	337

Table 2. 9: Workability of concrete with SDA (Elinwa & Mahmood, 2002)

Ash (%)	Slump (mm)	Compacting factor
0	80	0.95
5	75	0.94
10	60	0.93
15	58	0.93
20	54	0.92
25	46	0.92
30	40	0.92

Table 2. 10: Compressive strength for concrete mix with SDA (Elinwa & Mahmood, 2002)

Ash (%)	Compressive strength (MPa)			
	3 days	7 days	14 days	28 days
0	16.4	17.63	21.74	23.12
5	12.89	13.91	19.65	21.60
10	12.13	13.11	16.00	18.14
15	8.27	8.98	12.00	15.74
20	7.29	7.96	9.47	11.52
25	4.49	5.96	8.54	9.25
30	4.32	5.29	6.54	8.76

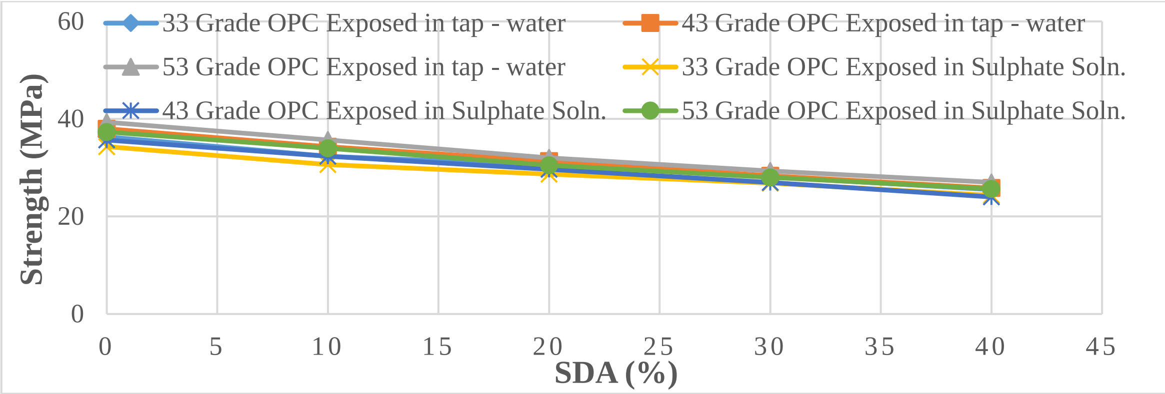
In their study William et.al., (2016) used OPC based concrete as a reference material shown in Table 2.11. The FA/GBFS samples were cured over 28 days at room temperature (26°C) under relative humidity (RH) values above 90%, and the OPC specimens were cured for the same period but totally immersed in water (100% RH). At a curing age of 28 days and before the samples were exposed to sulfates, their compressive strength, and capillary sorptivity were evaluated.

Table 2. 11: Component Amount per m^3 of concrete (William., et al., 2016)

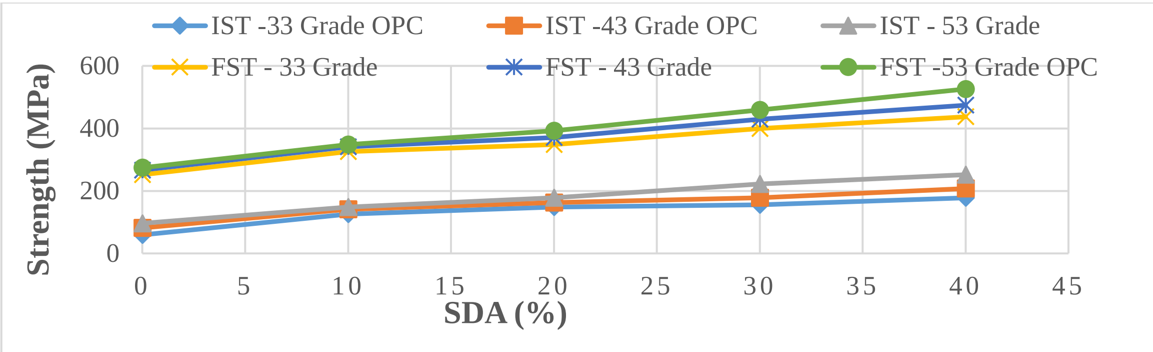
Mixtures	OPC (kg)	FA (kg)	GBFS (kg)	NaOH (kg)	SS (kg)	Sand (kg)	Gravel (kg)	L/S ratio
Control (OPC)	400	-	-	-	-	972.72	704.39	0.48
GEO FA/GBFS)	0	320	80	28.55	158.37	972.72	704.39	0.48

2.3 Durability/Acidic Environment Test

In their study, Buenfeld and Newman (1984) used a standard sodium sulphate (Na_2SO_4) solution to evaluate the resistance to sulphate attack on well-cured mortar specimens of varying cement grades after 28 days while Marthong (2012) used an enhanced sulphate salt concentration to simulate as high as eight times that of average salt concentration that of sea water. The specimen was alternately wetting and drying at 7 days' intervals then determining the strength loss as a result of sulphate exposure for 28 days for durability test (sulphate resistance). It was reported that the variation in compressive strength with SDA content for 28 days exposed in sulphate solution and tap-water are shown in Figure 2.3. The Figure demonstrates that, for each grades of cement the strength of ordinary cube and that partially replaced by SDA immersed in sulphate solution have less compressive strength than the corresponding referral cubes immersed in tap-water. Strength decreases as SDA contents increases. The decrease in cube strength exposed in sulphate solution over that exposed in tap-water are about 8% for ordinary cubes and that of 40% SDA content are about 10-20% for all grades of OPC. Thus, inclusion of SDA as partial replacement of cement seems that it does not improve the durability when exposed to sulphate environment. Comparing all the three grades of OPC, the strength loss seemed to be better for 53 grade OPC as compared to the other two grades.



a) Compressive strength of concrete



b) Setting time of Concrete

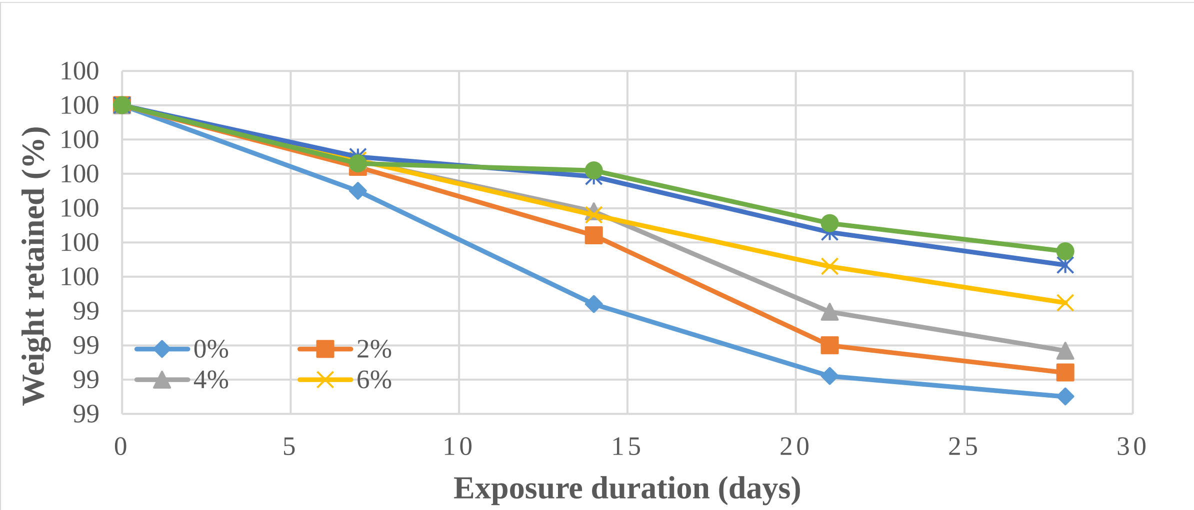
Figure 2. 3: Properties of concrete with SDA content (Marthong, 2012)

Important oxides content was 65.45% by weight of SDA and has a pH value of 11.12, which shows that it is alkaline in nature. This shows that SDA has a significant physical and chemical property that encourages its uses as a pozzolanas.

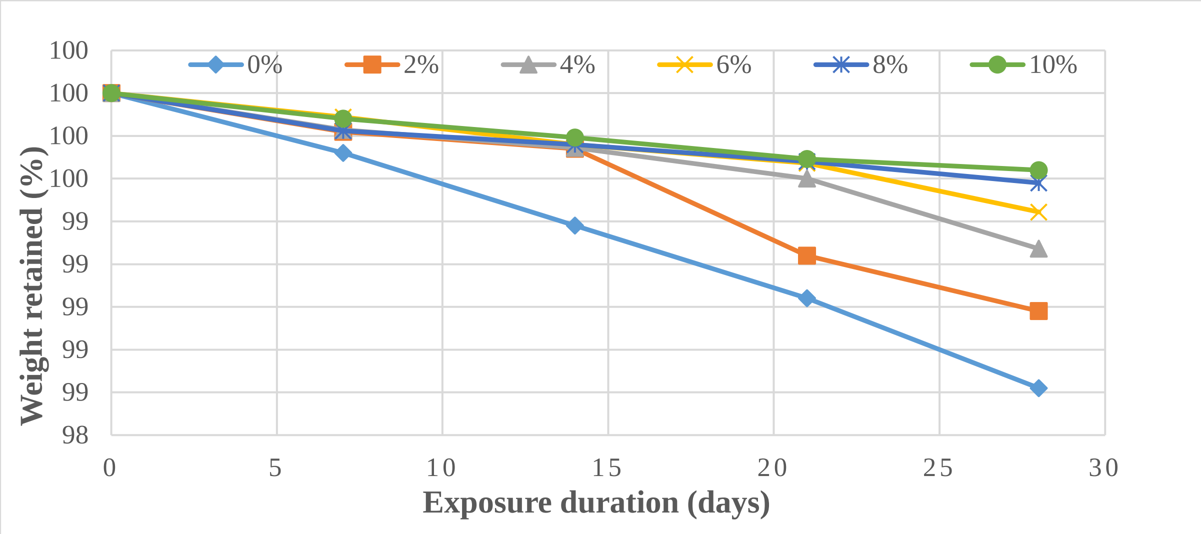
Setting times increased in all grades of OPC upon the addition of SDA but are in the range recommended for pure cement.

The workability decreased upon the inclusion of SDA. Thus, mixes containing SDA required higher water content than the corresponding conventional mixes. Compressive strength of concrete increases with grade of cement. Early strength development was observed to be about 50-60% of their 28 days' strength. Test results indicate that SDA concrete can attain the same order of strength as conventional concrete at longer curing periods. The rate of strength gain by SDA-33 grades OPC is lower as compared to 43 and 53 grades. However, study suggested the use of SDA as partial replacement of cement up to a maximum of 10% by volume in all grades of cement.

The study was carried out using crushed samples of the cube from the compressive strength test at 28 days curing for the six mixes (Ayuba, et al., 2014). Three pieces of crushed samples for each percentage addition of SDA were taken and weighed before exposure in 2.5% concentration of sulphuric acid (H_2SO_4) solution and hydrochloric acid (HCl) solution respectively. The test ran for 28 days with weight retained taken at 7 days' intervals. At the end of every 7th day, the samples were removed cleaned and left to dry before weighing to obtain the weight at the end of that regime. The behavior of SDA-Concrete resistance to acidic environment was determined in terms of weight retained and is shown in Figure 2.4 (a) and (b).



a) SDA concrete immersed in sulphuric acid solution

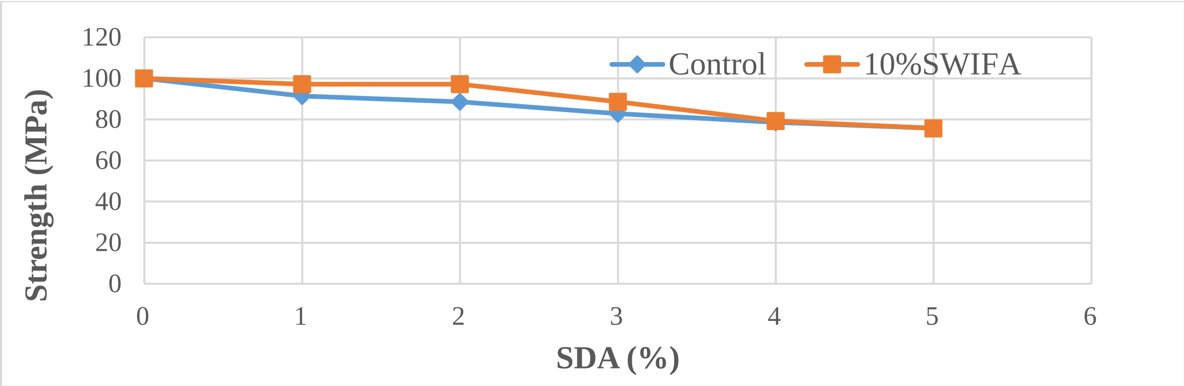


b) SDA concrete immersed in hydrochloric acid solution

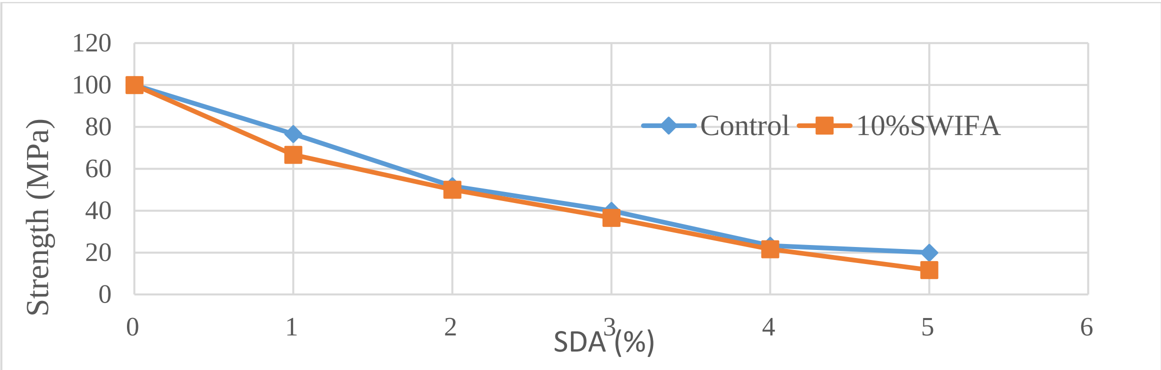
Figure 2. 4: Behavior of SDA- concrete in acidic medium (Ayuba, et al., 2014)

The weight of concrete retained decreased with increase in exposure duration but increased with increase in SDA content. There was minimal degradation in all cases tested in 2.5 % concentration of the acidic media. In case of the control mix there was about 1.0% reduction and less than 1.0% reduction in SDA concrete. It was reported that incorporating SDA in concrete improved its resistance against both sulphuric and hydrochloric acids. This is attributable to the reaction between lime and SDA and improved pore structure of the concrete due to the reduced permeability brought about by the SDA. The study concluded that SDA was not a good pozzalana as it decreased the slump, dry linear shrinkage, increased both initial and final setting time and the resistance of concrete to acidic environment.

Alanwa (2004) studied the effects of incorporating wood waste ash in concrete for resistance against corrosive action (durability test). Two types of corrosion tested were concentrated nitric acid and sulphuric acid both having a 20% concentration. A batch of concrete with wood waste ash used as a partial cement replacement level of 10% total binder weight and a corresponding batch of control concrete having similar mix proportion as the former but without wood waste ash content. Both specimens were immersed in both types of acid solution mentioned earlier. Their loss in mass was noted every week for total immersion up to 5 weeks. The resistance of concrete containing 10% of wood waste ash by total binder weight against corrosive action of nitric acid was observed to be higher than control concrete mix because loss in mass of wood waste ash concrete was less pronounced relative to the control concrete as can be seen in Figure 2.5 (a) and (b).



a) SWIFA mortar in nitric acid



b) SWIFA mortar in sulphuric acid

Figure 2. 5: Durability of SWIFA mortar cubes in 20% acid (Elanwa & Ejeh, 2004)

However, a 10% wood waste ash concrete mix was observed to have a lower resistance against the corrosive action of sulphuric acid in comparison to the control concrete containing only neat OPC as binder. This is due to higher loss in mass of 10% wood waste ash concrete as compared to OPC concrete when immersed in 20% sulphuric acid as indicated.

Figure 2.5 (a) shows that the mortar with SWIFA offered better resistance to deterioration by nitric acids than Portland - cement mortar. Figure 2.5 (b) shows that the effect of the sulphuric acid was very drastic both on the SWIFA mortar and Portland cement mortar. The rate of deterioration of the mortar cube in the nitric acid can be represented empirically by $y = a – bx$

– cx^2, where y is the weight (Kg) and a, b and c are coefficients. The values of the coefficients are 99.839, 1.7975 and0.6268 respectively. For such behavior the correlation factor (R^2) is 0.9585. The rate of deterioration of the mortar in sulphuric acid is exponential and can be represented by $y = ae^{-bx}$, where y is the weight (kg) and a and b are the coefficients with the values of 100.75 and 0.3422 respectively. X in the two equations is the percentage sawdust ash. The following conclusions were drawn from the study; Sawdust ash reacts with CH to produce C-S-H gel which improves the cement paste microstructure, delays the setting time, inversely correlated with the compressive strength, 10 % SWIFA content being the maximum. Required more water to attain consistent workability as opposed to the normal cement paste. Sulphuric acid adversely affected injected concrete as compared with nitric acid related by the empirical formula $y = a - bx - cx^2$ and $y = ae^{-bx}$ respectively in nitric and sulphuric acids.

William (2016) measured values of compressive strengths and capillary absorption coefficients of the 80/20 ratio of FA/GBFS alkaline-activated concretes and the control concrete specimens (OPC) after curing for 28 days and before their immersion in sulfate solutions are shown in Table 2.12. The FA/GBFS materials exhibited increased mechanical resistance by 35% and reduced capillary absorption by 44% compared to the OPC concretes. Figure 2.6 shows the evolution of the compressive strength in the concretes after their immersion in magnesium and sodium sulfate ($MgSO_4$ and Na_2SO_4) solutions for time frames as long as 360 days. The results obtained for the samples that were not immersed in a sulfate solution (FA/GBFS-Ref and OPC-Ref) are also included. Each reported result corresponds to the average measurement in at least three specimens per each immersion period and age; the deviation of results fluctuated between 0.4 and 6%.

Table 2. 12: Initial properties of concrete mixtures after 28 days of curing (William., et al., 2016)

Mixture	Compressive strength (MPa)	Capillary absorption coefficient (k, $kg/m^2s^{1/2}$)	Resistance to water penetration (m, s/m^2)
Control (OPC)	33.0 (s.d. 1.60)	0.0292	1.899
GEO (FA/GBFS)	44.6 (s.d. 0.44)	0.0162	3.242

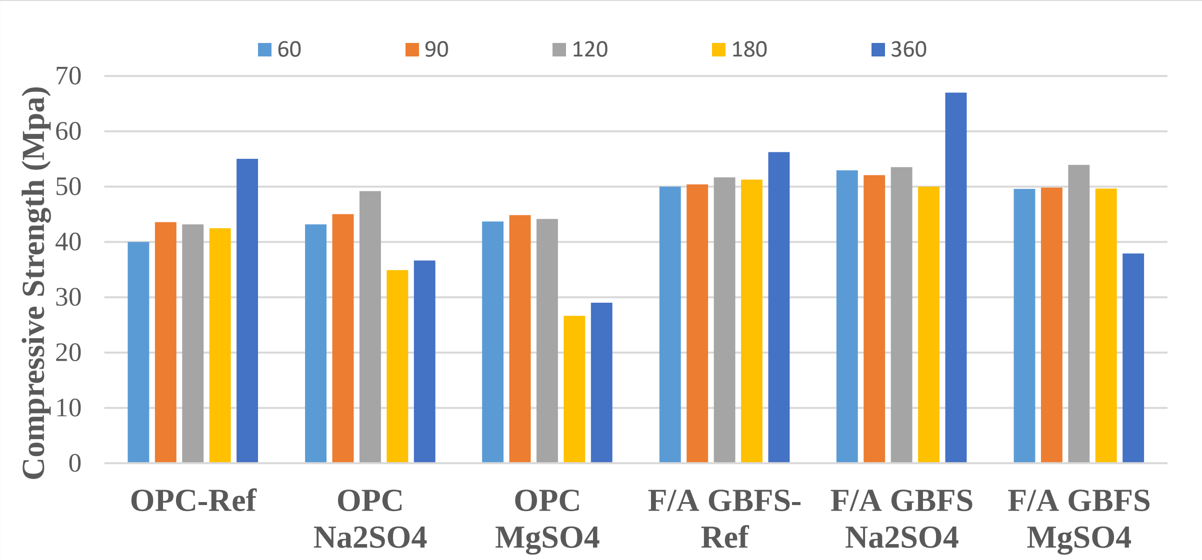


Figure 2. 6: Compressive strength of concretes exposed to $MgSO_4$ and $Na2SO_4$ (William., et al., 2016)

The results obtained in this study confirm that the evaluated geopolymer concrete (FA/GBFS 80/20) was less susceptible to attack by sulfates compared to traditional OPC concrete. Based on the sulfate solutions tested, magnesium sulfate promoted the greatest deterioration of the material, thus indicating its higher aggressiveness. This chemical attack led to a loss in mechanical properties due to the formation of new crystalline phases, particularly gypsum in the presence of magnesium sulfate.

Kaiwei (2018) reported that the pozzolanic reaction of fly ash also improved the pore structures and reduced the degree of super saturation of ettringite by preventing the ingress of external sulfate ions.

Wen (2013) reported that most coastal engineering or offshore structures were constructed by concrete. The coastal environmental factors cause great harm to concrete, with sulfate and chloride ions being the most. There are two types of sulfate attack: (1) reaction with alumina bearing hydration products and/or un hydrated Tricalcium Aluminate (C_3A) to produce ettringite; and (2) reaction with calcium hydroxide to produce gypsum. Gypsum is formed in low C_3A cement while ettringite is formed in high C_3A cement. A reduction in calcium hydroxide improves the durability of cement during sodium sulfate attack and limits gypsum and secondary ettringite formation. In addition, increased quantities of finely ground carbonates could increase the potential for thaumasite sulfate attack. It was concluded that Fly ash and slag can improve the durability of concrete, after 120-day curing, the chloride ion non-steady coefficient (M_n) of concrete added with 20% fly ash and 40% slag became 69% and 28% that of ordinary concrete.

It was reported that the use of specific mineral admixtures improved the resistance of the limestone cement concrete against sulfate attack. Fly ash blast furnace slag and metakaolin showed the best behavior, while natural pozzolana presented only a limited improvement of concrete's sulfate resistance (Karopoulou.S, et al., 2013)

Kaiwei et al (2018) reported that the lower CH content is accompanied by a reduction in the coefficient of compressive strength. The blended cement pastes in water, rather than the sodium sulfate solution, showed an obvious decrease in the CH content, which indicates that the pozzolanic reaction of fly ash can consume $Ca(OH)_2$ in the blend cement paste. As seen in the XRD and DSC-TG patterns, a larger amount of gypsum was detected in the PO, and the incorporation of fly ash reduced the formation of gypsum. The results obtained indicate that the addition of fly ash provides a proportional improvement in the resistance to sulfate attacks. Because the formation of ettringite is attributed to the expansion and cracks due to the crystallization pressure, gypsum formation is responsible for the decrease of Ca/Si ratio leading to the loss in strength.

In the current study, an assessment of the impact of partial cement replacement with sawdust ash in plastic and hardening Portland cement concrete was investigated using sulphuric acid solution, the average compressive strength of 3 concrete cubes after each exposure regime was established. Simulation of acidic environment as that encountered along Karuma – Lira Transmission Line, to plastic and hardening concrete designated as XA1 and XA2 was done in the Laboratory (BS EN206, 2013). An evaluation of the durability enhancement in terms of ingress of sulfate (SO_4^{2-}) ions into concrete was also conducted.

Available literature reveals a lot of work has been done in the area of sulfate attack on concrete with SDA being used to replace part of the OPC in concrete in the later stage of hardening (after curing for 28 days). This research work investigated the behavior of such concrete in the early and later stages of concrete hardening. That is to say, SDA/OPC concrete was exposed to sulfate attack, AX1 and XA2 in early stage of concrete hardening (6, 24 and 72 hours), and at the age of 28 days for the later stage of concrete hardening (after curing in a water tank at room temperature). Evaluation of the ingress of sulfate ions into various concrete grades.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The main purpose of the experimental set up at Kyambogo University was to assess the impact of sawdust ash (SDA) in plastic and hardened Ordinary Portland cement concrete in terms of improving its resistance to external SA. To assess this impact, concrete cubes of four different designed mixes were soaked in sulphuric acid solutions designated as XA1 and XA2 at the age of 6 hours, 24 hours, 72 hours and 28 days (BS EN206, 2013). Part of the cement in the concrete was replaced with SDA in proportions of 0%, 5%, 10% and 15% during the concrete batching. All concrete cubes were soaked in sulphuric acid solution for a period of 28 days. At the end of the 28 days of soaking, their weight and compressive strength were measured (BS EN12390, 2019). A powerful microscope was used to record images of the concrete before and after SA. In order to evaluate the ingress of deleterious sulfate (SO_4^{2-}) ions into subsequent concrete layers, 3 slices measuring about 15 mm from the edge of the soaked cube to the center were used as shown in Figure 3.2. The sliced concrete layers were pounded and their SO_4^{2-} content determined in accordance to (BSI, 1988) and compared with the un-soaked concrete. Concrete is a heterogeneous material that consists in a balanced mixture of aggregates made rigid by a binder composed of cement and water. When the material is subject to sulfate attack, the extent and the kinetics of the chemical reactions are strongly dependent on the mineralogical composition of the cement and on the amount of the individual reactant species within the material (Nicola, 2016)

3.2 Description of Study Area

It is noted that on most sites sulphate attack takes place when concrete comes into contact with soil which could be as early as 3 days when backfilling is done. In this study an assessment of the impact of cement replacement with SDA in ordinary Portland cement concrete before it reached final setting time with regards to the resistance to sulfate attack was done. That is to say, four different designed concrete grades were used with two sulphuric acid solutions XA1 and XA2 to simulate sulfate attack on concrete at various ages. The concentrations of the sulphuric acid solutions XA1 and XA2 were in accordance with (BS EN206, 2013). Setting concrete was exposed to sulfate attack within 6 hours, 24 hours, 72 hours and 28 days of mixing for a period of 28 days. Concrete cubes were crushed after 28 days in H_2SO_4 solution. Performance of the concrete was evaluated using compressive strength, variation in weight of cubes and ingress of sulfate ions (SO_4^{2-}).

3.2.1 Data collection instruments

The data collection instruments included; Digital Weighing Scale (1 µg precision), Slump Cone, Steel Tape Measure, Laboratory Thermometer, Hydrometer, Measuring Cylinder, Compression Machine, Funnel and Pipette, pH Meter and a High-Definition Digital Microscope (HD X1000).

3.2.2 Primary data source

The samples, materials and specimens prepared for the research study provided the primary sources of data including all laboratory test results for materials.

3.2.3 Secondary data sources

The secondary data sources included observations carried out from experiments on prepared samples, recorded test results, published previous research work. Other sources were the British Standard (BS), European Standards (EN), International Standards organization (ISO), Bureau of Indian Standard (BIS), ASTM International, East African Standards and Uganda standard.

3.2.4 Methods of data analysis

Statistical data methods of analysis were used, spread sheets, tabulation, bar graphs bar charts, curves as presented in Chapter Four.

3.3 Research design

The research work took an experimental design. This included all material tests on Water, Sand, Cement and SDA. Concrete mix design of four (4) grades of concrete C16/20, C20/25, C25/30 and C30/37 using the ACI method (ASTM International, 2002). Determination of Pozzolanic Activity Index (PAI), concrete slump test, and determination of the density of both fresh and hardened concrete. A total of three hundred eighty-four (384) concrete cubes with varying percentages 0%, 5%, 10% and 15% of OPC 42.5N replaced with SDA were cast. These were soaked in two simulated soil sulfate exposure classes XA1 and XA2 for the project (BS EN206, 2013).

3.3.1 Sample strategy

Concrete materials were collected from the geographical scope of the research area. A total of three hundred eighty-four (384) concrete cubes of four designed concrete grades with varying percentages 0%, 5%, 10% and 15% of cement replaced with SDA were cast. These were soaked in two simulated sulfate exposure classes XA1 and XA2 for the entire project (BS EN206, 2013). Tororo cement, CEM I 42.5N brand was used while the sawdust which was used to prepare the SDA was collected from the timber saw mills at Bwaise Industrial Area in the northern outskirts of Kampala Capital City, Uganda in East Africa.

3.3.2 Sampling strategy

Timber bio-mass waste which comes off as saw dust during timber processing was collected using gunny bags of hundred (100) kilograms from Bwaise Industrial Area. This was sorted to remove unwanted materials like plastic bottle tops, polyethene paper, wire nails etc. The saw dust was closely packed in metallic drums of two hundred (200) litres, modified to enable continuous oxygen flow during the first burning stage. An average temperature of 420 ^{o}C was attained and much of the carbon is burnt off during this stage. The ash comes off as a greyish loose powder of rough texture.

Table 3. 1: Limiting values for exposure classes for chemical attack from natural soil and ground water (BS EN206, 2013)

The aggressive chemical environments classified below are based on natural soil and ground water at water/soil temperature between 5 ºC and 25 ºC and water velocity sufficiently slow to approximate to static conditions. The most onerous value for any chemical characteristic determines the class. Where two or more aggressive characteristics lead to the same class, the environment shall be classified into the next higher class, unless a special study for this specific case proves that it is not necessary.

Chemical characteristics	**Reference test Method**	**XA1**	**XA2**	**XA3**
Ground water				
SO_4^{2-} mg/l	EN 196-2	≥ 200 and ≤ 600	>600 and ≤ 3000	> 3000 and ≤ 6 000
pH	ISO 4316	≤ 6,5 and ≥ 5,5	< 5,5 and ≥ 4,5	< 4,5 and ≥ 4,0
CO_2 mg/l aggressive	prEN 13577:1999	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
$NH4^+$ mg/l	ISO 7150-1 or ISO 7150-2	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^+ mg/l	ISO	≥ 300 and ≤ 1 000	> 1 000 and ≤ 3 000	> 3000 up to saturation
Soil				
SO_4^{2-} mg/kg total	EN 196-2b	≥ 2 000 and ≤ 3 000c	> 3 000 and ≤ 12 000	> 12 000 and ≤ 24 000
Acidity ml/kg	DIN 4030-2	> 200 Baumann Gully	Not encountered in practice	

[a] Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

[b] The test method prescribes the extraction of SO_4^{2-} by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of concrete.

c The 3 000 mg/Kg limit shall be reduced to 2 000 mg/Kg, where there is a risk of accumulation of sulfate ions in the concrete due to drying and wetting cycles or capillary suction.

The resultant sawdust ash was heated further using an electric Kiln at Uganda Industrial Research Institute (UIRI) at a temperature rate of 6 ºC/minute up to 900 ºC and maintained for thirty minutes, then allowed to cool. Screening through an 80 microns sieve to obtain the fine SDA for the research project. Concentrated sulphuric acid, H_2SO_4 was used with distilled water to simulate the two exposure classes, XA1 and XA2 for simulation of chemical attack on the concrete (BS EN206, 2013).

Reagents

- Distilled water
- Concentrated sulphuric acid

Specifications of distilled water

PH= 7.0

Specifications of Acid

Molecular weight = 98.08

Assay = 98.08%

Density = 1,880 g/l

Volume of stock solution for 1M standardization is 53 ml

Concentration (98.08/1000) = $98.08x10^{-3}$ mg/l

Volume of acid required for standardization of solution XA1

From BS EN 206-1:2013: 3000 mg/kg (for soil), mixing 40 liters of Distilled H_2O

Using $C_1V_1 = C_2V_2$ …………………………………………………………………………. (1)

$98.08\ x10^3 xV_{acid\ =}$ 3000x40; V_{acid} = 1.223 litres of standardized Acid solution

Volume of acid required for standardization of solution XA2

1 mole solution of H_2SO_4: 53 ml of Acid mixes 1 Litre of distilled H_2O for a standardized acid solution.

1.223 litres of standardized acid solution to mix 40 litres of XA1 solution requires → 1.223x53 ml of concentrated Acid = 64.845 ml of Acid.

XA2 Solution: (40 Litres)

Volume of Standardized Acid solution → $(1000x40)/98.08x10^3$ = 4.8939 Litres

Volume of acid required 53x4.8939 ml = 259.38 ml of concentrated Sulphuric Acid

3.4 Research approach

The research took both experimental and quantitative phenomenon, focusing on numerical variables; sulfate attack on concrete was initiated in the early stage of concrete hardening (at the age of 6, 24, 72 hours) and in the later stage of concrete hardening (at the age of 28 days). Variation of the amount of OPC replaced with SDA as 0%, 5%, 10% and 15% of the weight in concrete. Studying the performance of various grades of concrete, C16/20, C20/25, C25/30 and C30/37 in two different exposure classes XA1 and XA2. This involved a total of three hundred eighty-four (384) concrete cubes.

3.4.1 Water pH Value

3.4.1.1 Objective

The objective of the pH value test is to establish a measure of the acidity or alkalinity of the water on a scale reading from 0 to 14, on which 7 represents neutrality.

3.4.1.2 Reference Literature

- BS EN 1008: 2002

3.4.1.2 Significance

Gives a measure of acidity or alkalinity of water for concrete use, high or low pH can lead to corrosion/or spalling in concrete.

3.4.1.3 Apparatus

- Filtration funnel and stand
- Filter papers of a diameter to suit the funnel
- Three 500 mL glass conical beakers
- Two 250 mL conical beakers
- One 50 mL pipette
- Wash bottle, preferably made of plastics, containing distilled water
- filtered water to each of two clean dry 250 mL conical beakers
- pH meter, fitted with a glass electrode and a calomel reference electrode (which may be incorporated in one probe) covering the range pH 3.0 to pH 10.0. The scale shall be readable and accurate to 0.05 pH units.
- Three 100 mL glass or plastics beakers with cover glasses and stirring rods
- Two 500 mL volumetric flasks.
- 100 mL glass measuring cylinder
- Wash bottle, preferably made of plastics, containing distilled water.

3.4.1.4 Procedure

- From a sample of at least 500 mL of water two test samples were prepared as follows;
- Water was filtered through a filter paper into a clean flask, to remove any particles in suspension.
- The gravimetric method of analysis was used in this study, 50 mL of the filtered water were transferred to each of two clean, dry 500 mL conical beakers, and approximately 100 mL of distilled water to each was added.

3.4.1.5 Expected Results

Water for concrete should have a pH grater or equal to 4

3.4.2 Particle size distribution of Sand and Coarse Aggregates

3.4.2.1 Objective

To determine the particle size distribution of aggregates. These procedures included determining an appropriate blend of aggregates to produce a proper gradation of mineral aggregates.

3.4.2.2 Reference Literature

- BS 882: 1992

3.4.2.3 Significance

Gives the relative proportion of percentage of passing given sieve sizes to enable obtain the Fineness Modulus, Effective Size, Maximum Size of aggregates and uniformity coefficient. Quality control for conformity of fine and coarse aggregates.

3.4.2.4 Apparatus

- Test sieves with diameter 450 mm: 75 mm, 63 mm, 50 mm, 37.5 mm, 28 mm, 20 mm, 14 mm, 10 mm, 6.3 mm, 5 mm,

  Test sieves with diameter 300 mm: 3.35 mm, 2.36 mm, 1.70 mm, 1.18 mm, 825 µm, 600 µm, 425 µm, 300 µm, 212µm, 150µm, 75µm.
- Lid and receiver
- Balance readable and accurate to 0.5 g.
- A drying oven capable of maintaining temperature of 105 ℃ ± 5 ℃
- Riffle boxes
- Metal containers
- Metal trays
- Scoop
- Sieve brushes

3.4.2.5 Sample preparation

- The sample was reduced to produce a test portion of 2 Kg using a sample riffle box.
- Test specimen was dried by heating in the oven at a temperature of 105 ℃ ± 5 ℃ for 12 hours. Allowed to cool, weighed and its mass M_1 was recorded.

3.4.2.5 Procedure

- Appropriate sieves were assembled with a receiver at the bottom in increasing aperture size from top to bottom. The oven dried sample was placed on top of the coarsest sieve and were covered using a lid.
- Using hand shaking, sieves were agitated for sufficient times to separate the sample into different size fractions.
- Material retained on each sieve size was recorded, together with any material cleaned from the mesh.
- The mass retained on each sieve was recorded as a percentage of the original dry mass (M_1). The mass of sample passing each sieve was calculated as a cumulative percentage for the general relationship (Percentage passing this sieve) = (% Passing previous sieve) - (% retained on this sieve).

3.4.2.7 Expected Results

Well graded aggregates conforming to either Zone I or Zone II are acceptable for use in normal weight concrete.

3.4.3 Flakiness Index (FI)

3.4.3.1 Objective

Flakiness index is one of the tests used to classify aggregates and stones. In concrete mix design there are specific requirements regarding the flakiness index of materials. Flaky particles are considered undesirable as they may cause inherent weakness with possibility of breaking down under heavy impact and load.

3.4.3.2 Significance

Flaky particles may have adverse effects on the concrete, e.g. Flaky particles tend to lower the workability of a given concrete mix which may impair the long term durability.

3.4.3.3 References Literature

- BS 882: 1990

3.4.3.4 Apparatus

- A sample divider, riffle box.
- Drying oven with temperature of 105 ± 5°C.
- Balance – readable to1.0 g.
- Test sieves. (63mm,50mm,37.5mm,28mm,20mm,14mm,10mm and 6.3mm).
- Metal trays.
- A metal thickness gauge.

3.4.3.5 Sample Preparation

- The sample was reduced to produce a test portion 2 Kg.
- The test sample was washed and oven dried at 105 °C to 110 °C to substantially constant mass.
- The sample was allowed to cool and weighed to the nearest 1 g.

3.4.3.6 Procedure

- Sieve analysis of the sample was done using the sieves given above, discarding all aggregates retained on sieve 63 mm and all aggregates passing 6.3 mm sieve.
- Individual size- fractions retained on each of the sieves were weighed and stored on trays with their sizes marked on trays.
- From the sum of masses of fractions on the trays (M_1), the individual percentages retained on each of the various sieves were calculated, ignoring any fraction whose mass was 5% or less of mass M_1. The remaining mass M_2 recorded.

- Using thickness gauge each fraction was gauged. A selection of the gauge appropriate to sieve - fraction under test with each particle of that sieve - fraction separated by hand.
- All the particles passing each of the gauges were combined and weighed, M_3.
- The value of flakiness index is calculated from the expression: Flakiness Index, FI=$(\frac{M3}{M2})$x100%...(2)

3.4.3.7 Expected Results

- The flakiness Index of the aggregates shall not exceed 40%

3.4.4 Aggregate Impact Value (AIV)

3.4.4.1 Objective

Aggregate used for construction should be strong enough to resist crushing under loads.

The strength of aggregates may be measured in crushing or impact tests. The aggregate Impact Value (AIV) gives a relative measure of the resistance of an aggregate to sudden shock or impact.

3.4.4.2 Significance

To evaluate the toughness/resistance of an aggregate under impact loads.

3.4.4.3 References Literature

- BS 812: Part 112:1990

3.4.4.4 Apparatus

- Aggregate Impact Testing machine.
- Test sieves-14 mm and 10 mm, and woven wire 2.36 mm sieve.
- Cylindrical metal measure with internal diameter of 75 mm and an internal depth of 50 mm.
- Tamping rod, steel bar 16mm diameter and 600 mm long with both ends hemispherical.
- Sample divider e.g. a riffle box.

- Drying oven with temperature of 105 ± 0.5ºC.
- Balance – readable to1.0 g.
- Rubber mallet.
- Metal tray.
- Brush with Stiff bristles.

3.4.4.5 Sample preparation

- The sample was reduced to 8 Kg, to produce three test specimens of 14 mm to 10 mm size fraction.
- The entire dried sample was sieved on the 14 mm and 10 mm sieves to remove the over size and under size fraction.
- The resulting 14 mm -10 mm fraction of the sample was divided to produce three test specimens each of sufficient mass to fill the entire Cylindrical Metal Measure.
- The test specimens were oven dried at 105 ± 5℃ for not more than 4 hours. Then allowed to cool before testing.
- The Measure was filled to overflowing with aggregate. The aggregates were tamped 25 times evenly distributed blows of the rounded end of the tamping rod, each blow letting the tamping rod fall freely from about 50 mm above the surface of the aggregates.
- Surplus aggregates were removed by rolling the tamping rod across the container. The net mass of aggregates in the measure was recorded and the same was used for the second test specimen.

3.4.4.5 Procedure

- The impact machine was placed on the floor ensuring that it is rigid and the hammer guide columns were vertical. With the test specimen in the cup, it was fixed in position and compacted by 25 strokes with the tamping rod. The hammer height above the upper surface of aggregates was adjusted to 380 ± 5mm.

- The hummer was allowed freely fall on to the aggregate to achieve a total of 15 blows at an interval of not less than 1 second.
- The crushed aggregates were removed by holding the cup over a clean tray and hammering on the outside with a rubber mallet until the particles were sufficiently loose to enable the specimen to fall freely on the tray. A brash was used to remove the fine particles adhering to inside of the cup and underside of the hammer.
- The tray and aggregates were weighed, the mass of aggregates used record (M_1) to the nearest 0.1 g.
- The whole specimen in the tray was sieved using a 2.36 mm sieve until no further significant amount passed. The mass passing the sieve was weighed and recorded (M_2) to the nearest 0.1 g.
- The Aggregate Impact Value (AIV) was calculated and expressed as a percentage to the first decimal place for each test specimen from the following formula;

  AIV$=M_2/M_1*100$ (3)

  Where M_1= the mass of the test specimen (in grams). M_2 = the mass of material passing 2.36 mm sieve (in grams).

3.4.4.7 Expected Results

AIV is expected to be less than 25%.

3.4.5 Ten Percent Fines Value (TFV)

3.4.5.1 Objective

The Ten Percent Fines Value (TFV) gives a relative measure of the resistance of an aggregate to crushing under a gradually applied load. In concrete design there are specific requirements for the TFV of materials tested both dry and soaked.

3.4.5.2 Significance

The test is also known as the 10% Fines Aggregate Crushing Test- 10% FACT; it is done to obtain the force required to produce 10% of fine value of a given aggregate.

3.4.5.3 References Literature

- BS 812: Part 111: 1990

3.4.5.4 Apparatus

- A Steel Cylinder, open ended of nominal 150 mm internal diameter with Plunger and Baseplate.
- Test sieves – square-hole perforated-plate type of sizes 14 mm and10 mm, and a woven wire 2.36 mm sieve.
- Tamping rod, steel bar 16 mm diameter and 600 mm long with both ends hemispherical
- Compression Testing Machine, 500 kN capacity
- Cylindrical Metal Measure, with internal diameter of 115 mm and internal depth of 180 mm
- A sample divider, e.g. a riffle box
- Drying oven - with temperature of 105 °C ± 5 °C.
- Balance – min. 3 kg capacity readable to 1 g.
- Rubber mallet
- Metal tray of known mass
- Brush with stiff bristles.

3.4.5.5 Sample Preparation

- The sample was reduced to produce a test portion of 25 Kg, to produce three test specimens of 14 mm to 10 mm size fraction.

- The entire surface dry test portion was sieved on the 14 mm and 10 mm sieves to remove the oversize and undersize fractions.
- The resulting 14 mm – 10 mm fraction was divided to produce three test specimens each of sufficient mass such that the depth of the material in the Cylinder was approximately 100 mm after tamping.
- The test specimens were oven-dried at 105 ± 5°C for not more than 4 hours. Allowed to cool before testing and the mass of material comprising the test specimens was recorded.

3.4.5.6 Procedure

- The cylinder of the test apparatus was placed in position on the baseplate.
- The test sample was tamped in three layers; each layer being compacted by 25 strokes of the tamping rod evenly distributed over the surface of the layer.
- The tamping rod was dropped from a height of about 50 mm above the surface of the aggregate.
- Carefully levelled the surface of the aggregate and inserted the plunger so that it rests horizontally on this surface.
- The apparatus was placed with the specimen and plunger in position, between the platens of the compression testing machine. A force was applied at a uniform rate so as to cause a total penetration of the plunger in 10 min ± 30 s of approximately 20 mm for normal crushed aggregates
- The maximum force (f) was applied to produce the required penetration. The force was released and removed, the crushed material aggregate by holding the cylinder over a clean tray of known mass and hammering on the outside with the rubber mallet until the particles are sufficiently loose to enable the specimen to fall freely on to the tray.
- A brush was used to remove the fine particles adhering to the inside of the cylinder, the baseplate and the underside of the plunger.

- The weight of the tray and the aggregates were recorded and the mass of aggregate used (M1) was recorded to the nearest 1 g.
- The whole specimen in the tray was sieved using 2.36 mm sieve until no further significant amount passed. The masses of the fraction passing and retained on the sieves were weighed and recoded to the nearest 1 g (M2 + M3 respectively). The percentage of the material passing was calculated from $(\frac{M2}{M1})*100$……………………………(4) where M2 is the mass of the aggregate passing the 2.36mm sieve.
- Duplicate test was done on the second specimen of the same mass as the first specimen at the same force that gave a percentage fines value within the range 7.5% - 12.5%.
- Calculations, a force F (kN) was calculated, to the nearest whole number, required to produce 10% fines for each test specimen, with the percentage of material passing in the range 7.5% - 12.5%, from the following equation:

$$F = \frac{14\,f}{m+4} \qquad (5)$$

Where f is the maximum force (in KN).

m is the percentage of material passing the 2.36 mm sieve at the maximum force

3.4.5.7 Expected results

The minimum TFV_{dry} is 110 kN while the minimum TFV_{soaked} is 60% of the corresponding TFV_{dry}.

3.4.6 Relative density and water absorption of aggregates

3.4.6.1 Objective

The method was used for aggregates intended for concrete mixes. Relative density on saturated surface-dry basis was used for calculations in concrete mix design. Apparent relative density was used in production control to check if the density of the aggregate varied. Water absorption was used in the in concrete mix design calculations.

3.4.6.2 Significance

The specific gravity test gives a relative measure of the quality of an aggregate, while the water absorption test determines the water holding capacity of a given coarse and fine aggregate.

3.4.6.3 References Literature

- BS EN 12620:2013

3.4.6.4 Apparatus

- Drying oven with temperature of 105 ± 0.5°C.
- Balance –readable to 0.5 g.
- A wide mouthed glass vessel of 1.0 liter to 1.5 liters' capacity, with a flat ground lip and plane ground glass disc to cover it giving a water tight fit.
- Two dry soft absorbent cloths
- A shallow tray
- An airtight container large enough to take the sample
- A 5mm test sieve.
- Water free of impurities (e.g. dissolved air). Freshly boiled tap water cooled to room temperature was used.

3.4.6.5 Procedure

- the test sample was immersed in water in the glass vessel / jar for 24 hours. The vessel was agitated to remove entrapped air. This was achieved by rapid clockwise and anticlockwise rotation of the vessel. The vessel was filled by adding water and the plane ground disc was placed over the mouth so as to ensure that no air is trapped in the vessel. The vessel was dried and its weight recorded (Mass B).
- The vessel was emptied to allow the aggregates to drain while the vessel is refilled with water, sliding the glass disc into position as in step 1. The vessel was dried and its weight recorded (Mass C).

- The aggregates were dried by placing them on a dry cloth and gently surface dried with the cloth.
- The aggregates were spread out not more than one stone deep on the second dry cloth and left exposed to air away from direct sunlight all visible films of water were removed, but the aggregates still had a damp appearance. The weight of the aggregates recorded (Mass A).
- The aggregates were placed on the swallow tray in the oven to dry at 105℃ for 24 hours.
- The sample was allowed to cool in the air tight container and weight recorded (Mass D).
- Relative Density on an Oven –dry basis was calculated as below

Pd =D/A-(B-C) ………………………………………………………………………………. (6)

a) Relative Density on saturated and surface-dry basis.

Ps =A/A-(B-C) ………………………………………………………………………………. (7)

b) Apparent Relative Density.

Pa =D/D-(B-C) ………………………………………………………………………………. (8)

c) Water Absorption (% of dry mass).

Wabs = 100(A-D)/D ………………………………………………………………………. (9)

3.4.6.6 Expected Results

Water absorption shall not be less than 4 %, while the specific gravity should be greater than 2.65

3.4.7 Organic Impurities in Fine Aggregates

3.4.7.1 Objective

This test covers the determination of the presence of organic impurities in fine aggregates that are to be used.

3.4.7.2 Reference Literature

- ASTM C 33-2018

3.4.7.3 Significance

Organic impurities may interfere with the chemical reaction of hydration and may affect the strength of the mortar or the concrete where the aggregates are used.

3.4.7.4 Apparatus

- Glass Bottle-Colorless glass graduated bottle with approximately 350-470 ml capacity.
- Standard color solution-75 ml
- Fine aggregate level-130 ml
- NaoH solution level-200 ml
- Glass color standard-consist of five glass color standard mounted in plastic holder.

3.4.7.5 Sample Preparation

- Test sample mass of 450 g was measured from the large sample

3.4.7.6 Procedure

- Glass bottle was filled to approximately 130 ml level with the sample of fine aggregates to be tested.
- Sodium hydroxide solution was added until the volume of aggregates and the liquid, indicated after shaking is 200 ml.
- A stopper was put on the bottle and vigorously agitated and then allowed to stand for 24 hours.
- Determination of color value, after 24 hour standing period, the glass was filled with to 75 ml level with fresh prepared standard color solution.

- Color comparisons were made with the test sample and the bottle with the standard solution side-by-side.
- Observed whether the color of the supernatant liquid is lighter, darker or equal to standard color of the solution.

3.4.7.7 Expected Results

Lighter than standard colour

3.4.8 Concrete Slump Test

3.4.8.1 Objective

The objective of the slump test was to determine the workability and consistency of fresh concrete. This is the measure of relative fluidity or mobility of the concrete mixture.

3.4.8.2 Significance

The slump test gives a measure of the ease with which a given concrete mix may be placed into position in relation to its consistency.

3.4.8.3 References Literature

- BS 881: Part 102:1983

3.4.8.4 Apparatus

- Slump Mold-of galvanized iron or steel. The mold shall be in form of cut off cone with the following internal diameter,

  - Diameter of base 200 ± 2 mm
  - Diameter of top 100 ± 2 mm
  - Height 300 ± 2 mm
- Tamping Rod-Around, smooth, straight steel rod, with 16 mm diameter and 600 mm long.
- Rule, graduated from 0 mm to 300 mm at 5 mm intervals, the zero point being at one end of the rule.

- Scoop- of a size large enough so each amount of concrete obtained from the sampling receptacle is representative.
- Sampling tray
- Shovel

3.4.8.5 Sampling

- The sample was taken from the laboratory mix within 2 minutes of mixing the concrete and determination of the slump was instantly done.

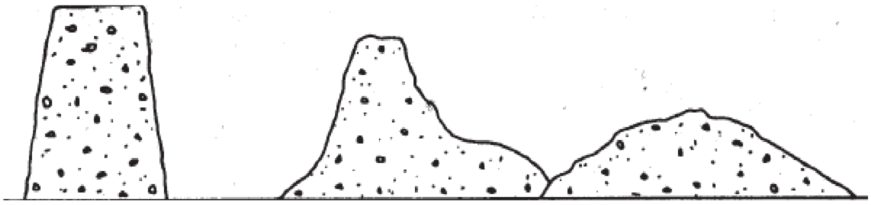
3.4.8.6 Procedure

- The inner surface of the mould was cleaned and kept damp. The bottom of the mould was placed on a clean, horizontal smooth steel plate.
- While firmly holding the mould, the sampled fresh concrete was filled within two minutes after mixing. The mould was filled in three layers, each approximately one third the volume of the mould.
- Each layer was tamped with 25 strokes uniformly over the cross section with the rounded end of the rod. For the bottom layer, this will necessitate inclining the rod slightly and making approximately half of the stroke near the perimeter, and then progressing with vertical strokes spirally towards the center. Each layer was tamped to its full depth.
- The concrete was hipped above the mould before the top layer is tamped. After tamping the top layer, concrete was struck off level with the top of mould with a sawing motion of the tamping rod.
- With the mould still held down, excess concrete found outside the mould was cleaned away.

- The mould was removed from the concrete by raising it vertically, slowly and carefully, in 5 to 10 seconds. The entire operation from filling the mould with concrete up to removal of the mould took about $2\frac{1}{2}$ minutes.
- Immediately after the mould was removed, the slump was measured to the nearest 5mm by using a rule to determine the between the height of the mould and the displaced original center of the surface of the specimen.

3.4.8.7 Expected Results

- The test is only valid if it yields a true slump. This being a slump in which the concrete remains substantially intact and symmetrical as shown in figure 3.1 (a)



(a) True slump (b) Shear slump (c) Collapsed slump

Figure 3. 1: Forms of slump (BS, 1992)

If the specimen shears as shown in Figure 3.1 (b) or collapses as shown in Figure 3.1 (c), take another sample and repeat the procedure.

3.4.9 Preparation of concrete test cubes

3.4.9.1 Objective

To establish the compressive strength of concrete in an acceptable manner.

3.4.9.2 Significance

To obtain regularly shaped concrete moulds of nominal size 100 mm and or 150 mm.

3.4.9.3 References Literature

- BS 1881: Part 116: 1983

3.4.9.4 Apparatus

- Mould of cast iron with removable base plate. The depth of the mould and the distance between the two pairs of opposite internal faces were maintained in the nominal size of 100 ± 0.15 mm and 150 ± 0.15 mm.
- Scoop
- Steel compacting bar weighing 1.8 Kg, 380 mm long and having a ramming face of 25mm square.
- Plaster's steel float
- Sampling tray
- Shovel

3.4.9.5 Sample Preparation

- A Sample of fresh concrete was obtained from the mix and thoroughly mixed before moulds were made.
- The moulds were placed on the floor. Concrete was filled in layers of approximately 50 mm deep and each layer compacted 35 strokes using a compacting bar evenly over the cross section of the mould.
- Concrete cubes were covered (in the moulds) with an impervious sheet and stored within the Laboratory, free of vibration at room temperature and about 90% humidity.
- After initial curing period of 24 hours, each cube was clearly marked for easy identification and removed carefully from the mould.
- Test cubes were soaked in a water tank kept within the Laboratory at room temperature and humidity.

3.4.9.6 Expected Results

The dimensions of the cube should not differ by 1% of its nominal value.

3.4.10 Concrete cube strength

3.4.10.1 Objective

All concrete design is based on a specific strength of concrete and this may vary from project to project but is usually in the range of 15 MPa – 50 MPa.

This procedure was used to determine the compressive strength of the concrete cubes. Concrete Strength is normally tested at an age of 7 days, 14 days and 28 days.

3.4.10.2 Significance

To give a measure of the compressive strength characteristics of already cast concrete.

3.4.10.3 Apparatus

- Compression Testing Machine
- Auxiliary platens
- A balance with minimum 10 Kg capacity accurate to 1 g.

3.4.10.4 Test Procedure

- The test specimen was weighed after removal from curing tank and their masses recorded.
- The dimensions were also measured and recorded their density was determined.
- The concrete cubes were then placed at the center of the lower platen of the compression-machine and the load applied at a rate of 0.2 MPa/sec.
- At the point of failure, the machine was stopped, the crushing load recorded and the compressed cube observed for the type of failure mode.
- Calculations, the ultimate compressive strength was obtained by dividing the crushing load by the cross-sectional area of the test specimen and the results expressed to the nearest 0.5 MPa.
- The average of the three tested concrete cubes was reported as the compressive strength of the test sample.

3.4.10.5 Expected results

The characteristic strength of the cubes at 28 days of normal curing shall not deviate by ± 5% of the designed compressive strength of any concrete grade.

3.5 Concrete Mix Design

The main objective of undertaking concrete mix design was to establish appropriate proportions of the various concrete constituent materials sourced from the geographical area of the research project, i.e., coarse aggregates, fine aggregates (sand), cement and water that would produce concrete mixes complying with the selected compressive strength required for the concrete after twenty-eight (28) days of curing. The outcome of the mix design was used to form the basis for decisions regarding the set of materials used for the research project.

Table 3.2 is an extract from BS EN206-1:2013.

Table 3. 2: Recommended limiting values (BS EN206, 2013)

	Aggressive chemical environments		
	XA1	XA2	XA3
Maximum w/c	0.55	0.50	0.45
Minimum strength class	C30/37	C30/37	C35/45
Minimum cement content (Kg/m^3)	300	320	360
Minimum air content (%)	-	-	-
Other requirements		Sulfate-resisting cement*	

*When SO_4^{2-} leads to exposure Classes XA2 and XA3, it is essential to use sulfate-resisting cement. Where cement is classified with respect to sulfate resistance, moderate or high sulfate-resisting cement should be used in exposure class XA2 (and in exposure class XA1 when applicable) and high sulfate-resisting cement should be used in exposure Class XA3.

Given the above information, the research work focused on four concrete mix designs C30/37, C25/30, C20/25 and C16/20. Grade C30/37 means the characteristic compressive strength of a concrete cylinder/Cube sample is 30/37 MPa respectively (BS EN1992, 2004).

3.5.1 Concrete mix design for grade C30/37

(a) Concrete designation/grade: C30/37

(b) Type of Cement: CEM I 42.5N, conforming to US EAS 18-1:2017

(c) Maximum nominal size of aggregates: 19 mm

(d) Minimum cement content: 300 Kg/m^3

(e) Maximum water-cement ratio: 0.55

(f) Workability: 75 mm – 100 mm (slump)

(g) Exposure condition: mild/moderate

(h) Method of concrete placing: manually placed

(i) Degree of supervision: good

(j) Aggregate type: crushed angular aggregate

(k) Chemical admixture type: Timber sawdust ash (SDA)

3.5.1.1 Choice of slump

The choice of slump was taken from ACI 211.1-91 reproduced below;

Table 3. 3: Recommended slumps for various types of construction (ASTM International, 2002)

Type of Construction	Slump (mm)	
	Maximum*	Minimum
Reinforced foundation walls and footings	75	25
Plain footings, caissons and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

*May be increased 25 mm for consolidation other than vibration

It was noted that the Quality Control and Quality Assurance (QA and QC) of the majority of local construction works is seldomly done or for the few sites where it was being done, it was never done to sastifactory levels. Also bearing in mind that the research work was focusing widely on sub-structure works including mass concrete for strip foundations, reinforced foundation walls and footings, ground beams, and building columns a slump of 75 – 100 mm was preferred for the research project.

3.5.1.2 Choice of maximum size of aggregates

Basically, the nominal maximum size of aggregates should be the largest that is readily avaible on the local market in terms of quantity and cost since these require less fillers. However, there were several limitations to the choice of nominal maximum size of aggregates that were used for thes research work. These included, method of placing and consolidating the concrete to ensure no segration, nature of rebar lay out for the intended structural concrete elements. In no event should the nominal maximum size exceed one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, nor three-fourths of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands (ASTM, 2018).

The research work used aggregates of nominal maximum size of 19 mm since they were readily vailable and used by the majority of population in the project area.

3.5.1.3 Estimation of mixing water

The concrete used was non-air entrained since the structures intended for the research work were not projected to be exposured to severe weathering. From ACI 211: 1-91: 2000, Table 3.4 is reproduced below. The estimated mixing water for non-air-entrained concrete mix using 19 mm nominal maximum size of aggregates and slump of 75-100mm is 205 Kg/m^3. Apart from the Sawdust Ash, the concrete was designed without other admixtures.

Table 3. 4: Approximate mixing water and air content requirements for different slump and nominal maximum sizes of aggregates (ASTM International, 2002).

Water, kg/m^3 of concrete for indicated nominal maximum sizes of aggregates								
Slump, mm	9.5	12.5	19	25	37.5	50	75	150
Non-air-entrained concrete								
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
Approximate amount of entrapped air	3	2.5	2	1.5	1	0.5	0.3	0.2

3.5.1.4 Determination of average compressive strength

Where concrete production is to be done in the absence of sizable data to be used as a basis for calculating sample standard deviation, S_s, table 5.3.2.2 of ACI 318-05 reproduced below as Table 3.5 was used. The average compressive strength calculated for grade C30/37 from the Table was 38 MPa.

Table 3. 5: Required average compressive strength when data are not available to establish a sample standard deviation (ASTM, 2004) converted to SI units

Specified compressive strength (MPa)	Required average compressive strength (MPa)
$f'_c < 20.68$	$f'_{cr} = f'_c + 6.89$
$20.68 \leq f'_c \leq 34.47$	$f'_{cr} = f'_c + 8.27$
$f'_c > 34.47$	$f'_{cr} = 1.10f'_c + 4.83$

3.5.1.5 Determination of water-cement ratio

The required water/cement (w/c) ratio was governed by the average compressive strength, durability and finish-ability of concrete. Appropriate value for the water/cement ratio for concrete grade, C30/37 was chosen from Table A1.5.3.4(a) of ACI 211: 1-91:2000 reproduced below as Table 3.6, the w/c ratio was interpolated between the values given in Table 3.6.

Table 3. 6: Relationship between water-cement ratio and compressive strength of concrete (SI) (ASTM, 2018).

Compressive strength at 28 days, MPa	Water-cement ratio, by mass	
	Non-air-entrained concrete	Air-entrained
40	0.42	-
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

The water-cement ratio for concrete of avarage compressive strength 38 MPa at 28 days of curing was determined as 0.44.

3.5.1.6 Determination of mass of cement

Using information from sections 3.5.1.3, 3.5.1.4 and 3.5.1.5 the required cement per unit volume of garde C30/37 concrete was calculated as follows; cement required (205/0.44) which gave 466 Kg/m^3.

3.5.1.7 Determination of mass of Coarse Aggregates

From the material test results, data for sieve analysis of the sand presentated in Appendix A.2 The Fineness Modulus (FI) of the sand was calculated;

$$FI = \frac{Sum\ of\ cumulative\ \%\ retained}{100} \quad \text{...(10)}$$

$$= \frac{0.2+0.2+4.2+29.6+81.9+92.8+95.6}{100} = 3.045$$

Using Table 3.8 reproduced from ACI 211.1-91: 2000 below;

Table 3. 7: Volume of Coarse Aggregate per unit volume of Concrete (ASTM International, 2002)

Nominal maximum size of aggregates (mm)	Volume of dry-rodded coarse aggregates per unit volume of concrete for different fineness moduli of the fine aggregate.			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

For less workable concrete such as required for concrete pavement construction they may be increased about 10 percent. For more workable concrete, such as may sometimes be required when placement is to be done by pumping, they may be reduced up to 10 percent.

With the calculated Fineness Modulus (FI) coupled with Table 3.6 above, for a fine aggregate having a fineness modulous 3.045 and 19 mm nominal maximum size of aggregates, the table indicates that 0.60 m^3 of coarse aggregates on a dry-rodded basis, may be used in each cubic meter of concrete. The required dry mass is therefore 0.60 x 1545 = 927 Kg.

3.5.1.8 Determination of mass of fine Aggregates

Using Table 3.8 below extracted from ACI 211.1-91:2000, the first estimate of the mass of a unit volume of fresh non-air entrained concrete made with aggregates having a nominal maximum size of 19 mm is estimated to be 2,345 Kg/m^3.

Table 3. 8: First estimate of mass of fresh concrete (ASTM, 2018)

Nominal maximum size of ggregate, mm	First estimate of concrete unit mass, Kg/m^3	
	Non-air-entrained concrete	Air-entarined concrete
9.5	2280	2200
12.5	2310	2230
19	2345	2275
25	2380	2290
37.5	2410	2350

50	2445	2345
75	2490	2405
150	2530	2435

Water requirements based on values for 75 to 100 mm slump in Table 3.3. If desired, the estimate of unit mass may be defined as follows if necessary information is available: for each 5 Kg diffrence in mixing water from Table 3.3 values for 75 to 100 mm slump, correct the mass per m^3 8 Kg in the opposite direction; for each 20 Kg difference in cement content from 330 Kg, correct the mass per m^3 3 Kg in the same direction; for each 0.1 by which aggregate specific gravity deviates from 2.7, correct the concrete mass 60 Kg in the same direction. For air-entrained concrete the air content for severe exposure from Table 3.3 was used. The mass can be increased 1 percent for each percent reduction in air content from that amount.

Masses already known are;

Water	205 Kg
Cement	466 Kg
Coarse Aggregates	927 Kg
Total	**1598 Kg**

The mass of fine aggregates, therefore, is estimated to be 2345 - 1598 = 747 Kg.

Water (net mixing)	205 Kg
Cement	466 Kg
Coarse Aggregate (dry)	927 Kg
Sand (dry)	747 Kg

The material test results indicated total moisture of 2 percent in the coarse aggregates and 7 percent in the fine aggregates. Trial batch proportions based on assumed concrete mass were used, the adjusted aggregate masses were calculated;

Coarse aggregate (wet) = 927(1.02) = 945 Kg

Fine aggregates (wet) = 747(1.07) = 799 Kg

Consideration was given to the surface water contributing to the mixing water and further adjustments were made for this; surface water contributed by coarse aggregates amounts to 2-0.5 = 1.5%, by the fine aggregates 7 - 0.7 = 6.3%. The estimated required water was; 205 – 927(0.015) – 747(0.063) = 144 Kg

The estimated batch masses for a cubic meter of concrete were;

Water (to be added)	144 Kg
Cement	466 Kg
Coarse aggregate (wet)	945 Kg
Fine aggregate (wet)	799 Kg
Total	2354 Kg

The laboratory trial batch was scaled down to 0.0388 m^3 of concrete to allow for all necessary tests on the concrete. Altough the calculated quantity of water to be added was 7.954 Kg, the amount actually used in an effort to obtain the desired 75 to 100 mm slump was 8.144 Kg. The batch as mixed consisted of

Water (added)	5.777 Kg
Cement	18.081 Kg
Sand	31.001 Kg
Coarse aggregates	36.666 Kg
Total	91.525 Kg

The concrete had a measured slump of 78 mm and unit mass of 2320 Kg/m^3.

The yield of the trial batch was 91.525/2320 = 0.0394 m^3 and the mixing water content was 5.777 (added) + 0.550 (on coarse aggregates) + 1.953 (on fine aggregates) = 8.280 Kg. The mixing water required for a cubic meter of concrete with the same slump as the trial batch was calculated as 8.28/0.0394 = 210 Kg.

According to table 3.7 above, the mass of water per cubic meter of conceret was corrected by 8 Kg to rise the slump from the measured 78 mm to desired 75 to 100 mm range.bringing the total mixing water to 218 Kg.

With the increased amount of water, additional cement was needed in oredr to keep the water – cement ratio of 0.44. The new cement content became 210/0.44 = 477 Kg.

The workability of the mix was found to be sastifactory, the quantity of coarse aggregate per unit volume of concrete was maintained the same as the trail batch. The amount of coarse aggregates per cubic meter; $\frac{36.666}{0.0393}$ = 933 Kg wet, $\frac{933}{1.02}$ = 915 Kg dry and 915 x 1.005 = 920 Kg SSD. The new estimate for mass of a cubic meter of concrete of the measured unit mass of 2320 Kg/m^3. The amount of fine aggregate required was therefore;

2320 – (218 + 477 + 920) = 705 Kg.

The adjusted basic batch masses per cubic meter of concrete were;

Water (net mixing)	218 Kg
Cement	477 Kg
Fine aggregate (dry)	705 Kg
Coarse aggregates (dry)	920 Kg

A similar procedure was used to deduce the material mix proportions for the other three concrete grades, C25/30, C20/25 and C16/20 and the summary of the calculations is shown in the table 3.9 below;

Table 3. 9: Summary of material proportions for various grades of concrete

Material Descrption (Kg)	Concrete Grade			
	C16/20	C20/25	C25/30	C30/37
Water	218	218	218	218
Cement	322	364	420	477

Water/Cement ratio	0.68	0.60	0.52	0.46
Sand	712	695	673	705
Coarse Aggregates	1,068	1,042	1,009	920

3.6 Determination of sulphate content of concrete

3.6.1 Objective

The of this test is to keep the amount of sulfate ions within the concrete in standard acceptable range. In order not to introduce excessive levels of these detrimental ions which could attack the concrete from within its matrix.

3.6.2 Significance

To determine the susceptibility of concrete to internal sulfate attack as these reactions may lead to cracking, spalling or strength loss of concrete structures in deleterious amount.

3.6.3 Reference Literature

- BS 1881-124:1988

3.6.4 Apparatus

- Weighing scale of 1 g accuracy
- A pair of tongs
- 400 mL glass beaker
- Two 100 mL glass beakers
- Filtration funnel and stand
- Two ceramic crucibles
- Riffle box
- Hammer mill
- Test sieves of sizes 150µm, 5 mm 2.5 mm and 600 µm complete

3.6.5 Sample preparation

- Concrete cubes were sliced in three identical slices of approximately 15 mm marking the outer slice as the 1st layer, the second inner slice as the 2nd layer and the third slice as the 3rd layer as shown in Figure 3.2.
- The analytical sample was subdivided to produce a sub-sample of 500 g.
- The sample was crushed to pass a 2.36 mm sieve and the reduced by two separate operations discarding one half on each occasion.
- The remaining sample was further crushed to pass a 600 µm sieve and the reduced by two separate operations discarding one half on each occasion.
- Further crushing was done on the sample to pass a 600 µm sieve and the reduced by two separate operations discarding one half on each occasion to obtain the final sample.

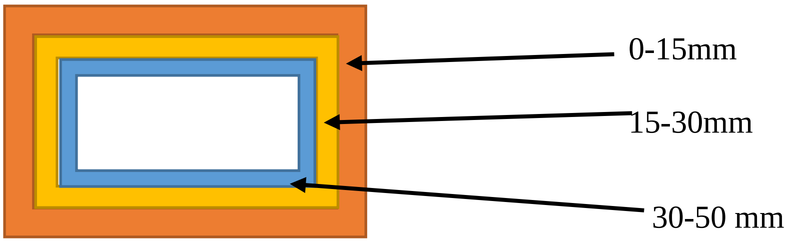


Figure 3. 2: Cube slicing for ingress of sulfate test

3.6.6 Test Procedure

- 5 g of the sample were weighed in a 400 mL Beaker.
- The solution was filtered through a medium ash less filter paper, washing the residue thoroughly with dilute hydrochloric acid.
- Three drops of methyl red indicator were added, the filtrate was heated gently for 5 minutes and kept just below boiling for 30 minutes.
- It was allowed to stand at room temperature for 24 hours
- The filter paper was burnt off in a weighed ceramic crucible at 800℃ in an electric furnace to constant mass.

Calculate the sulfate content G of the concrete expressed as SO_3 as a % of the cement to the nearest 0.1%;

$$G = \frac{L}{Md} \times 34.3 \times 100/C1 \quad (11)$$

Where;

M_d is the mass of the sample used (g)

C_1 is the cement content of the sample used (g)

L is the mass of ignited barium sulfate (g).

3.6.7 Expected Results

Sulfate content should be < 2000 mg/L

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This Chapter presents all experimental laboratory test results, their discussion and analysis done for the study. It was aimed at evaluating the impact of Sawdust ash (SDA) on the resistance to sulfate attack of fresh and hardening concrete. A total of 384 concrete cubes of four designed concrete mixes were used in two different sulphuric acid solutions of differing concentrations in accordance with standards to simulate sulphate attack on concrete using laboratory grade concentrated sulphuric acid and distilled water (BS EN206, 2013). In order to achieve sulphate attack, concrete cubes were soaked in sulphuric acid solutions after curing regimes of 6, 24 and 72 hours (early stages of concrete hardening) and after a curing regime of 28 days (later stage of concrete hardening).

4.2 Materials

4.2.1 Water

Water used for mixing concrete was tested for pH, Sulphate and Chloride content. This was done to ensure that the results were not influenced by external sources of chemicals. The test results are given in Table 4.1 The quality of the water met requirements for use in concrete (BS EN1008, 2002).

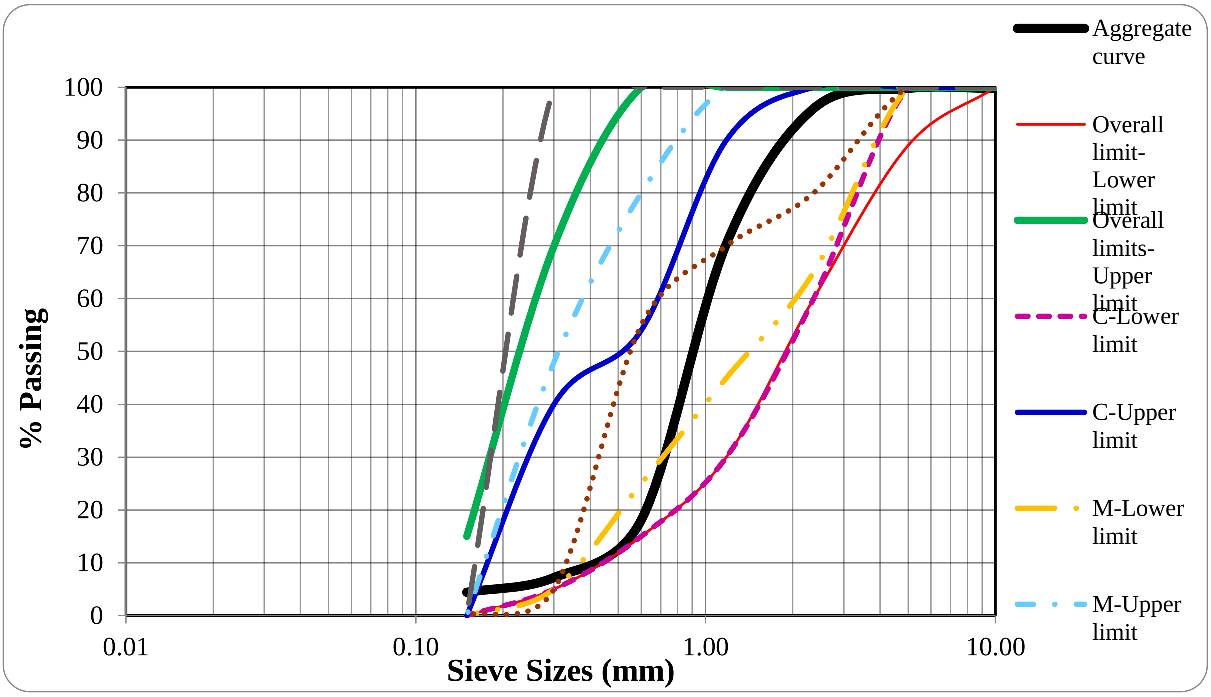
Table 4. 1: Summary of the laboratory tests on water samples

	Test Parameter	Unit	Result	Specifications (BS EN 1008)
1	pH		7.5	≥ 4
2	Sulphate Content	mg/L	0.002	≤ 2000

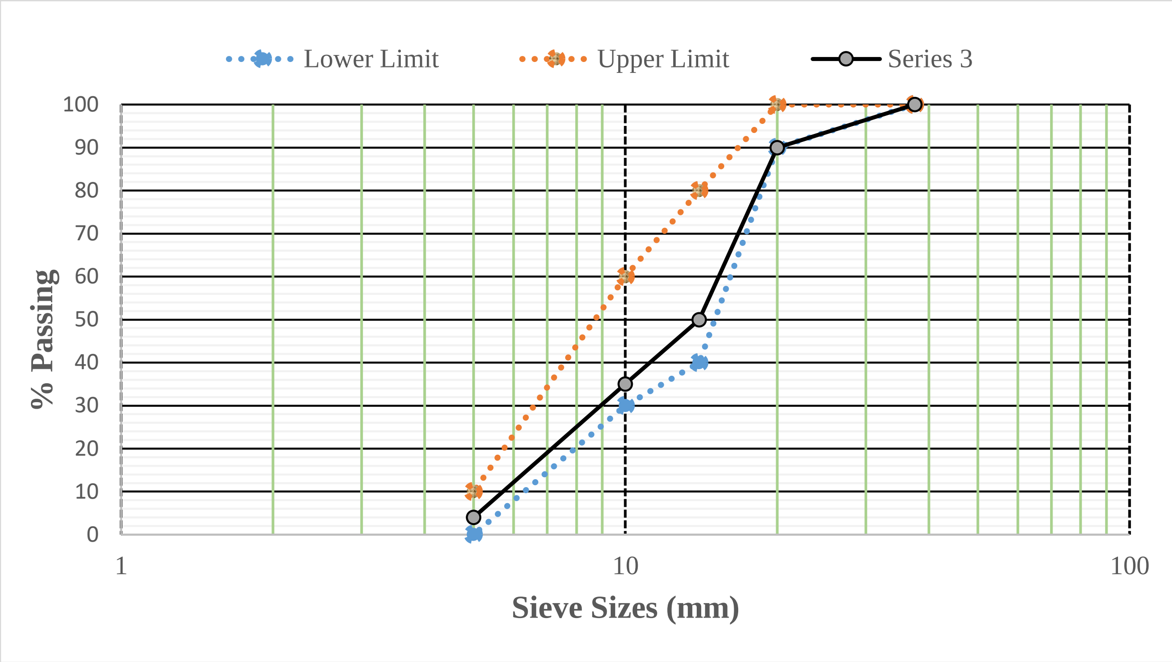
3	Chloride Content	mg/L	0.001	≤ 1000

4.2.2 Aggregates

Sieve analysis was carried out on coarse and fine aggregates as shown in Figures 4.1 (a) and (b) below and detailed in Appendices A.2 and A.3 respectively. All the aggregates were within the specification envelope and met the requirements of aggregates for use in concrete production



a) Fine aggregates



b) Coarse aggregates

Figure 4. 1: Gradation of aggregates

4.2.4 Cement/SDA

X-RF test was conducted on SDA and results are as shown in Table 4.2. The combined composition of Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3) and Iron oxide (Fe_2O_3) was 80.44% which is greater than the minimum value of 70 % specified in the Standards (ASTM, 2005). This clearly shows that SDA has pozzolanic properties and therefore can be used as a mineral admixture in concrete.

Furthermore, Uganda Standards (Uganda Standard, 2017) specify that fly ash with more than 25% Silicon dioxide (SiO_2) and having less than 10% reactive Calcium Oxide (CaO) is classified as Siliceous fly ash. Therefore, since SDA contains 6.74% reactive calcium oxide which is less than 10% it can be categorized as Siliceous fly ash. Other physical properties of SDA are shown in Table 4.3 with certified test certificates provided in Appendix A.5.

Table 4. 2: Oxide composition of OPC (Tororo Brand 42.5N) and SDA compared

Parameter	% Composition			
	OPC	Specification	SDA	Specification
Total SiO_2	20.05	-	52.31	-
Total Alkali –Na equal Ent	0.44	≤0.6	NR	0.756

Reactive SiO_2	-		35.61	>25
Al_2O_3	4.66	Max 8.0	23.41	-
Fe_2O_3	3.70	-	4.72	-
Reactive CaO	64.03	-	6.74	<10
MgO	2.08	Max 3.0	1.93	-
Na_2O	0.15	-	0.21	-
K_2O	0.44	-	0.83	-
SO_3	1.70	Max 3.5	0.02	NR

Low calcium SDA, which contains less than 10 percent analytic CaO is more efficient at binding the calcium than high calcium Sawdust ash because of a dilution effect. The SDA replaces the calcium rich Portland cement which consumes large quantities of calcium as it hydrates, whereas high calcium SDA both contributes and consumes calcium from the hydrating paste. This reaction between lime and SDA probably improves the pore structure of the concrete as its permeability is reduced.

Table 4. 3: Physical Properties of SDA compared with OPC compared

Parameter	OPC		SDA	
	Specification	Results	Specification	Results
Bulk Density (kg/L)	-	1.12	-	0.97
Moisture Content	-	0.02	-	0.53
Loss on Ignition (%)	5.0	3.52	7.0 Max	4.62
Specific Gravity	-	3.15	-	2.11
pH	-	NA	-	12.31
Blain (M^2/Kg)	-	327.6	-	415.8

4.3 Compressive strength results

A mix design of four different grades of concrete which included grade C16/20, grade C20/25, grade C25/30 and grade C30/37 were prepared. Grade C16/20 means that the characteristic compressive strength of a concrete cylinder/Cube sample is 16/20 MPa respectively (BS EN1992, 2004). Three samples of each of the different grades of concrete were prepared and exposed to different curing periods of 7, 14 and 28 days. The three samples were tested after curing and the average values obtained are shown in Figure 4.3 with more detailed information provided in Appendix A. 4. The factors for calculation of the target strength of concrete at 7 and 14 days mixed using CEM 42.5N cement with 20°C mean curing temperature were calculated as 77.88% and 90.16% of the characteristic strength of the concrete grade respectively (BS EN1992, 2004). The target strength of C16/20 concrete at the age of 7 and 14 days were calculated as 15.58 MPa (i.e. 77.88% X 20 MPa) and 18.04 MPa (i.e. 90.16% X 20 MPa) respectively. Therefore, it can be observed in Figure 4.1 that the target strength of concrete at 7 and 14 days was above 15.58 MPa and 18.04 MPa respectively. Similarly, all the concrete grades passed the minimum target strength at the age tested. The characteristic compressive strength at 28 days of the designed concrete was used as the baseline strength for SDA incorporated concrete.

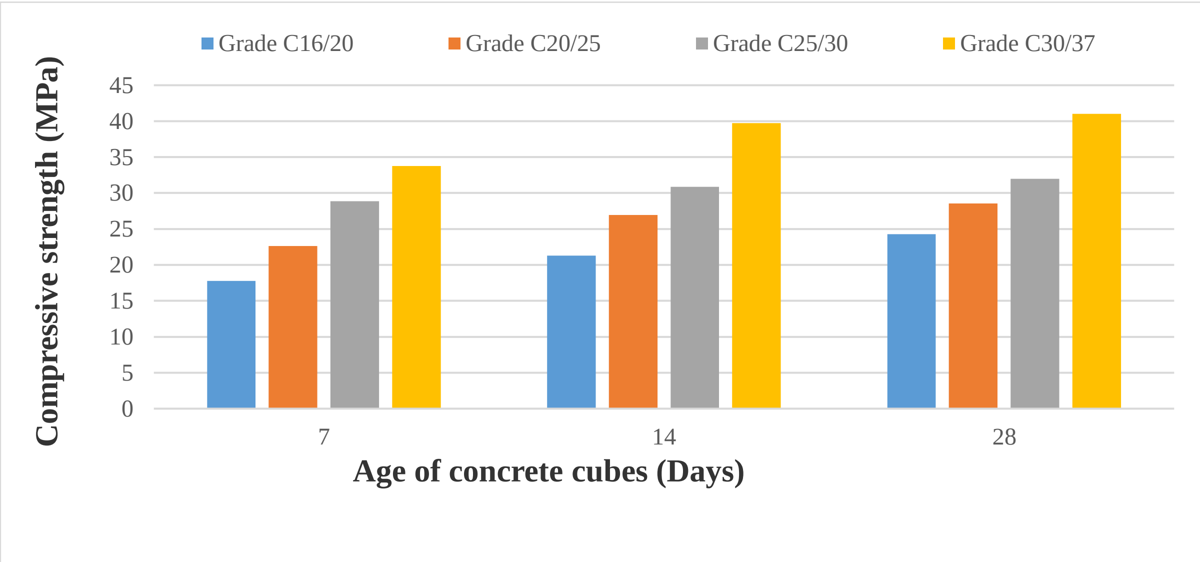


Figure 4. 2: Summary of Concrete Mix Design

4.4 Pozzolanic Activity Index

The pozzolanic activity index was established in accordance with (ASTM, 2018) using grade C16/20 concrete. C16/20 concrete was chosen in order to minimize the effect of the reactive silica from the cement hence focusing on the silica from the SDA since grade C16/20 had the lowest amount of cement. Six cube samples of C16/20 concrete were prepared with 3 of the samples containing 0% SDA content (control sample) and the other 3 samples containing 35% SDA content the results are shown in table 4.4.

Table 4. 4: PAI results for the SDA

Sample	% Replacement of OPC with SDA	Average Compressive Strength (MPa)
00-SDA	0	23.1
35-SDA	35	14.4

Pozzolanic Activity Index, PAI = $\frac{Average\ compressive\ strength\ of\ 35\%\ SDA\ concrete}{Average\ compressive\ strength\ of\ 0\%\ SDA\ concrete}$ =

$\left(\frac{14.4}{23.1}\right) x100\%$, PAI = 62.34%

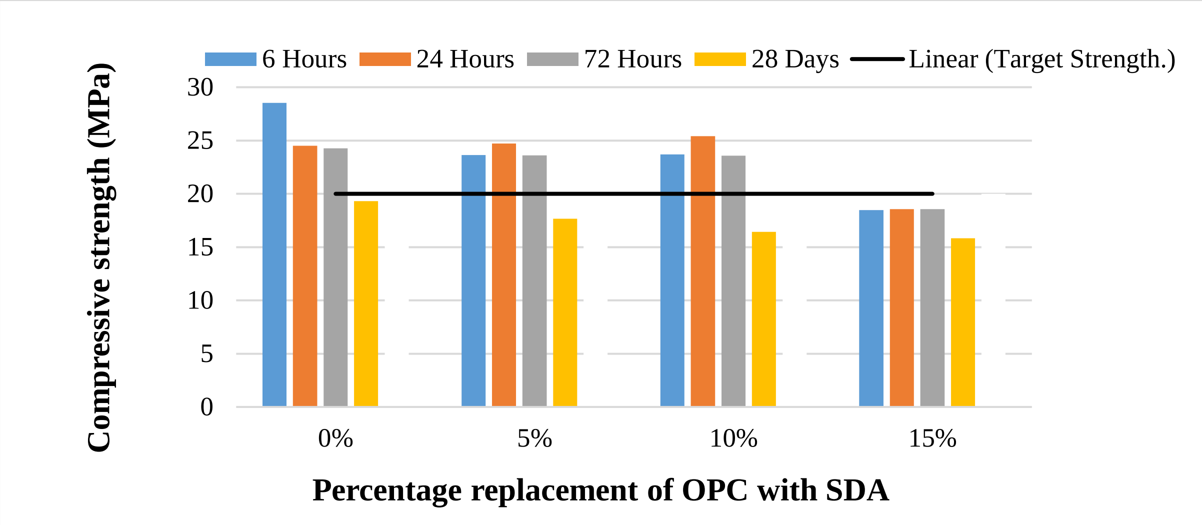
As shown above, PAI of 62.34% was obtained which is below the minimum specified value 70% (ASTM, 2018). Pozzolanic activity is a measure of the reaction rate between a pozzolan calcium hydroxide or other reactive metals in the presence of water as stated in Section 2.2.2. The fineness of cement is measured as specific surface. Specific surface is measured as the total surface area in square meters of all the cement particles in one kilogram of cement. The higher the specific surface, the finer cement will be. The SDA had a specific surface of 415.8 M^2/Kg which is much finer than the OPC which had a specific surface of 327.6 M^2/Kg its affinity for $Ca(OH)_2$ within the concrete was probably interrupted by Ca^{2+} ions from the cement. Hence the lower value of Pozzolanic Activity Index, 62.34% obtained for the SDA compared to the standard value of 70% .The SDA could be accepted for use in concrete since it met all other requirements for a siliceous fly ash (East African Standard, 2017).

4.5 Exposure of concrete to Sulphuric acid

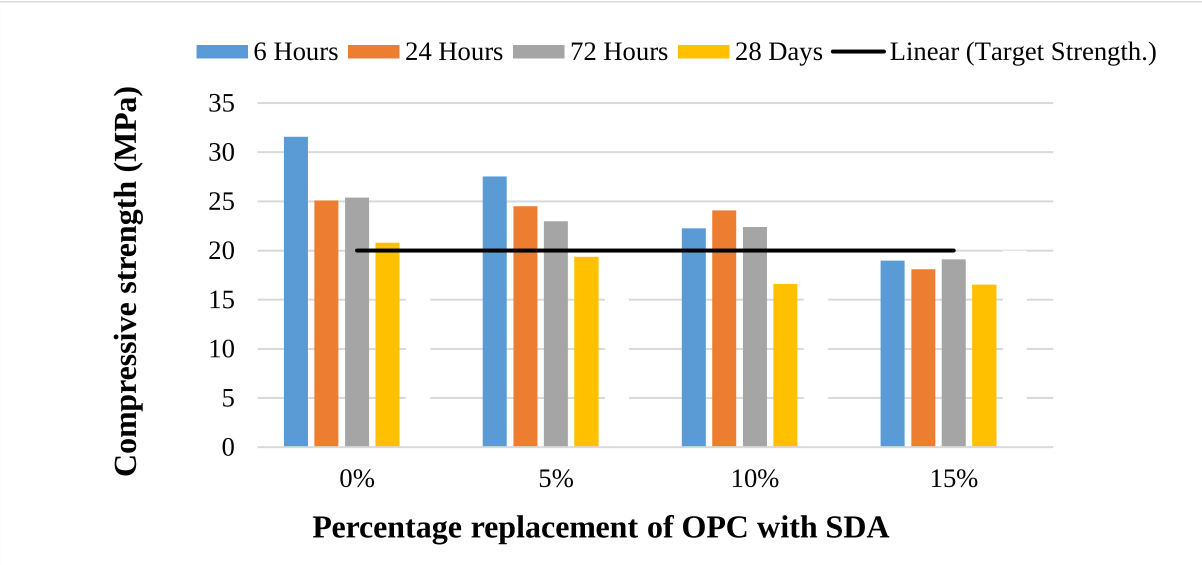
Different grades of concrete were exposed to varying concentrations of sulphuric acid in order to simulate the sulfate attack of concrete at an early stage (i.e. 6 hours, 24 hours and 72 hours) and late stage (i.e. 28 days) of hardening. Two sulphuric acid solutions designated as XA1 and XA2 (British Standard Institution, 2013) were used to soak all cubes for 28 days. In order to observe the effect of sulfate attack, a high definition (HDX1000) Digital Microscope was used to record images of concrete cubes before exposure to acid and after the exposure period.

4.5.1 C16/20 Concrete

Figure 4.4 (a) and (b) show the exposure to sulphuric acid solution of XA1 and XA2 respectively with varying percentage of replacement of cement with SDA and at different periods of exposure ranging from 6 hours to 28 days.



a) Solution XA1



b) Solution XA2

Figure 4. 3: C16/20 concrete behavior in acidic medium

As shown in Figures 4.3 (a) and (b) it can generally be observed that compressive strength decreased with increasing age at exposure with concrete samples exposed after 6 hours generally having higher strength values compared to those exposed after longer periods.

Furthermore, it was observed that concrete samples with higher percentages of cement replaced with SDA experienced lower strengths compared to those with low or no cement replacement. This is because of two types of SDA reactions that contribute to concrete strength. The first type of reaction is a "cementitious" reaction that takes place between the constituents of SDA and water. The C_3A, C_2S (from the cement) and reactive calcium aluminosilicate glass in the SDA reacts with calcium sulfate and calcium hydroxide to form calcium silicate hydrate, mono-sulfoaluminate and calcium aluminate hydrate according to the equations below;

$C_nA_mS_l$	+	CH	+	H	→	C-S-H(C-A-H)	
glass		calcium hydroxide		water		calcium silicate (aluminate) hydrate	

C_3A	+	3CS	→	$C_6AS_3H_{32}$	+	$2C_3A$	→	$3C_4ASH_{12}$
Tricalcium aluminate		anhydrite		ettringite		Tricalcium aluminate		mono sulphoaluminate

These reactions give the SDA a "self-cementing" property independent of the availability of external sources of reactive calcium. The second type of reaction which contributes to the strength of concrete is the "pozzolanic" reaction. A pozzolanic reaction is a reaction of silica, alumina, water and an external source of calcium to form calcium silicate hydrate and calcium aluminate hydrate all of which are binder compounds. The SDA is largely comprised of soluble aluminosilicate or calcium aluminosilicate glasses, and the hydration of ordinary Portland cement provides a source of calcium in the form of calcium hydroxide. Due to the slow solubility rate of glassy forms, the pozzolanic reaction is known to occur over a long period of time than the cementitious reaction. Therefore, pozzolans do not generally contribute to the early strength of concrete but substantially contribute to strength development in the long term. The presence of SO_4^{2-} ions in a chemically aggressive environment interrupts this reaction yielding expansive products that can lead to internal cracking of the concrete. This therefore lowers the compressive strength of concrete in the later stage of hardening as shown in Figures 4.3 (a) and (b).

4.5.1.2 Coefficient of Variation (CV)

Statistical methods of data analysis were used to quantify the impact of the age of SDA concrete in sulphuric acid media using Standard Deviation and the Coefficient of Variation. The Coefficient of Variation (CV) using the formula as shown in in equation (13) is a mathematical ratio of standard deviation to sample mean of a given data. Therefore, Coefficient of Variation is a measure of the disparity of the data from the sample mean. A smaller value of Coefficient of Variation indicates closer alignment of the data to the sample mean and vice versa. As shown in Figures 4.3 (a) and (b) and detailed in Appendix A.14 (Tables A.15 and A.16) concrete that failed the compressive strength test included all concrete in the later stage of hardening (i.e. concrete cured for 28 days before exposure to sulfate attack) and 15% SDA concrete. Emphasis was given to concrete that passed the compressive strength test and excluded all failed data for this analysis. Standard deviation (S) of the mean compressive strength of concrete after 28 days of sulfate attack together with the corresponding Coefficient of Variation (CV) were calculated using the design compressive strength as the sample mean. The Coefficient of Variation was calculated using formulas shown in equations (12) and (13). The results are shown in Table 4.5.

Standard Deviation (S) = $\sqrt{\frac{\sum_{i=1}^{n}(X_i-\overline{x})^2}{n-1}}$ ……………………………………………………(12)

Coefficient of Variation (CV) = $\frac{S}{\overline{x}}$ ………………………………………………………..(13)

Where: S = sample standard deviation

X_i = the observed values of the sample data

$\overline{x}$ = the sample mean value of the data n = number of observations

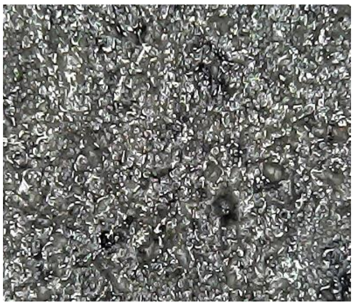
Table 4. 5: Coefficient of variation of compressive strength of C16/20 concrete after sulfate attack

Chemically Aggressive environment	Age of concrete at exposure to sulfate attack		
	6 hours	24 hours	72 hours
Solution XA1	0.13	0.04	0.03
Solution XA2	0.24	0.03	0.07

From Table 4.5 it can be observed that C16/20 concrete exposed to sulfate attack after 24 hours performed better in the stronger sulphuric acid media XA2 as compared to the other exposure period of XA1. This is probably as a result of the chemical interactions already discussed in section 4.5.1 above which are known for strength gain in concrete. These results imply that it is necessary to partially backfill C16/20 concrete structural elements (i.e. ground beams and pad footings) cast in chemically aggressive soils/environment at least 24 hours after casting for better performance.

4.5.1.3 Microscope images

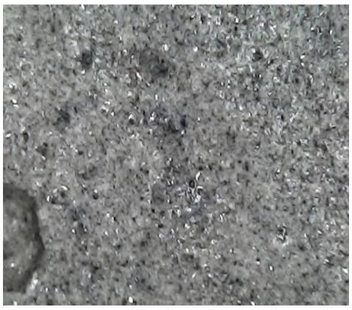
Figures 4.4 (a), (b), (c) and (d) show the Microscope images of C16/20 concrete cube surfaces taken before and after soaking in sulphuric acid solutions. Figures 4.4 (a) and (b) represent solution XA1 while Figures 4.4 (c) and (d) represent solution XA2.



Solution XA1

a) C16/20-0% SDA before

b) C16/20-0% SDA after



Solution XA2

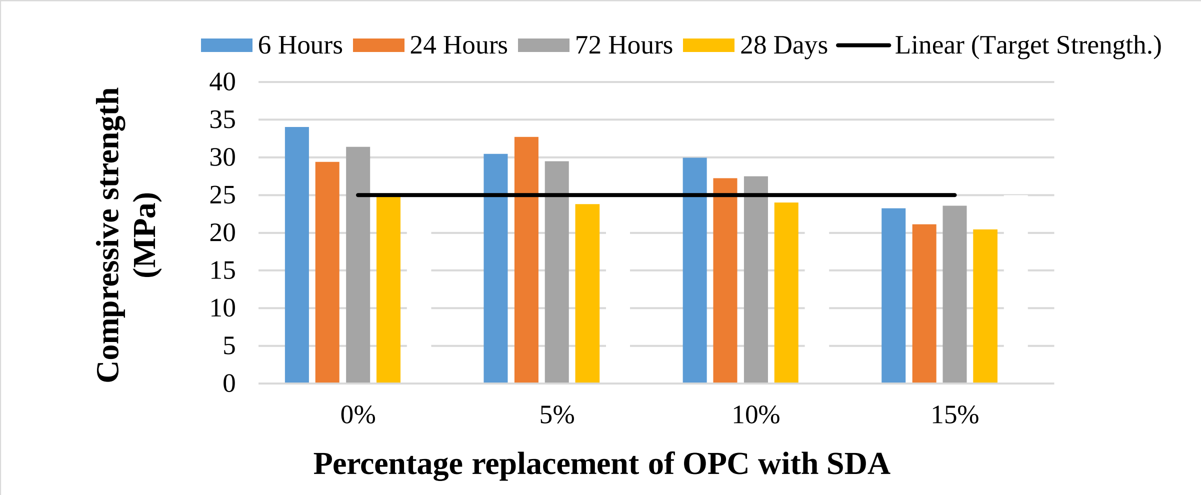
c) C16/20-5% SDA before d) C16/20-5% SDA after

Figure 4. 4: Surface scaling in concrete as a sign for initiated concrete failure

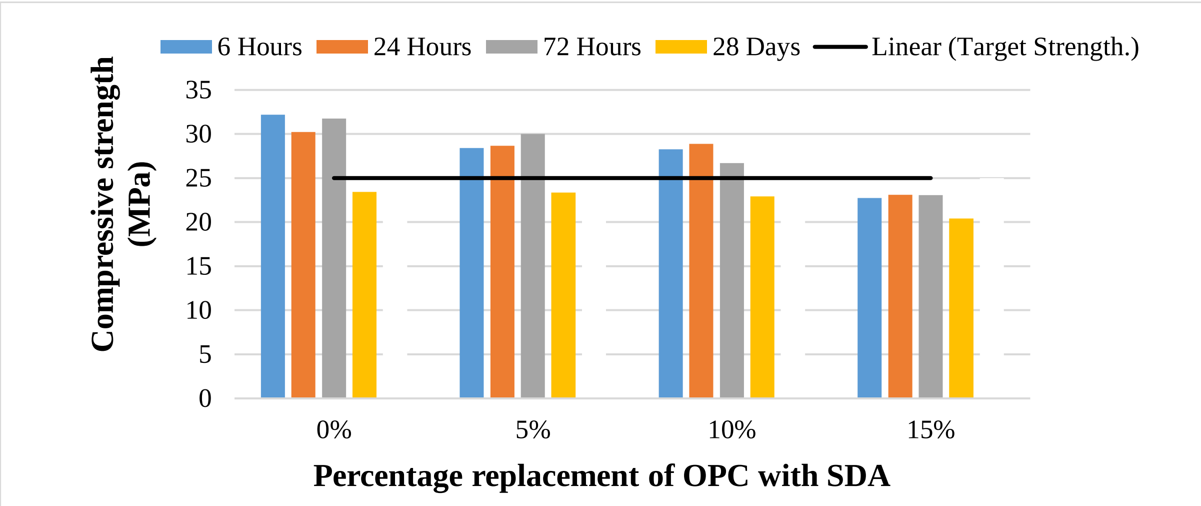
Chalking on the cube surface can be observed in Figures 4.4 (c) and (d). Both calcium Silcate hydrate and $Ca(OH)_2$ in powdery form appear as a whitish chalk on concrete surface in acidic media. This may be due to the degradation of the concrete in sulphuric acid solution XA2 being the strongest and hence presented more visible concrete chalking as is observed in Figure 4.4 (d). The yellowish rusty appearance observed in Figure 4.4 (c) is probably due to the mild acid stain of the concrete surface.

4.5.2 C20/25 Concrete

Figure 4.5 (a) and (b) show the exposure to sulphuric acid solution XA1 and XA2 respectively with varying percentage of replacement of cement with SDA and at different periods of exposure ranging from 6 hours to 28 days. As shown in Figures 4.5 (a) and 4.5 (b) it can generally be observed that compressive strength decreased with increasing age of concrete at exposure to sulfate attack, concrete samples exposed at 6 hours generally having higher strength values compared to those exposed after longer curing periods. Concrete in the later stage of hardening (i.e. age of 28 days) failed the compressive strength test. Similar observations of concrete in the later stage of hardening experiencing failure after sulfate attack were reported by Hardik (2017). Due to pozzolanic and cementitious characteristics of the SDA, calcium from the calcium hydroxide is bound in a stable C-S-H phase, hence decreasing the amount of reactive calcium remaining in the hardened concrete.



a) Solution XA1



b) solution XA2

Figure 4. 5: C20/25 concrete behavior in acidic medium

Calcium is present throughout the concrete in many forms. SDA used in the study had a fineness of 415.8 M^2/Kg as analyzed using the Air Blain apparatus and the results are presented in Table 4.3. SDA is expected to make the concrete less permeable while in its early stages of hardening, therefore the concrete may be less susceptible to sulfate attack by keeping the influx of sulfate ions to a minimum. Sulfate ions in the environment chemically react with the internal composition of concrete by entering into the concrete through diffusion, convection, capillary adsorption, and other processes to generate expansive products such as ettringite, gypsum and sulfate crystals when concrete is corroded by sulfate solution. The expansive products continuously fill the internal pores of concrete, thus making the concrete more compact with slightly improved concrete strength. Therefore, the early stage of corrosion increases the strength of concrete. Reactive silica in the glassy phase of the SDA consumes calcium hydroxide and water from the mortar matrix to form a stronger and less permeable concrete. In addition, the formation of C-S-H at later ages, or secondary C-S-H, may form a protective coating over crystalline phases containing reactive alumina such as mono-sulfoaluminate and calcium aluminate hydrates. Each of these effects contributes to greater sulfate resistance. On the other hand, continuous contact of sulphate with the pore walls of concrete in the later stage of hardening generates internal expansive stresses gradually. When the magnitude of the internal stress eventually exceeds the tensile strength of concrete, the concrete cracks, accompanied by the loss of tobermorite, the primary hydration product of concrete, the concrete then enters a degradation stage and undergoes strength deterioration. This phenomenon was observed for all concrete cured for 28 days before initiation of sulfate attack in both solution XA1 and XA2.

4.5.2.1 Coefficient of Variation (CV)

Similar procedure for obtaining the Coefficient of Variation (CV) provided for C16/20 concrete in section 4.5.1.2 was used to obtain the Coefficient of Variation for C20/25 concrete shown in Table 4.6. From Table 4.6 it can be observed that C20/25 concrete exposed to sulfate attack after 72 hours performed better in stronger sulphuric acid media XA2.

Table 4. 6: Coefficient of variation of compressive strength of grade C20/25 concrete after sulfate attack

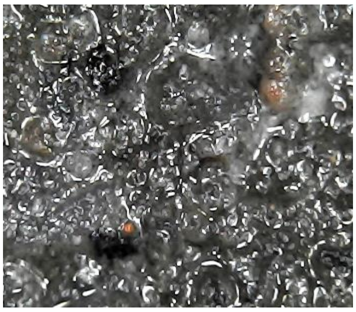
Chemically Aggressive environment	Age of concrete at exposure to sulfate attack		
	6 hours	24 hours	72 hours
Solution XA1	0.15	0.11	0.08
Solution XA2	0.09	0.04	0.01

Therefore, Coefficient of Variation is a measure of the disparity of the data from the sample mean. A smaller value of Coefficient of Variation indicates closer alignment of the data to the sample mean and vice versa. These results suggest that it is necessary to partially backfill C20/25 concrete structural elements (i.e. ground beams and pad footings) cast in chemically aggressive soils/environment after 72 hours of casting for better performance.

4.5.2.2 Microscope images

Figures 4.6 (a), (b), (c) and (d) show the Microscope images of C20/25 concrete cube surfaces taken before and after soaking in sulphuric acid solutions at the age of 6 hours. Figures 4.6 (a) and (b) represent solution XA1 while Figures 4.6 (c) and (d) represent solution XA2.

Solution XA1



b) C20/25-10% SDA before

b) C16/20-10% SDA after

Solution XA2

d) C20/25-10% SDA before

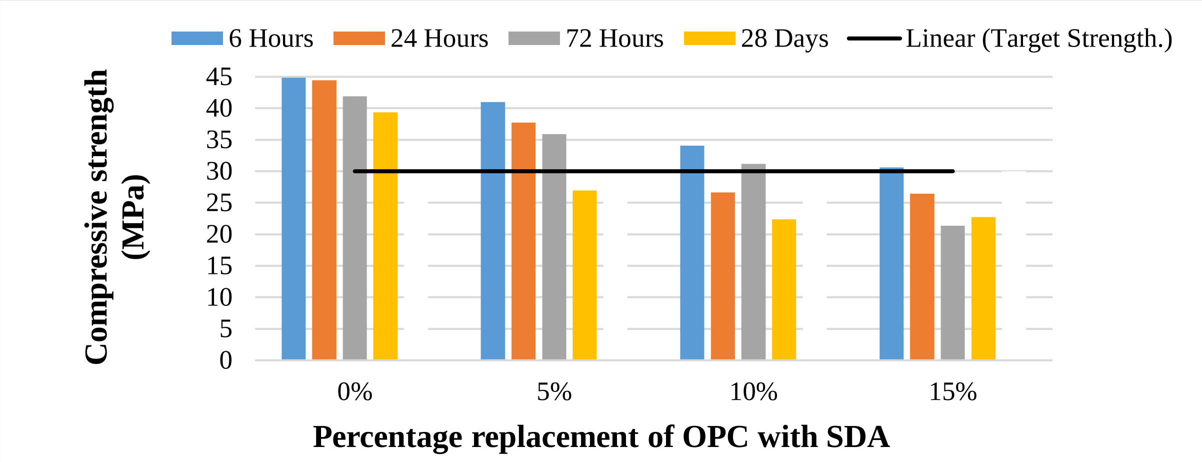
d) C20/25-10% SDA after

Figure 4. 6: Presence of calcium aluminate as a product of the chemical reaction that took place

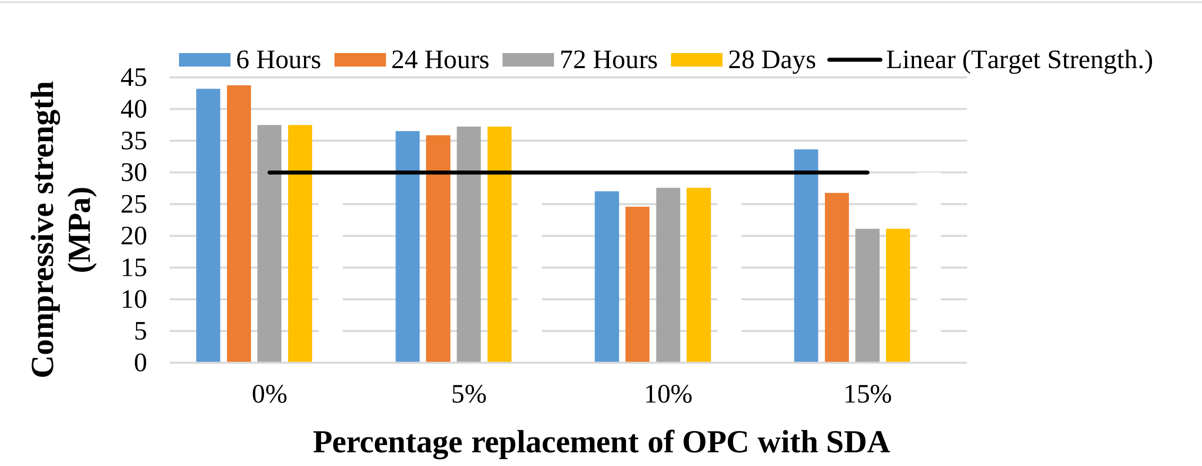
Similar explanation as stated in Section 4.5.1.3 for images observed. There is propagation concrete degradation due the chalking seen on the cube surface.

4.5.3 C25/30 concrete

Figures 4.7 (a) and (b) show the exposure to sulphuric acid solutions XA1 and XA2 respectively with varying percentage replacement of cement with SDA and at different periods of exposure ranging from 6 hours to 28 days.



a) Compressive strength after soaking in solution XA1



b) Compressive strength after soaking in solution XA2

Figure 4. 7: C25/30 concrete behavior in acidic medium

As shown in Figures 4.7 (a) and (b) a similar trend to that observed for C16/20 concrete explained in section 4.5.1 was experienced. However, there is an exception as observed in Figure 4.7 (b) for 5% OPC replacement with SDA for all curing regimes exposed in the stronger sulphuric acid solution XA2. The mean compressive strength of concrete increased by 12.8% from the design compressive strength after exposure for all curing regimes. This is an indicator that sulphate resistance was enhanced for C25/30 concrete with 5% SDA.

4.5.3.1 Coefficient of Variation

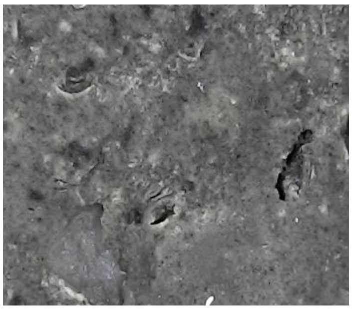
The coefficients of variation of compressive strength of C25/30 concrete presented in Table 4.7 showed a similar trend with the values obtained for C20/25 concrete presented in Table 4.6. The same phenomenon for the similar behavior of both C20/25 and C25/30 concrete as presented in section 4.5.2.1 can be drawn for the coefficient of variation of compressive strength. These results suggest that it is necessary to partially backfill C25/30 concrete structural elements (i.e. ground beams and pad footings) cast in chemically aggressive soils/environment after 72 hours of casting for better concrete performance.

Table 4. 7: Coefficient of variation of compressive strength of grade C25/30 concrete after sulfate attack

Chemically Aggressive environment	Age of concrete at exposure to sulfate attack		
	6 hours	24 hours	72 hours
Solution XA1	0.35	0.33	0.24
Solution XA2	0.29	0.32	0.27

4.5.3.2 Microscope images

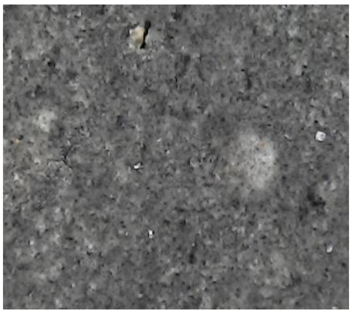
Figures 4.8 (a), (b), (c) and (d) show the Microscope images of C25/30 concrete cube surfaces at the age of 6 hours before exposure to sulfate attack.



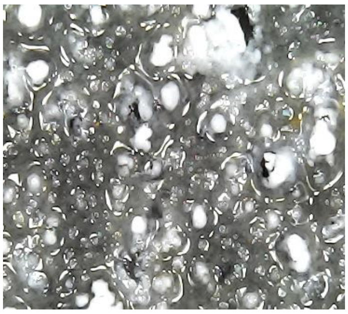
Solution XA1

c) C25/30-5% SDA before

b) C25/30-5% SDA after



Solution XA2



e) C25/30-10% SDA before

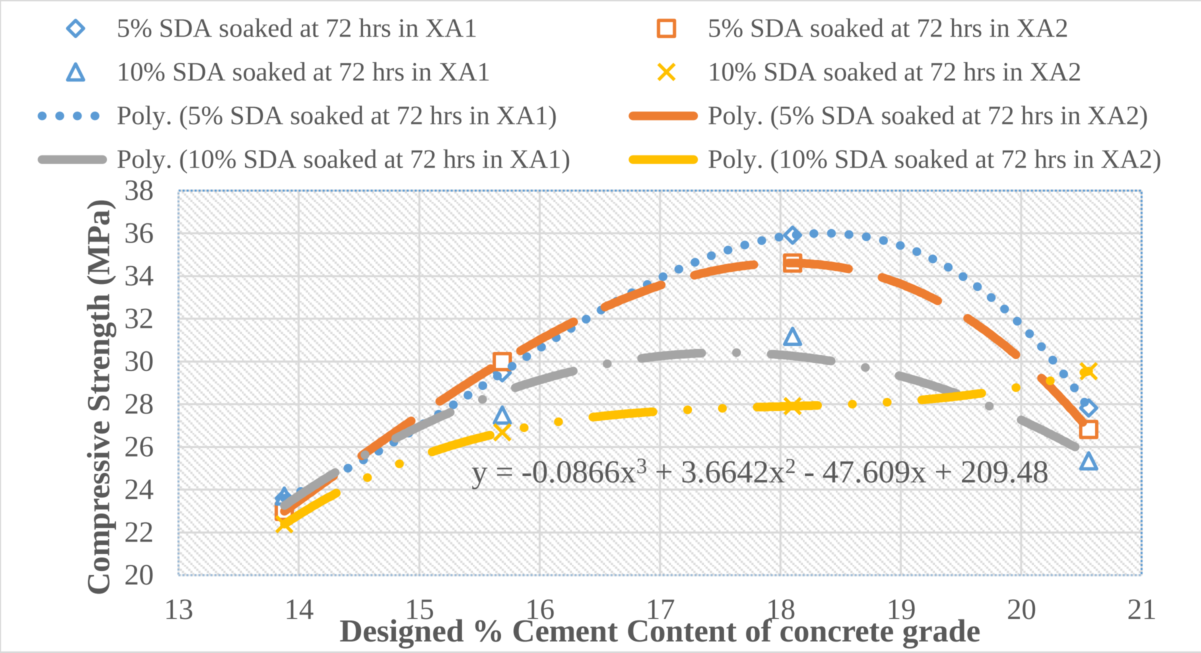
d) C25/30-10% SDA before

Figure 4. 8: Microscopic images showing surface scaling as a sign of initiated failure

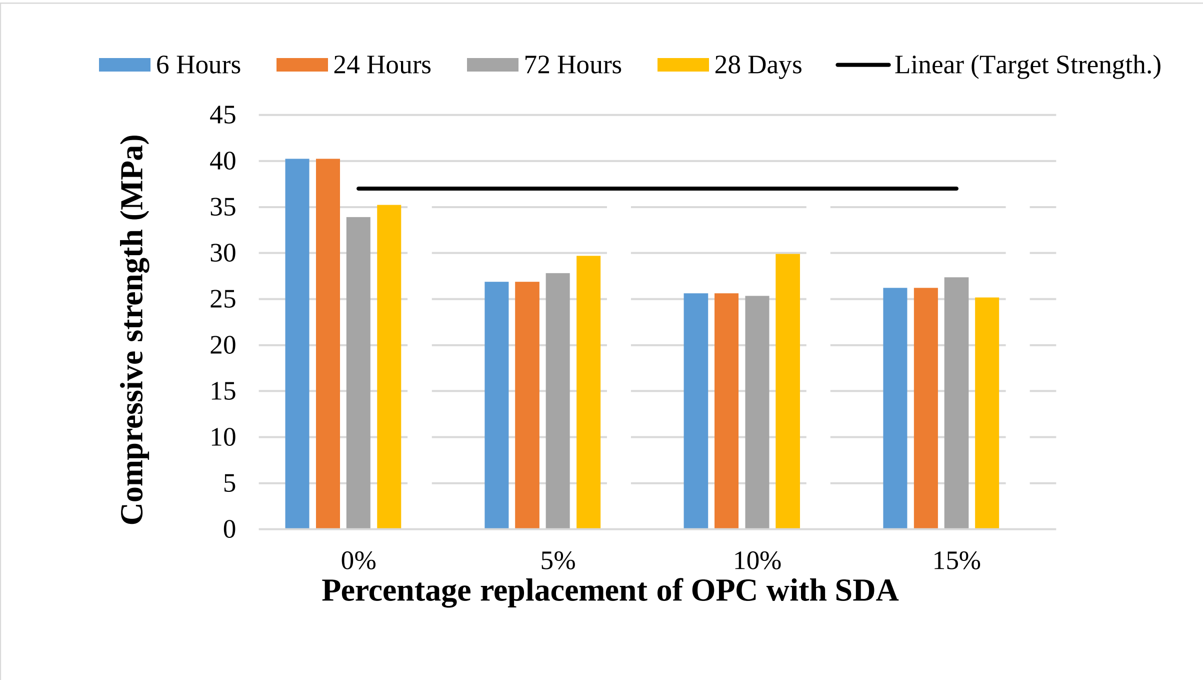
Similar explanation for the image in Figure 4.8 is drawn from Figures 4.6 and Figure 4.4 in Sections 4.5.1.3.

4.5.4 C30/37 Concrete

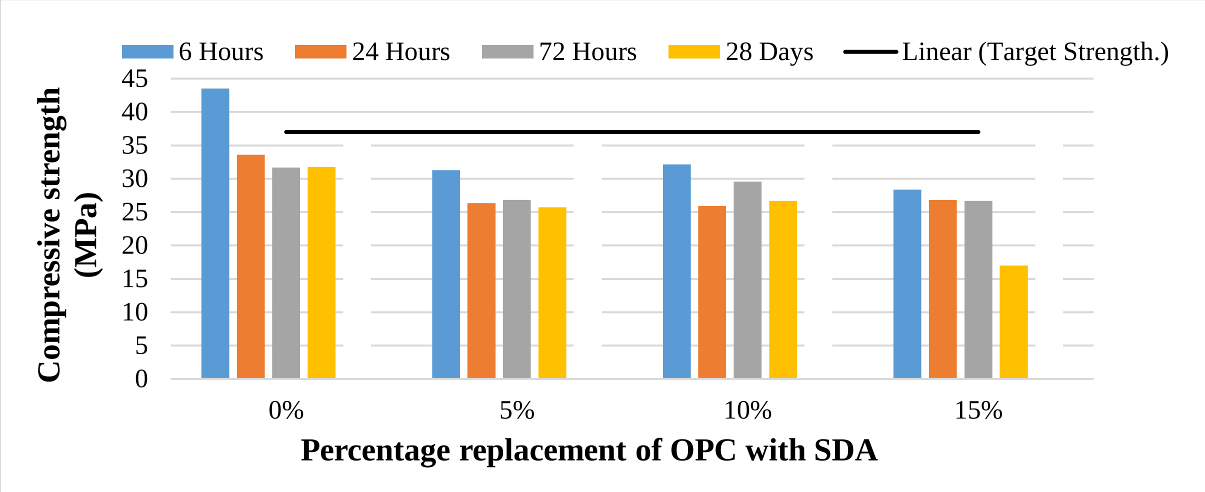
Figure 4.9 (a) shows the variation of compressive strength of SDA concrete with varying design cement content after soaking in sulphuric acid solutions XA1 and XA2. As shown in Figure 4.9 (a), the compressive strength continued to rise with increasing cement content of the concrete grade to an optimum value of 18.1% and then gradually decreased following a polynomial function as shown in Figure 4.9 (a). With reference to Figures 4.3 (b), 4.5 (b), 4.7 (b) and 4.9 (c), the general performance of C30/37 concrete with SDA was poor in sulphuric acid media XA2. This is because both OPC and SDA contribute reactive CaO which reacts with mixing water to form $Ca(OH)_2$ in concrete. C30/37 concrete had a design cement content of 20.56% as detailed in Appendix A.7 which is above the optimum cement content of 18.1% as shown in Figure 4.9 (a). Excessive calcium hydroxide in concrete results into internal stresses which induce micro crucks in the concrete structure hence weakening it.



a) Compressive strength against cement content of concrete in chemically aggressive medium



b) Compressive strength of C30/37 concrete after soaking in solution XA1



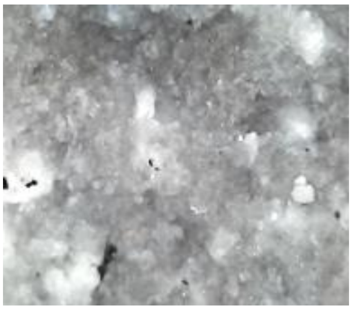
c) Compressive strength of C30/37 concrete after soaking in solution XA2

Figure 4. 9: Behavior of C30/37 concrete in sulphuric acid medium

4.5.3.2 Microscope images

Figures 4.8 (a), (b), (c) and (d) show the Microscope images of C30/37 concrete cube surfaces at the 6 hours before exposure to sulfate attack.

Solution XA1



a) C30/37-10% SDA before

b) C30/37-10% SDA after

Solution XA2

b) C30/37-15% SDA before

(d) C30/37-15% SDA after

Figure 4. 10: Microscopic images showing surface degradation as a sign of initiated failure

The severe concrete degradation can be observed in Figure 4.10 (d) for C30/37 concrete soaked in stronger sulphuric acid solution XA2 is probably due to the fact that the concrete had excessive cement content beyond the minimum 18.1% explained above.

4.6 Sulfate ion (SO_4^{2-}) ingress into concrete

The stronger of the two sulphuric acid solution XA2 was used to evaluate sulfate ion ingress in two concrete grades of C20/25 and C30/37 since it provided the worst-case scenario. These concrete grades were selected since they both gave the extreme opposite results with the later giving positive meaningful results while the former gave very poor results. Solution XA2 was preferred since it presents the worst case scenario for most of the geographical scope of the research and probably in Uganda at large i.e. a land locked Country with no sulfate interface from Sea water. The results are summarized in Figures 4.11 and 4.12 and detailed in Appendix A.6. A gradual decrease in the concentration of sulphate ions is observed from the edge to the center of the concrete cubes as shown in Figures 4.11 and 4.12. This is due to the chemical interactions which consumes part or some of the sulphate ions during the formation of ettringite as explained in Section 4.5.1 above.

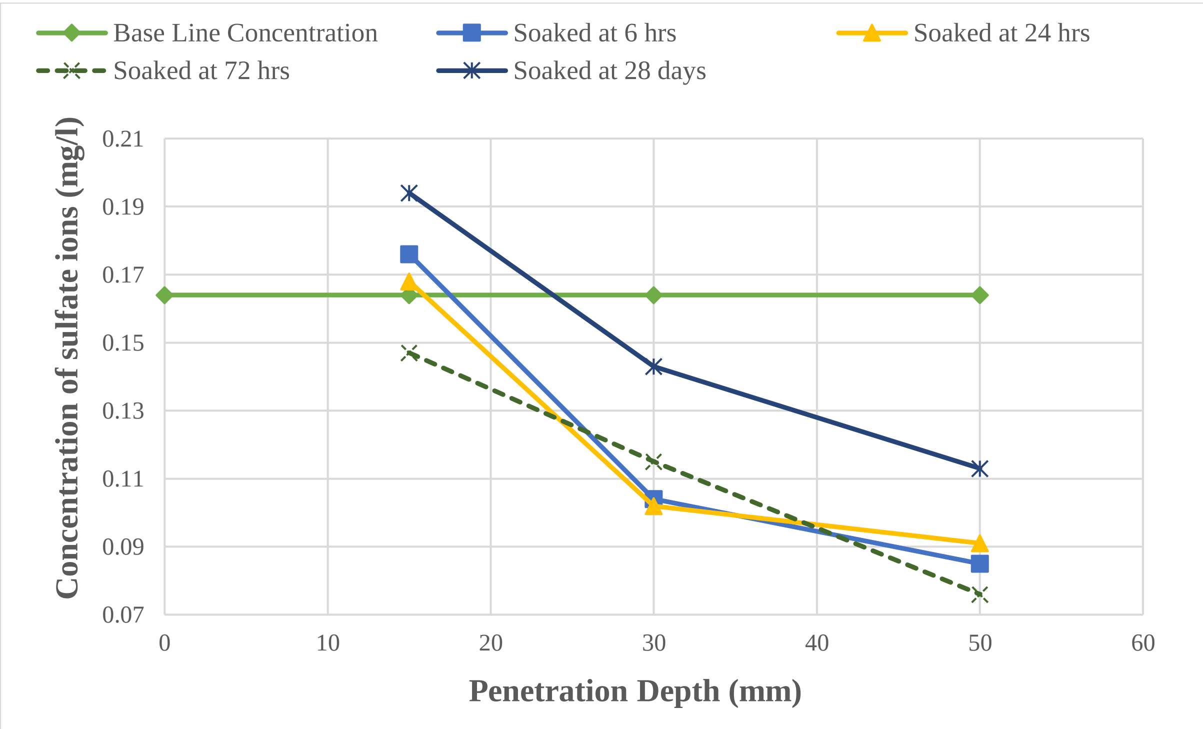


Figure 4. 11: Ingress of SO_4^{2-} ions in grade C20/25-5% SDA in solution XA2

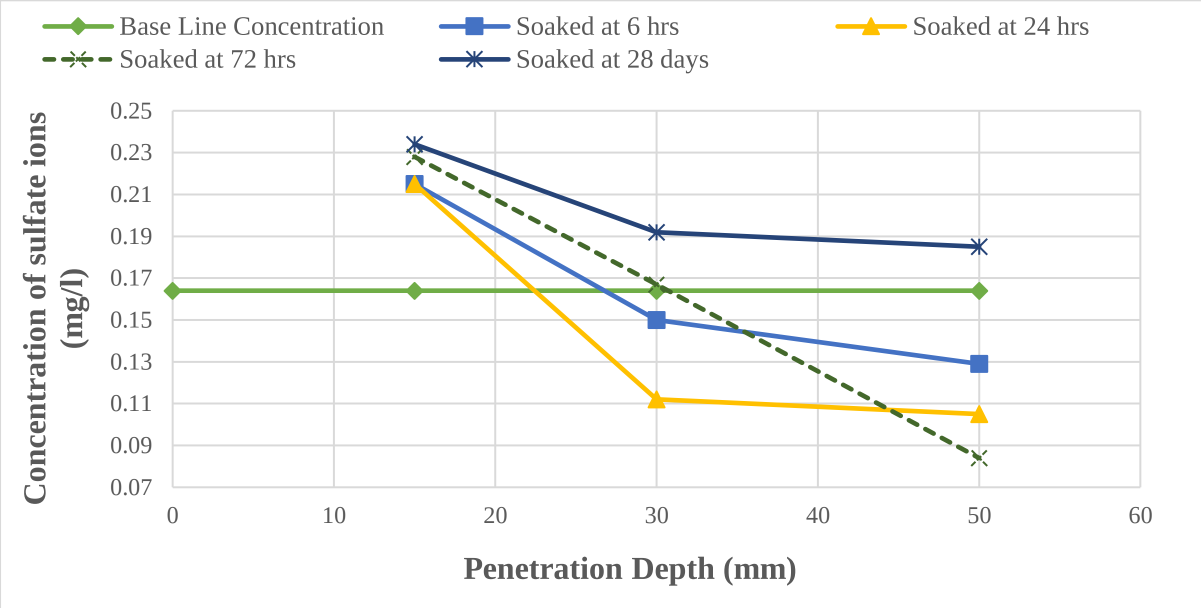
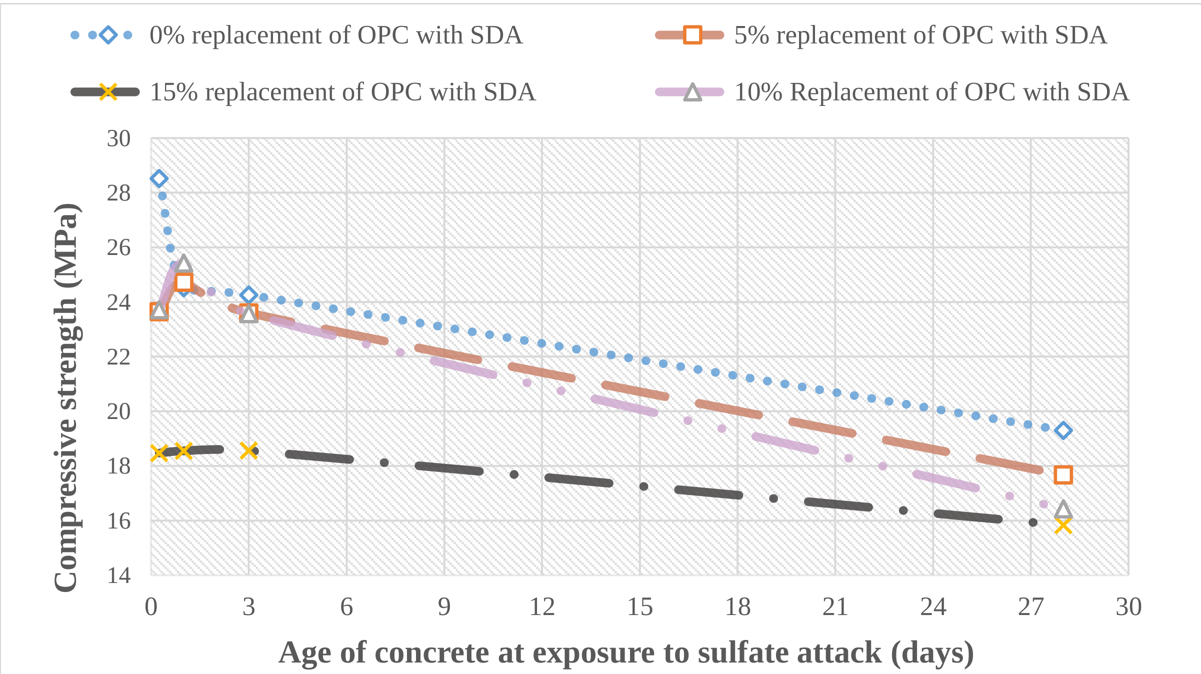


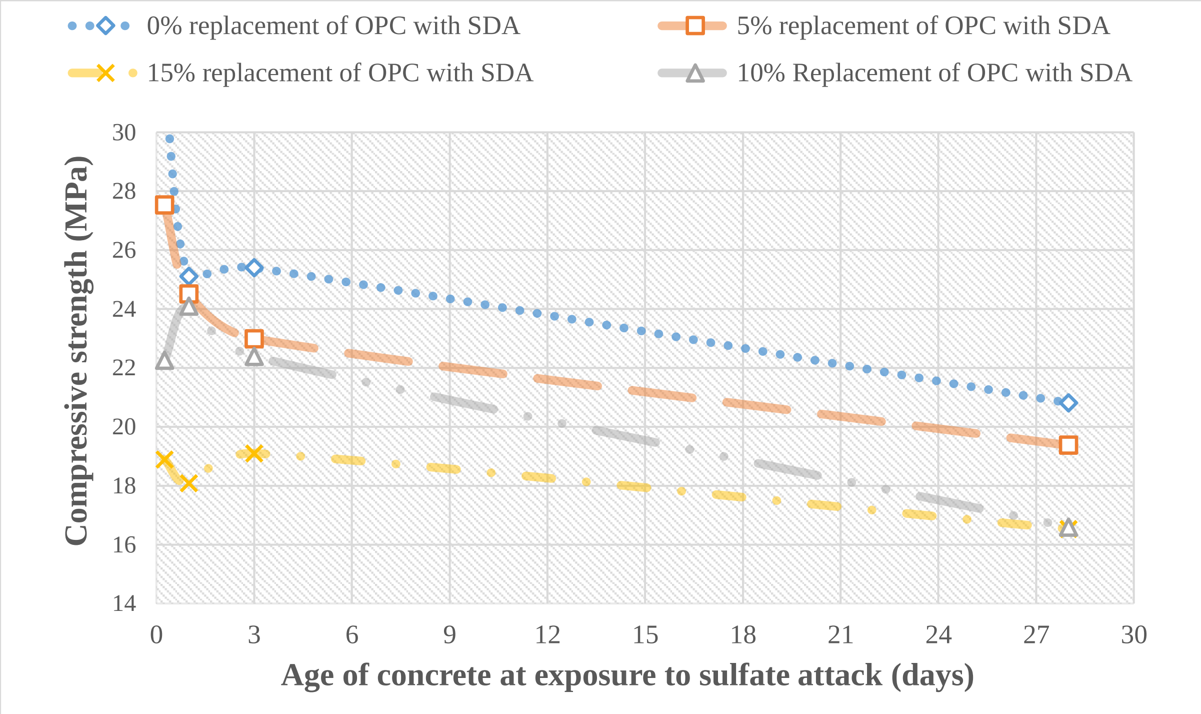
Figure 4. 12: Ingress of SO_4^{2-} ions in grade C30/37-5% SDA in solution XA2

4.7 Variation of compressive strength with age of concrete at sulfate attack

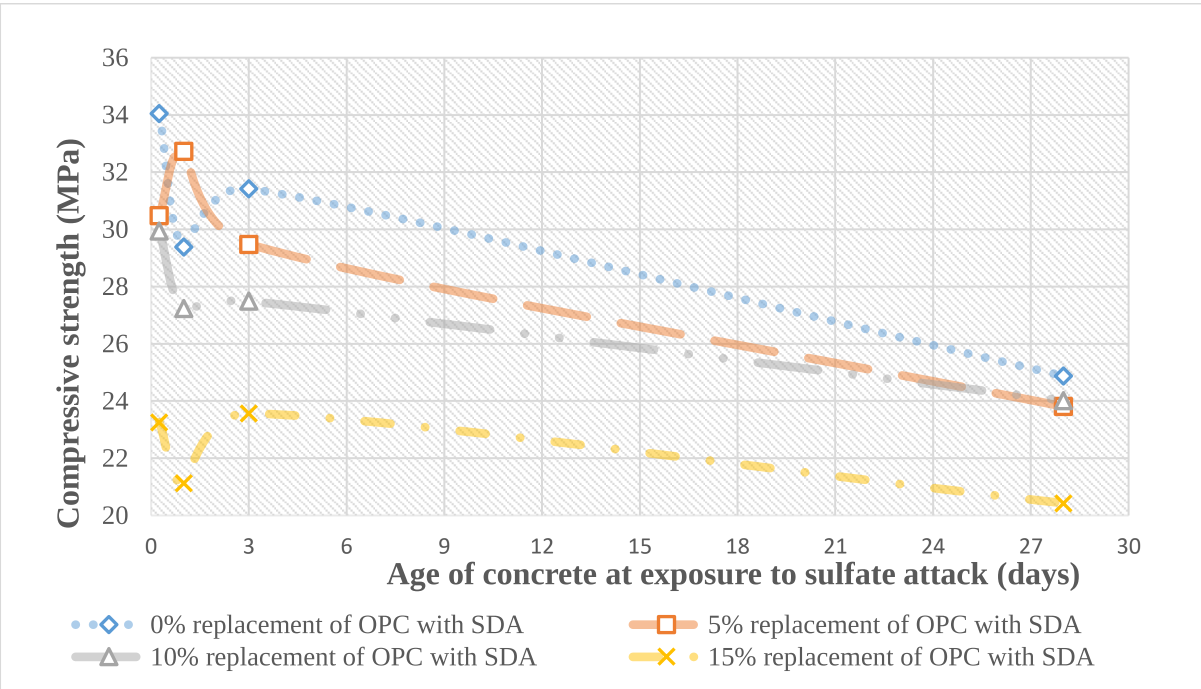
Figures 4.13 (a), (b), (c) and (d) shows the variation of compressive strength with age of SDA concrete before exposure of C16/20 and C20/25 concrete in sulphuric acidic media.



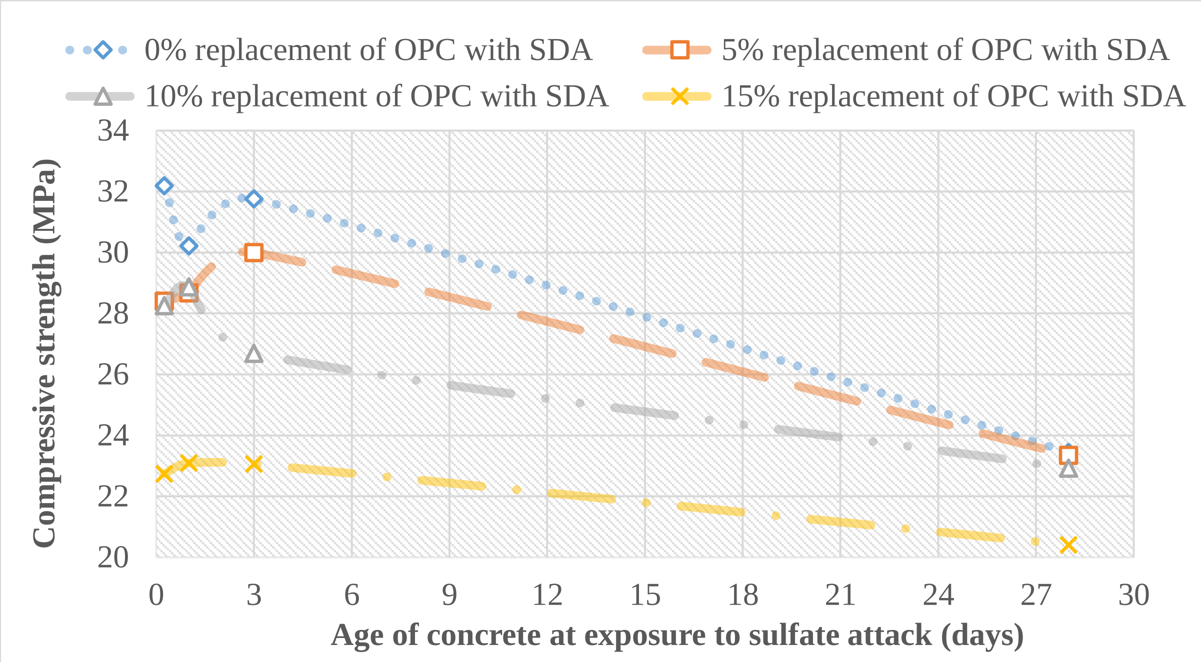
a) Variation of compressive strength with age before sulfate attack of C16/20 concrete in solution XA1



b) Variation of compressive strength with age before sulfate attack of C16/20 concrete in solution XA2



c) Variation of compressive strength with age before sulfate attack of C20/25 concrete in solution XA1



d) Variation of compressive strength with age before sulfate attack of C20/25 concrete in solution XA2

Figure 4. 13: SDA concrete behavior in relation to the curing regime before exposure to sulfate attack

It is generally observed from Figures 4.13 (a), (b), (c) and (d) that concrete in the early stages of hardening performed better in terms of resisting sulfate attack as compared to concrete in the late stage of hardening. This is because the hydration of the glassy alumina with calcium hydroxide leads to a C-A-H crystalline structure. The C-A-H structure may react in a sulfate environment to form ettringite and hence contributing to sulfate attack. Sulfate resistance of concrete containing SDA is related to the state of reactivity of the alumina bearing phases in SDA. Reactive alumina in the SDA leads to the formation of substantial amounts of mono-sulfoaluminate and C-A-H in concrete in the late stage of hardening before sulfate exposure. Therefore, SDA is expected to decrease the sulfate resistance of the concrete in the late stage of hardening.

4.8 Cost of using SDA and SRC compared

Grade C20/25 concrete was used for computation of the cost savings and comparison between the use of 10% SDA replacement of OPC in concrete as an alternative to SRC concrete for use in chemically aggressive soils/environment. A maximum value of 10% replacement of OPC with SDA in C20/25 concrete was chosen because it is stronger than C16/20 concrete although both passed the compressive strength test after exposure to sulfate attack in sulphuric acid media XA1 and XA2. Considering all other materials used in concrete production remain constant except for cement i.e. sulfate resisting cement (SRC) and OPC with 10% replaced with SDA. Focus was given to the cost of SRC and OPC as well as the associated cost of production for SDA required for a unit volume of C20/25 concrete based on the material proportioning shown in Table 3.9. Considering that C20/25 concrete had a cement content of 364 Kg/m^3 as shown in Table 3.9 the cost variation of the two concretes is shown in Table 4.7.

Table 4. 8: Cost variation of SRC against OPC with 10% SDA per m^3 of C20/25 Concrete

<table>
<tr><th>Item</th><th colspan="2">SRC</th><th colspan="2">OPC with 10% SDA</th></tr>
<tr><th></th><th>Description</th><th>Amount</th><th>Description</th><th>Amount</th></tr>
<tr><td>1</td><td rowspan="7">This type of cement, Sulfate Resisting Cement (SRC) is not readily available on the local market in Uganda. Either one has to import it or if the quantity involved is more than 200 tons, a special order of this type of cement may be accepted by the local Manufacturers. The cost of a ton of this type of cement is 1,270,000 UGX.</td><td rowspan="7"></td><td>Collection and transportation of sawdust from timber mill to the yard (one 100 Kg bag), including transport.</td><td>6,000</td></tr>
<tr><td>2</td><td>Sorting and burning in a metallic drum to 60 % ash</td><td>3,000</td></tr>
<tr><td>3</td><td>Further burning in an electric furnace to fine sawdust ash at UIRI, 4.4 Kg of SDA were obtained</td><td>6,500</td></tr>
<tr><td>4</td><td>Sub-Total 1</td><td>15,500</td></tr>
<tr><td>5</td><td>Cost of 1 Kg of SDA</td><td>3,523</td></tr>
<tr><td>6</td><td>10% of 364 Kg of OPC will be replace with SDA in C20/25 concrete = 36.4 Kg as shown in Table 3.9</td><td>128,237</td></tr>
<tr><td>7</td><td>OPC required in C20/25 concrete, 90% of 364 Kg. One 50 Kg bag of OPC is assumed to cost 31,500 including transport to site</td><td>206,388</td></tr>
</table>

8	The quantity of cement required as shown in Table 3.9 is 364 Kg	**462,280**	Combined cost of OPC with 10% SDA required as substitute for SRC in chemically aggressive media (Item 6 and 7)	**334,625**
9	Cost saving on cement per cubic meter of grade C20/25 in aggressive environment using 10% SDA with OPC instead of SRC			**127,655**

A cost saving on cement of UGX. 127, 655 would be attained per cubic meter of grade C20/25 concrete if SDA is used to replace 10% OPC instead of using the scarce and expensive SRC in chemically aggressive environment XA1 and XA2.

The SDA would be packaged in 5 Kg bags which is 10% of the common weight of a bag of cement for sale. For each 50 Kg bag of Ordinary Portland cement, 5 Kg of SDA is required to replace 10% of the cement in order to counter sulphate attack on concrete. This application methodology is easier to follow for the artisans on various sites where this technology may be applicable.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this study was to evaluate the impact of SDA on the resistance to sulfate attack by concrete in the early and late stage of hardening. This was achieved by replacing part of the cement in four grades of concrete (C16/20, C20/25, C25/30 and C30/37) with SDA in portions of 0%, 5%, 10% and 15%. Simulation of sulfate attack was done using solutions of laboratory grade concentrated sulphuric acid mixed with distilled water of pH 7.1.0 in Laboratory conditions. Sulfate attack was initiated at various curing regimes of the concrete, at age 6 hours, 24 hours, 72 hours and 28 days, all concrete cubes were soaked for 28 days in the acid solutions designated as XA1 and XA2 (BS EN12390, 2019). The ingress of SO_4^{2-} ions into concrete, the weight and variation of compressive strength of concrete cubes after exposure to sulfate attack as compared to the average design strength were investigated. The following conclusions were drawn from the results presented in Chapter Four:

1. Concrete in the early stages of hardening (i.e., age of 6 hours, 24 hours and 72 hours) with the SDA used to replace part of the cement (up to 10 % of OPC) exhibited improved resistance to sulfate attack as compared to that in the later stage of hardening (cured for 28 days before exposure to sulfate attack) in sulphuric acid media. Concrete in the later stage of hardening for all the four concrete grades, C16/20, C20/25, C25/30 and C30/37, gave poor performance as they failed the compressive strength test after 28 days of sulfate attack.
2. Moderate strength concrete grades (i.e., C16/20, C20/25) performed better than the higher strength concrete (i.e., C25/30 and C30/37) in terms of resisting sulfate attack. This is a good result since high strength concrete grade C30/37 normally is used by clients that can easily afford Sulfate Resisting Cement. Whereas in the local

communities the commonly used grades of concrete are C16/20 and C20/25 which SDA helps to improve.

3. The ingress of SO_4^{2-} ions followed a decreasing linear function for C20/25-5% SDA concrete cured for 72 hours before exposure to sulfate attack with the concentration decreasing below the base line value from the outer edge of the cube.
4. The compressive strength of concrete made using CEM I, OPC 42.5N conforming to US EAS 18-1:2017, gave compressive strength results higher than the target strength in sulphuric acid media with the Coefficient of Variation (CV) ranging from 0.01 to 0.27 as compared to the design strength.
5. Timber sawdust ash conforming to (Uganda Standard, 2017) can be used to replace part of OPC for concreting in chemically aggressive environment to provide cheaper methods of protection.

5.2 Recommendations

a. Low cement content, (≤18.1%) of the concrete mix in the presence of SDA is recommended for improved performance of OPC in chemically aggressive environment.

b. Partial back filling of concrete structural elements (i.e., ground beams and pad footings) whose service conditions are chemically aggressive should preferably be done after 72 hours of casting in order to achieve good performance.

c. There is need to extend this study of sulfate attack on concrete during early age strength development using SDA to improve its resistance beyond 28 days.

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Appendices

Appendix A. 1: Research Work plan

Table A. 1: Research work plan

RESEARCH WORK PLAN																																
Period/Month	May-20				Jun-20				Jul-20				Aug-20				Sep-20				Oct-20				Nov-20				Dec-20			
Description of Works	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4
Review of Literature																																
Submission of Research Title																																
Proposal development																																
Experiment and observation																																
Submission of Proposal																																
Questionnaire development																																
Data collection																																
Analyzing and interpreting the output																																
Draft report writing																																
Final Report submission																																
Presentation																																

Appendix A. 2: Test results for coarse aggregates

Table A. 2: Test results for coarse aggregates

Sample Reference	Sample Description	Sample Source	W.Abs %	AIV %	TFV kN	FI %	SO42-	Cl	pH	G as Wet	e	e loose kg/m3	% Passing Given Sieve Sizes (mm)									Remarks
													37.5	20.0	14.0	10.0	6.3	5.0	2.0	1.2	0.1	
CA2019/001	20/5 mm	Krima Quarry	0.3	17.0	225.0	25.9	0.11	0.01	5.8	2.65	2.663	1,545	100	90	50	35	0	4	0	0	0	Dry condition
				19.0	182.0																	Wet condition
Average				18.0	203.5	25.9	0.11	0.01	5.8	2.65	2.663	1,545	100	90	50	35	0	4	0	0	0	computed
Specification: BS 882:1992	Min				150.0								100	90	40	30		0			0	Sastifactory results
	Max			25.0		40.0		0.0					100	100	80	60		10			4	

Appendix A. 3 : Grading results for Coarse Aggregates

Table A. 3: Sieve Analysis results for Coarse Aggregate

Particle size distribution for Coarse Aggregates 5/20 mm							
Reference No.:	G/A/2017/066		Sampling Date:				
Sampling Location:			Testing Date:				
Material Source:			Tested By:				
Description:	Crushed Aggregates (20-5)mm		Dry Mass Before Washing:(g)				
Moisture Content (%)	0		Dry Mass After Washing: (g)				
Dry Mass Before Washing (g):		0					
BS SIEVE SIZE (mm)	Wt Retained (g)	% Retained	% Passing	Specification Limits as Per BS 882: 1992			Remarks.
37.5			100	100	-	100	
20			90.0	90	-	100	
14			50.0	40	-	80	
10			35.0	30	-	60	
5			4.0	0	-	10	

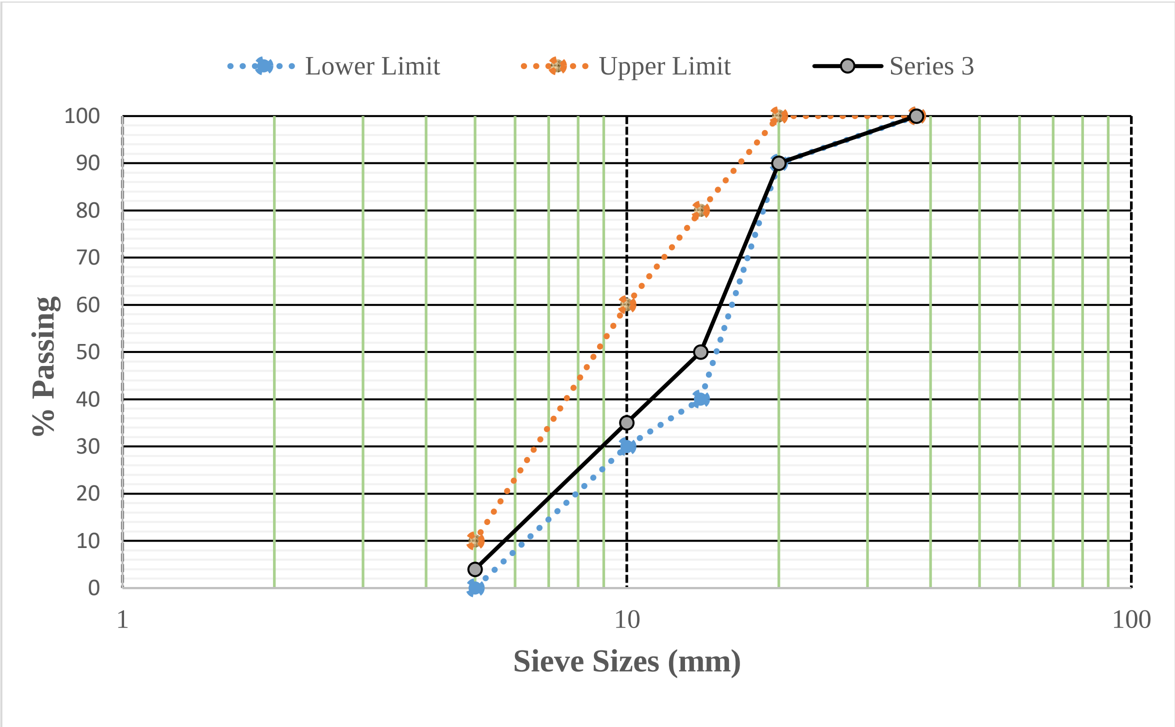

Figure A. 1: Grading curves for coarse aggregates

Appendix A. 4 : Grading results for Fine Aggregates

Table A. 4: Test results for fine aggregates

Particle Size Distribution Testt Report for Fine aggregates													
Initia wt before washing (g):		1503.8		Moisture Content (%)							0.0		
Dry wt after washing (g):		1467.2		Initial Dry Weight (g)							1503.8		
Sieve Sizes (mm)	Partial Retained Mass (g)	Cumulative Retained Mass (g)	Cumulative Retained (%)	% Passing	Grading Limits (%) BS 882:1992 TABLE 4								
					Overall Limits		C		M		F		
10.00	3.2	3.2	0.2	100	100	100	100	100	100	100	100	100	
5.00	0	3.2	0.2	100	89	100	100	100	100	100	100	100	
2.36	60.1	63.3	4.2	96	60	100	60	100	65	100	80	100	
1.18	381.7	445	29.6	70	30	100	30	90	45	100	70	100	
0.60	787.2	1232.2	81.9	18	15	100	15	54	25	80	55	100	
0.30	163.3	1395.5	92.8	7	5	70	5	40	5	48	5	100	
0.15	41.9	1437.4	95.6	4	0	15	0	0	0	0	0	0	
Pan	29.8	1467.2	97.6										

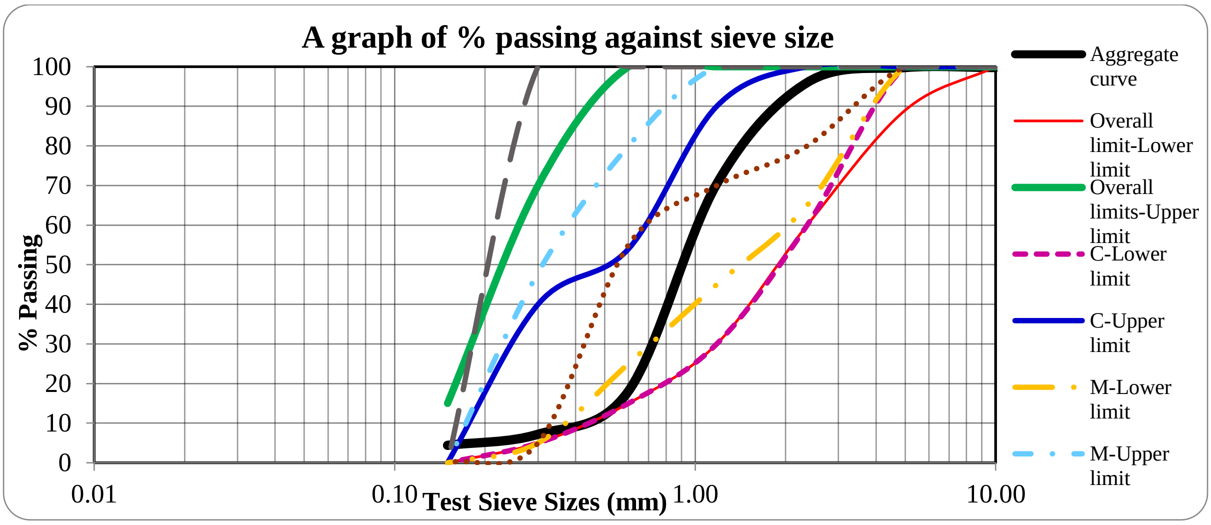

Figure A. 2: Grading curve for fine aggregates

Appendix A. 5: Results for Concrete Mix Design

Table A. 5: Concrete mix design results for C30/37

Cube Mark	Date Cast	Date Crashed	Age (Days)	Concrete Class	Cube Dimension (mm)			Mass in Air (g)	Density (Kg/m^3)	Crashing load (KN)	Compressive Strenght (MPa)	Average Compressive Strenght (MPa)
					Length	Wid	Height					
MD-4-1	27.Jul.19	19.Jul.19	7	C30/37	150	150	150	7973	2,362	752.20	33.43	33.74
MD-4-2	"				150	150	150	7977	2,364	751.30	33.39	
MD-4-3	"				150	150	150	8174	2,422	774.20	34.41	
MD-05-4	"	10.Aug.19	14	C30/37	151	153	152	8019	2,284	899.30	38.93	39.72
MD-05-5	"				153	151	151	8079	2,316	927.30	40.14	
MD-05-6	"				151	152	152	8103	2,323	920.00	40.08	
MD-4-7	"	23.Aug.19	28	C30/37	150	150	150	8100	2,400	872.00	38.76	41.03
MD-4-8	"				150	150	150	8000	2,370	938.60	41.72	
MD-4-9	"				150	150	150	8100	2,400	958.70	42.61	

Table A. 6: Concrete mix design results for C25/30

Cube Mark	Date Cast	Date Crashed	Age (Days)	Concrete Class	Cube Dimension (mm)			Mass in Air (g)	Density (Kg/m^3)	Crashing load (KN)	Compressive Strenght (MPa)	Average Compressive Strenght (MPa)
					Length	Width	Height					
MD-4-1	27.Jul.19	3.Aug.18	7	C25/30	150	150	150	7990	2,367	645.40	28.68	28.86
MD-4-2	"				150	150	150	7920	2,347	685.20	30.45	
MD-4-3	"				150	150	150	7980	2,364	617.40	27.44	
MD-05-4	"	10.Aug.19	14	C25/30	150	150	150	7985	2,366	697.80	31.01	30.86
MD-05-5	"				150	150	150	7940	2,353	690.70	30.70	
MD-05-6	"				150	150	150	7960	2,359	694.60	30.87	
MD-05-7	"	23.Aug.19	28	C25/30	150	150	150	7950	2,356	737.00	32.76	31.98
MD-05-8	"				150	150	150	7950	2,356	700.10	31.12	
MD-05-9	"				150	150	150	7950	2,356	721.60	32.07	

Table A. 7: Concrete mix design results for C20/25

Cube Mark	Date Cast	Date Crashed	Age (Days)	Concrete Class	Cube Dimension (mm)			Mass in Air (g)	Density (Kg/m^3)	Crashing load (KN)	Compressive Strenght (MPa)	Average Compressive Strenght (MPa)
					Length	Width	Height					
MD-05-1	27.Jul.19	3.Aug.19	7	C20/25	150	150	150	7900	2,341	513.20	22.81	22.65
MD-05-2	"				150	150	150	7930	2,350	508.90	22.62	
MD-05-3	"				150	150	150	7900	2,341	507.00	22.53	
MD-4-4	"	10.Aug.19	14	C20/25	100	100	100	2375	2,375	269.10	26.91	26.94
MD-4-5	"				100	100	100	2375	2,375	278.20	27.82	
MD-4-6	"				100	100	100	2350	2,350	260.90	26.09	
MD-05-7	"	23.Aug.19	28	C20/25	150	150	150	7950	2,356	662.30	29.44	28.53
MD-05-8	"				150	150	150	7900	2,341	630.80	28.04	
MD-05-9	"				150	150	150	7950	2,356	632.40	28.11	

Table A. 8: Concrete mix design results for C16/20

Cube Mark	Date Cast	Date Crashed	Age (Days)	Concrete Class	Cube Dimension (mm)			Mass in Air (g)	Density (Kg/m^3)	Crashing load (KN)	Compressive Strenght (MPa)	Average Compressive Strenght (MPa)
					Length	Width	Height					
MD-05-1	19.Jul.19	3.Aug.19	7	C16/20	150	150	150	7950	2,356	409.80	18.21	17.78
MD-05-2	"				150	150	150	7890	2,338	397.80	17.68	
MD-05-3	"				150	150	150	7880	2,335	392.70	17.45	
MD-05-4	"	10.Aug.19	14	C16/20	100	100	100	2375	2,375	203.00	20.30	21.29
MD-05-5	"				100	100	100	2380	2,380	218.60	21.86	
MD-05-6	"				100	100	100	2365	2,365	217.20	21.72	
MD-05-7	"	23.Aug.19	28	C16/20	150	150	150	7800	2,311	542.40	24.11	24.29
MD-05-8	"				150	150	150	7850	2,326	545.80	24.26	
MD-05-9	"				150	150	150	7850	2,326	551.30	24.50	

Appendix A. 6: Results for sulfate ion ingress into C30/37 concrete

Table A. 9: Sulfate ion ingress into C30/37- 10% SDA concrete in XA2

Penetration depth (mm)	Sulfate ion SO_4^{2-} Concentration (mg/L)				Remarks
	6 hours	24 hours	72 Hours	28 days	
0-15 mm	0.215	0.215	0.228	0.234	Sliced from soaked cube
15-30 mm	0.150	0.112	0.167	0.192	Sliced from soaked cube
30-50 mm	0.129	0.105	0.084	0.185	Sliced from soaked cube
	0.164				Base line concentration

Table A. 10: Sulfate ion ingress into C20/25- 5% SDA concrete in XA2

Penetration depth (mm)	Sulfate ion SO_4^{2-} Concentration (mg/L)				Remarks
	6 Hours	24 Hours	72 Hours	28 days	
0-15 mm	0.176	0.168	0.147	0.194	Sliced from soaked cube
15-30 mm	0.104	0.102	0.115	0.143	Sliced from soaked cube
30-50 mm	0.085	0.091	0.076	0.113	Sliced from soaked cube
	0.106				Base line concentration

Appendix A. 7: General relationship of cement content with compressive strength after SA

Table A. 11: Compressive strength against designed cement content

Concrete Grade	Cement Content	Designed % Cement Content	Designed Compressive Strength (MPa)	Average Compressive Strength after 28 days of SA on 5% SDA Concrete at		Average Compressive Strength after 28 days of SA on 10% SDA Concrete at 72	
				XA1	XA2	XA1	XA2
C16/20	322	13.88	24.29	23.60	22.99	23.71	22.39
C20/25	364	15.69	28.53	29.48	30.00	27.49	26.69
C25/30	420	18.10	31.98	35.91	34.61	31.18	27.91
C30/37	477	20.56	41.03	27.82	26.82	25.36	29.55

Appendix A. 8 : Deviation of compressive strength

Table A. 12: Grade C16/20 concrete after exposure to Sulfate attack

% SDA Replacement in Concrete	Compressive strength of concrete 28 days after exposure to sulfate attack C16/20 (MPa)					
	6 Hours		24 Hours		72 Hours	
	XA1	XA2	XA1	XA2	XA1	XA2
0	28.52	31.57	24.52	25.11	24.26	25.40
5	23.64	27.53	24.72	24.51	23.60	22.99
10	23.71	22.26	25.42	24.10	23.57	22.39

Table A. 13: Grade C20/25 concrete after exposure to Sulfate attack

% SDA Replacement in Concrete	Compressive strength of concrete 28 days after exposure to sulfate attack C20/25 (MPa)					
	6 Hours		24 Hours		72 Hours	
	XA1	XA2	XA1	XA2	XA1	XA2
0	34.05	32.19	29.39	30.22	31.42	31.76
5	30.48	28.40	32.73	28.68	29.48	30.00
10	29.95	28.26	27.24	28.87	27.49	26.69

Table A. 14: Grade C25/30 concrete after exposure to Sulfate attack

% SDA Replacement in Concrete	Compressive strength of concrete 28 days after exposure to sulfate attack C25/30 (MPa)					
	6 Hours		24 Hours		72 Hours	
	XA1	XA2	XA1	XA2	XA1	XA2
0	44.86	43.21	44.44	43.78	41.89	43.06
5	41.00	36.53	37.74	35.89	35.91	34.61
10	34.08	27.06	26.65	24.63	31.18	27.91

Appendix A. 9: Certified XRF Test Certificates

TORORO CEMENT LIMITED

KAMPALA OFFICE:
P.O. Box 22753 Kampala
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NAMANVE GODOWN
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NEW ROCK BRAND

TORORO FACTORY:
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Email:tcl@tororocement.com
Website: www.tororocement.com
MALABA:
Tel: +256(454)442481
Fax: +256(454)442278

Date: 6/04/2020

CERTIFICATE No. ES-PC/2020/0051
*External Sample Analysis for **Portland Cement, CEM I 42.5N***
*Standard Specification: **US EAS 18-1:2017, CEM I 42.5N, Equivalence; EN 197-1***
Analysis requested by: Patrick Kabiito Basajjansolo.
Date of sample receipt: 10st/02/2020

TEST CERTIFICATE

CHEMICAL ANALYSIS			
PARAMETER	**SPECIFICATION**	**UNIT**	**RESULTS**
Sulphuric Anhydride (SO_3)	MAX : 3.50		**1.7**
L.O.I	MAX; 5.0		**3.52**
Total alkali -Na equalent	≤0.6		**0.440**
Al_2O_3	MAX: 8.0		**4.66**
Fe_2O_3	-		**3.70**
SiO_2	-	%	**20.05**
CaO	-		**64.03**
MgO	MAX: 3.0		**2.08**
Na_2O	-		**0.15**
K_2O	-		**0.44**
C_3A	-		**6.089**
Moisture Content	-		**0.02**
Bulk Density	-	**Kg/L**	**1.12**
Specific Gravity	-		**3.15**
Blaine	-	M^2/Kg	**327.6**

TORORO CEMENT LTD.
P.O.BOX 74
TORORO - UGANDA

Ronald Olem
Asst- Manager (P & QC)

TORORO CEMENT LIMITED

KAMPALA OFFICE:
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Website: www.tororocement.com
MALABA:
Tel: +256(454)442481
Fax: +256(454)442278

Date: 6/04/2020

CERTIFICATE No. ES-FA/2020/0052
*External Sample Analysis for **Saw Dust Ash.***
*Standard Specification: **US EAS 18-1:2017, Clause 5.2.4***
Analysis requested by: Patrick Kabiito Basajjansolo.
Date of sample receipt: 10st/02/2020

TEST CERTIFICATE

CHEMICAL ANALYSIS			
PARAMETER	**SPECIFICATION**	**UNIT**	**RESULTS**
Sulphuric Anhydride (SO_3)	NR	%	**0.02**
L.O.I	MAX; 7.0	%	**4.62**
Total alkali -Na equalent	NR	%	**0.756**
Al_2O_3	-	%	**23.41**
Fe_2O_3	-	%	**4.72**
Total - SiO_2	-	%	**52.31**
Reactive – SiO_2	> 25.0	%	**35.61**
Reactive - CaO	< 10.0	%	**6.74**
MgO	-	%	**1.93**
Na_2O	-	%	**0.21**
K_2O	-	%	**0.83**
Moisture Content	-	Kg/ L	**0.53**
Bulk Density	-	Kg/ L	**0.97**
Specific Gravity	-	-	**2.11**
Blaine	-	M^2/Kg	**415.8**

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Asst- Manager (P & QC)

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Email:tcl@tororocement.com
Website: www.tororocement.com
MALABA:
Tel: +256(454)442481
Fax: +256(454)442278

Date: 6/04/2020

CERTIFICATE No. ***ES-AG/2020/0057***
External Sample Analysis for ***Aggregates.***
Analysis requested by: ***Patrick Kabiito Basajjansolo.***
Date of sample receipt: ***11th/02/2020***

TEST CERTIFICATE

CHEMICAL ANALYSIS			
PARAMETER	SPECIFICATION	UNIT	RESULTS
Na_2O	-	%	**8.61**
K_2O	-	%	**9.73**

TORORO CEMENT LTD.
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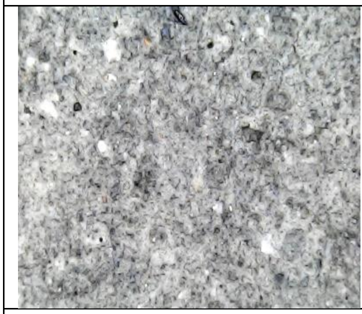
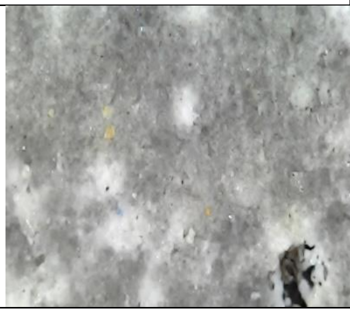
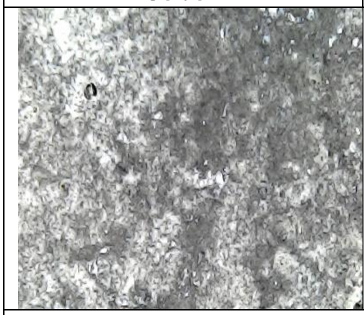
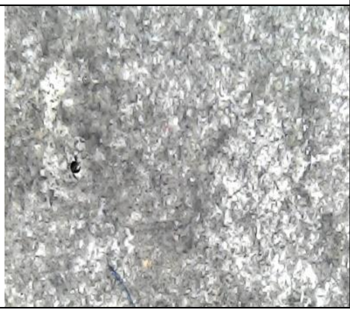
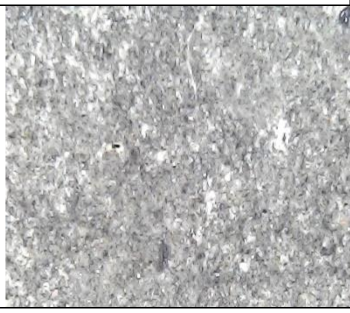
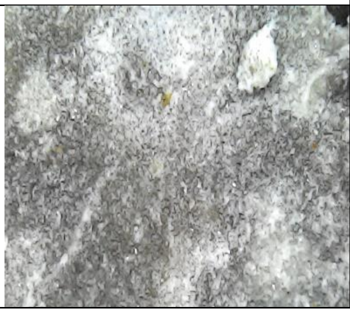
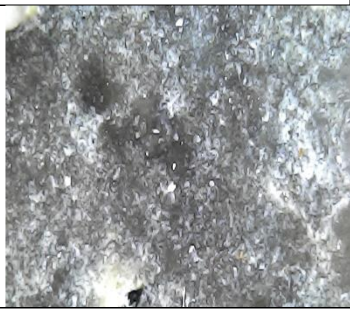
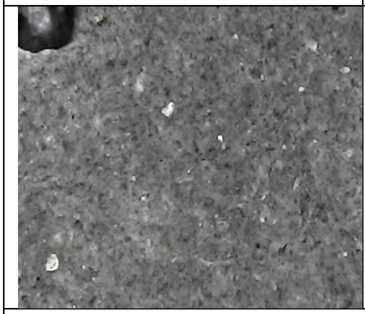
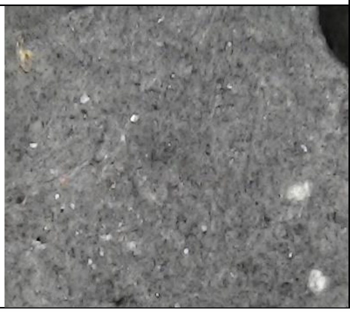
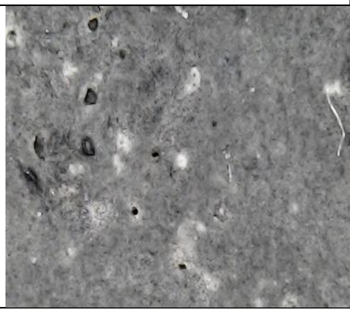
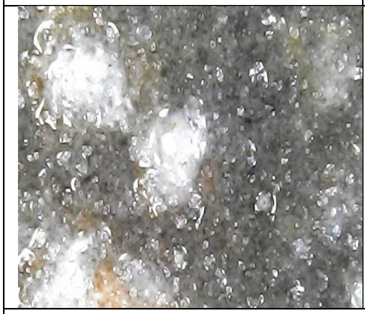
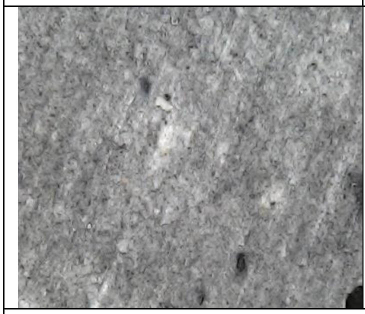
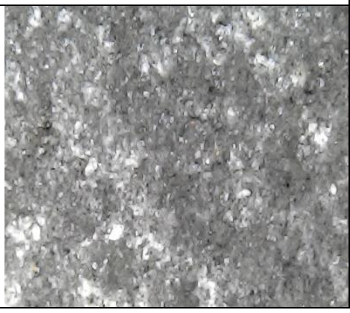
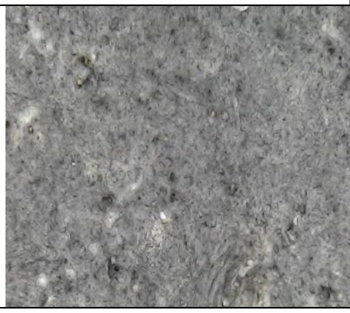
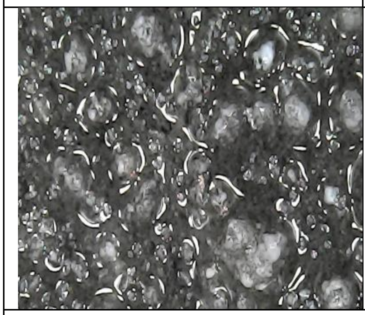
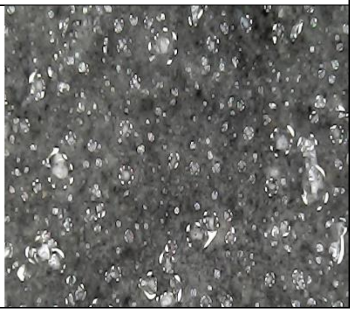
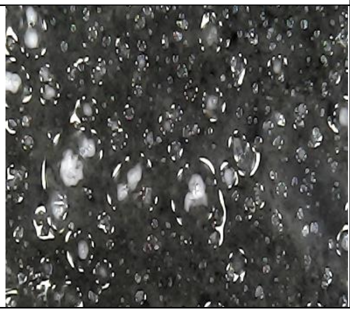
TORORO - UGANDA

Ronald Olem
Asst- Manager (P & QC)

Appendix A. 10: Microscopic Images for grade C30/37 concrete

C355”	C356”	C357”	Remarks
			
C30/37 – 10% SDA before initiation of sulfate attack in XA2 Solution			
C355	C356	C357	Remarks
			Calcium Silcate hydrate seen of surface indicating serious concrete degradation
C30/37 – 10% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA2			
C373”	C374”	C375”	Remarks
			
C30/37 – 0% at age of 24 hours before initiation of Sulfate Attack in XA2 solution			
C373	C374	C375	Remarks
			Calcium Silcate hydrate seen of surface indicating serious concrete degradation
C30/37 – 0% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA2			

Appendix A. 11: Microscopic Images for grade C25/30 concrete

<table>
<tr><td>C256”</td><td>C257”</td><td>C258”</td><td>Remarks</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">C25/30 –5% SDA at age of 24 hours before initiation of sulfate attack in XA2 Solution</td></tr>
<tr><td>C256</td><td>C257</td><td>C258</td><td>Remarks</td></tr>
<tr><td></td><td></td><td></td><td>Chalking of concrete after sulfate attack showing concrete degradation</td></tr>
<tr><td colspan="4">C25/30 – 5% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA2 Solution</td></tr>
<tr><td>C208”</td><td>C209”</td><td>C210”</td><td>Remarks</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">C25/30 – 5% at age of 24 hours before initiation of Sulfate Attack in XA1 solution</td></tr>
<tr><td>C208</td><td>C209</td><td>C210</td><td>Remarks</td></tr>
<tr><td></td><td></td><td></td><td>Propagation of concrete degradation by sulfate attack</td></tr>
<tr><td colspan="4">C25/30 –5% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA1</td></tr>
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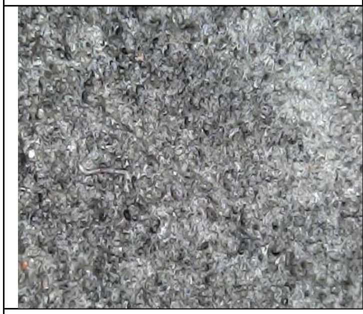
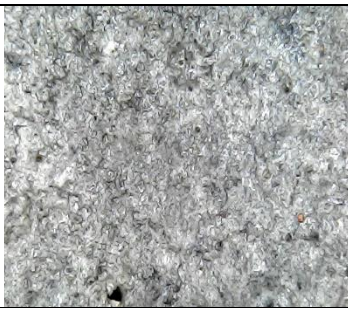
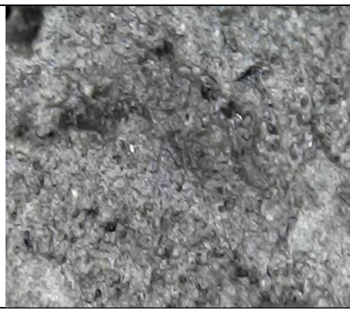
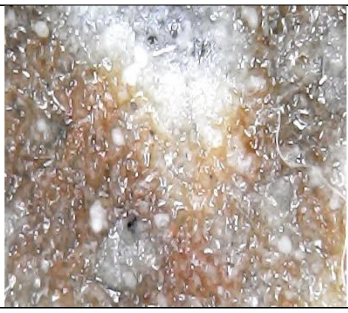
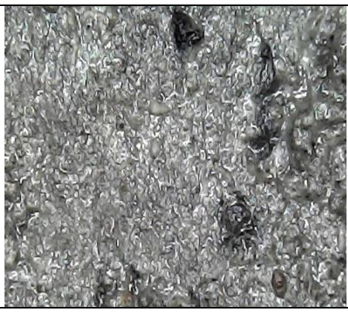
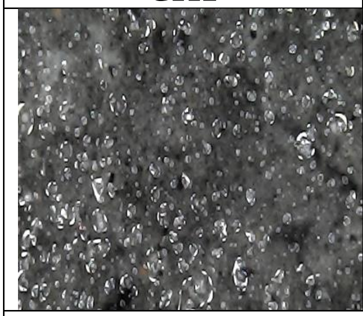
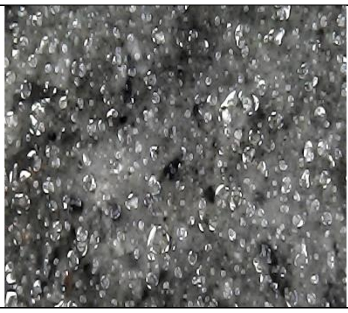
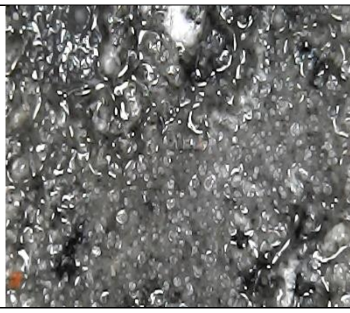
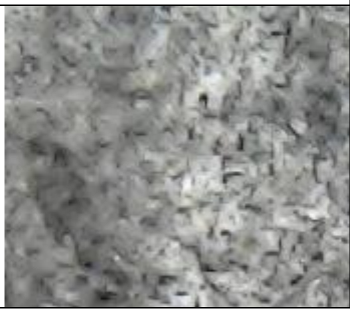
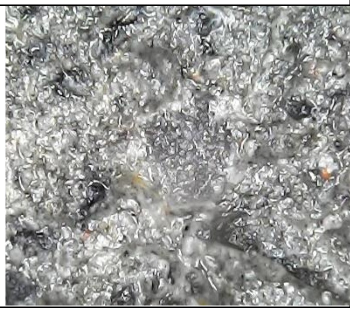
Appendix A. 12: Microscopic Images for grade C20/25 concrete

C160”	C161”	C162”	Remarks
			
C20/25 – 5% SDA before initiation of sulfate attack in XA2 Solution			
C160	C161	C162	Remarks
			Calcium Silcate hydrate seen of surface indicating serious concrete degradation
C20/25 –5% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA2			
C112”	C113”	C114”	Remarks
			
C20/25 – 5% at age of 24 hours before initiation of Sulfate Attack in XA1 solution			
C112	C113	C114	Remarks
			Propagation of concrete degradation due to sulfate attack
C20/25 – 5% SDA after 28 days of Sulfate Attack initiated at age of 24 hours in XA1			

Appendix A. 13: Microscopic Images for grade C16/20 concrete

C82”	C83”	C84”	Remarks
			
C16/20 – 15 % SDA before initiation of sulfate attack in XA2 Solution			
C82	C83	C84	Remarks
			Chalking of concrete after sulfate attack showing concrete degradation
C16/20 – 15 % SDA after 28 days of Sulfate Attack initiated at age of 72 hours in XA2			
C34”	C35”	C36”	Remarks
			
C16/20 – 15 % at age of 72 hours before initiation of Sulfate Attack in XA1 solution			
C34	C35	C36	Remarks
			Sulphuric acid stain seen on the cube surface
C16/20 – 15 % SDA after 28 days of Sulfate Attack initiated at age of 72 hours in XA1			

Appendix A. 14: Compressive strength results after 28 days of Sulfate attack on concrete

Table A. 15: Results for grade C16/20 soaked in XA1

Grade Concrete C16/20 Soaked in XA1 Solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
1	6	0	9/15/19	28	104	101	101	2399	2261	324.9	30.93	28.52
2					101	101	101	2370	2300	266.3	26.11	
3					103	101	101	2385	2270	225.3	21.66	
4		5	9/15/19	28	102	102	101	2481	2361	230.5	22.15	23.64
5					104	102	101	2449	2286	266.5	25.12	
6					101	102	101	2399	2306	201.7	19.58	
7		10	9/15/19	28	103	100	101	2317	2227	231.1	22.44	23.71
8					103	101	101	2396	2280	260.9	25.08	
9					103	101	102	2392	2254	245.5	23.60	
10		15	9/15/19	28	101	101	102	2404	2310	202.3	19.83	18.47
11					104	103	102	2406	2202	193.5	18.06	
12					103	102	102	2427	2265	183.9	17.50	
13	24	0	9/16/19	28	103	102	103	2407	2224	242.5	23.08	24.52
14					103	102	102	2436	2273	260.1	24.76	
15					102	102	101	2408	2292	267.7	25.73	
16		5	9/14/19	28	102	103	102	2442	2279	273.5	26.03	24.72
17					101	102	103	2407	2268	245.5	23.83	
18					104	104	103	2467	2214	262.7	24.29	
19		10	9/16/19	28	104	103	104	2432	2183	284.5	26.56	25.42
20					105	102	102	2432	2226	260.1	24.29	
21					105	103	102	2427	2200	236.6	21.88	
22		15	9/16/19	28	103	102	101	2426	2286	206.6	19.66	18.55
23					102	101	102	2365	2251	195.6	18.99	
24					102	102	101	2318	2206	177.0	17.01	
25	72	0	9/17/19	28	102	103	103	2430	2246	253.9	24.17	24.26
26					102	104	102	2439	2254	258.4	24.36	
27					103	104	103	2445	2216	294.0	27.45	
28		5	9/18/19	28	101	104	103	2418	2235	248.8	23.69	23.60
29					102	103	102	2458	2294	261.6	24.90	
30					102	103	102	2468	2303	233.4	22.22	
31		10	9/19/19	28	102	104	102	2461	2274	211.8	19.97	23.57
32					101	104	100	2401	2285	267.8	25.50	
33					102	102	102	2436	2295	225.1	21.64	
34		15	9/18/19	28	102	103	103	2408	2225	195.1	18.57	18.56
35					102	101	104	2435	2273	191.1	18.55	
36					101	103	103	2359	2202	157.5	15.14	
37	28 Days	0	9/18/19	28	100	100	100	2,332	2,332	219.7	21.97	19.30
38					100	100	100	2,329	2,329	196.4	19.64	
39					100	100	100	2,390	2,390	189.6	18.96	
40		5	9/18/19		100	100	100	2,375	2,375	165.3	16.53	17.67
41					100	100	100	2,358	2,358	185.0	18.50	
42					100	100	100	2,384	2,384	179.9	17.99	
43		10	9/18/19		100	100	100	2,372	2,372	165.1	16.51	16.43
44					100	100	100	2,396	2,396	164.0	16.40	
45					100	100	100	2,405	2,405	163.8	16.38	
46		15	9/18/19		101	100	100	2,388	2,364	166.7	16.50	15.83
47					100	100	100	2,380	2,380	151.5	15.15	
48					100	100	100	2,353	2,353	135.5	13.55	

Table A. 16: Results for grade C16/20 soaked in XA2

Grade C16/20 Concrete Soaked in XA2 solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	duration of Soacking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
49	6	0	9/15/19	28	101	102	101	2401	2308	269.8	26.19	31.57
50					104	102	102	2386	2205	325.5	30.68	
51					102	102	100	2378	2286	337.6	32.45	
52		5	9/15/19	28	103	101	101	2397	2281	290.7	27.94	27.53
53					103	100	101	2386	2294	279.2	27.11	
54					104	102	102	2455	2269	227.0	21.40	
55		10	9/15/19	28	100	101	100	2332	2309	220.6	21.84	22.26
56					101	101	101	2354	2285	231.4	22.68	
57					101	101	101	2347	2278	173.9	17.05	
58		15	9/15/19	28	104	102	103	2439	2232	212.1	19.99	18.98
59					101	101	101	2369	2299	183.2	17.96	
60					103	103	102	2412	2229	168.8	15.91	
61	24	0	9/16/19	28	102	103	103	2460	2273	273.5	26.03	25.11
62					105	102	103	2472	2241	259.0	24.18	
63					102	102	101	2368	2254	208.3	20.02	
64		5	9/16/19	28	104	103	102	2484	2273	238.7	22.28	24.51
65					104	100	103	2453	2290	278.0	26.73	
66					104	101	103	2444	2259	216.9	20.65	
67		10	9/16/19	28	103	102	102	2439	2276	254.9	24.26	24.10
68					103	102	103	2449	2263	251.4	23.93	
69					104	102	102	2414	2231	225.0	21.21	
70		15	9/16/19	28	101	101	101	2340	2271	117.3	11.50	18.08
71					102	102	101	2394	2278	195.3	18.77	
72					102	101	101	2354	2262	179.2	17.39	
73	72	0	9/17/19	28	102	103	103	2421	2237	278.2	26.48	25.40
74					102	105	104	2452	2201	259.2	24.20	
75					103	103	103	2443	2236	270.8	25.53	
76		5	9/18/19	28	103	104	102	2458	2250	238.0	22.22	22.99
77					103	103	103	2450	2242	246.7	23.25	
78					101	102	103	2411	2272	242.0	23.49	
79		10	9/18/19	28	102	104	101	2421	2260	238.5	22.48	22.39
80					101	102	104	2454	2290	241.5	23.44	
81					102	103	103	2417	2234	223.1	21.24	
82		15	9/18/19	28	102	104	103	2403	2199	203.8	19.21	19.10
83					102	103	104	2430	2224	200.0	19.04	
84					101	101	103	2415	2298	194.3	19.05	
85	28 Days	0	9/18/19	28	100	100	100	2,404	2,404	221.3	22.13	20.81
86					100	100	100	2,377	2,377	204.3	20.43	
87					100	100	100	2,376	2,376	198.6	19.86	
88		5	9/18/19	28	100	100	100	2,350	2,350	168.7	16.87	19.37
89					100	100	100	2,385	2,385	184.3	18.43	
90					100	100	100	2,422	2,422	203.0	20.30	
91		10	9/18/19	28	100	100	100	2,414	2,414	157.5	15.75	16.60
92					100	100	100	2,365	2,365	181.7	18.17	
93					100	100	100	2,395	2,395	158.7	15.87	
94		15	9/18/19	28	100	100	100	2,419	2,419	163.3	16.33	16.53
95					100	100	100	2,373	2,373	167.2	16.72	
96					100	100	100	2,384	2,384	165.5	16.55	

Table A. 17: Results for grade C20/25 soaked in XA1

Grade C20/25 Concrete soaked in XA1 Solution												
Cube No.	Age at Soaking (Hrs)	SDA content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
97	6	0	9/16/19	28	102	101	101	2375	2283	346.0	33.59	34.05
98					104	102	103	2457	2249	360.8	34.01	
99					102	102	102	2461	2319	359.4	34.54	
100		5	9/16/19	28	103	102	104	2485	2274	342.5	32.60	30.48
101					102	101	102	2440	2322	292.1	28.35	
102					103	101	103	2449	2286	174.9	16.81	
103		10	9/16/19	28	101	101	102	2366	2274	293.9	28.81	29.95
104					101	102	101	2362	2270	320.2	31.08	
105					101	104	101	2404	2266	287.7	27.39	
106		15	9/16/19	28	102	101	102	2447	2329	241.9	23.48	23.26
107					104	102	102	2453	2267	244.4	23.04	
108					101	103	102	2428	2288	189.4	18.21	
109	24	0	9/16/19	28	101	102	101	2453	2358	287.4	27.90	29.39
110					101	101	101	2445	2373	315.1	30.89	
111					103	101	101	2431	2314	268.3	25.79	
112		5	9/19/19	28	102	104	101	2434	2272	361.9	34.12	32.73
113					102	103	101	2444	2303	329.3	31.34	
114					101	101	103	2387	2272	283.4	27.78	
115		10	9/16/19	28	102	101	103	2455	2314	292.5	28.39	27.24
116					104	102	102	2455	2269	276.6	26.07	
117					103	101	101	2460	2341	283.5	27.25	
118		15	9/17/19	28	102	102	103	2417	2255	221.8	21.32	21.13
119					102	102	104	2425	2241	227.8	21.90	
120					102	102	103	2440	2277	210.0	20.18	
121	72	0	9/19/19	28	104	102	103	2456	2247	352.3	33.21	31.42
122					103	102	102	2376	2217	311.2	29.62	
123					101	103	102	2449	2308	299.3	28.77	
124		5	9/19/19	28	103	101	101	2428	2311	321.6	30.91	29.48
125					103	102	101	2457	2315	294.6	28.04	
126					104	102	102	2450	2264	265.5	25.03	
127		10	9/19/19	28	102	103	100	2449	2331	303.1	28.85	27.49
128					102	105	102	2491	2280	279.2	26.07	
129					103	104	101	2480	2292	295.0	27.54	
130		15	9/19/19	28	102	104	102	2461	2274	211.8	19.97	23.57
131					101	104	100	2401	2285	267.8	25.50	
132					102	102	102	2436	2295	225.1	21.64	
133	28 Days	0	9/20/19		100	100	100	2397	2397	243.2	24.32	24.88
134					100	100	100	2398	2398	254.4	25.44	
135					100	100	100	2406	2406	229.7	22.97	
136		5	9/29/19		100	100	100	2427	2427	287.2	28.72	23.81
137					100	100	100	2427	2427	240.4	24.04	
138					100	100	100	2425	2425	235.8	23.58	
139		10	9/29/19		100	100	100	2334	2334	238.2	23.82	24.02
140					100	100	100	2353	2353	235.6	23.56	
141					100	100	100	2340	2340	246.8	24.68	
142		15	9/29/19		100	100	100	2316	2316	212.1	21.21	20.43
143					100	100	100	2384	2384	205.1	20.51	
144					100	100	100	2346	2346	195.6	19.56	

Table A. 18: Results for grade C20/25 soaked in XA2

Grade C20/25 concrete in XA2 Solution												
Cube No.	Age st Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
145	6	0	9/16/19	28	101	104	101	2423	2284	340.0	32.37	32.19
146					104	102	101	2447	2284	334.5	31.53	
147					103	101	101	2399	2283	340.0	32.68	
148		5	9/16/19	28	102	102	102	2433	2293	298.2	28.66	28.40
149					101	102	104	2461	2297	284.7	27.64	
150					103	100	105	2468	2282	297.8	28.91	
151		10	9/16/19	28	100	103	101	2392	2299	286.9	27.85	28.26
152					102	101	101	2382	2289	274.1	26.61	
153					101	102	101	2401	2308	312.3	30.31	
154	6	15	9/16/19	28	103	102	102	2480	2314	225.4	21.45	22.74
155					103	101	102	2488	2345	249.7	24.00	
156					102	101	103	2488	2345	234.4	22.75	
157	24	0	9/16/19	28	103	103	103	2458	2249	331.5	31.25	30.22
158					101	102	103	2426	2286	300.7	29.19	
159					100	101	102	2397	2327	219.5	21.73	
160		5	9/16/19	28	104	101	104	2479	2269	294.1	28.00	28.68
161					101	102	101	2377	2284	302.4	29.35	
162					101	100	101	2358	2312	239.6	23.72	
163		10	9/16/19	28	103	103	101	2459	2295	248.1	23.39	28.87
164					103	103	103	2487	2276	306.4	28.88	
165					103	103	103	2474	2264	306.1	28.85	
166		15	9/17/19	28	102	104	103	2484	2273	245.0	23.10	23.09
167					104	103	101	2465	2278	242.0	22.59	
168					102	102	103	2432	2269	245.2	23.57	
169	72	0	9/19/19	28	103	102	103	2417	2234	308.4	29.35	31.76
170					102	102	103	2429	2267	355.4	34.16	
171					104	102	103	2463	2254	252.5	23.80	
172		5	9/19/19	28	102	103	104	2401	2197	285.8	27.20	30.00
173					102	103	101	2439	2298	322.0	30.65	
174					104	102	102	2450	2264	311.3	29.35	
175		10	9/19/19	28	103	102	102	2445	2282	284.3	27.06	26.69
176					102	102	103	2450	2286	273.9	26.33	
177					103	104	102	2493	2281	305.2	28.49	
178		15	9/19/19	28	103	105	101	2456	2248	222.9	20.61	23.06
179					103	101	101	2413	2297	259.8	24.97	
180					101	101	102	2386	2293	240.7	23.60	
181	28 Days	0	9/29/19		100	102	100	2427	2379	235.8	23.12	23.44
182					100	100	100	2403	2403	235.6	23.56	
183					100	100	100	2419	2419	236.5	23.65	
184		5	9/29/19		100	100	100	2453	2453	243.8	24.38	23.35
185					100	100	100	2343	2343	227.4	22.74	
186					100	100	100	2399	2399	229.2	22.92	
187		10	9/29/19		100	100	100	2338	2338	232.7	23.27	22.93
188					100	100	100	2335	2335	231.6	23.16	
189					100	100	100	2329	2329	223.6	22.36	
190		15	9/29/19		100	100	100	2332	2332	206.1	20.61	20.41
191					100	100	100	2393	2393	209.9	20.99	
192					100	100	100	2383	2383	196.2	19.62	

Table A. 19: Results for grade C25/30 soaked in XA1

Grade C25/30 Concrete in XA1 Solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
193	6	0	9/14/19	28	193	101	100	2315	1188	467.1	23.96	23.30
194					194	103	100	2406	1204	452.3	22.64	
195					195	103	101	24105	11883	514.3	25.61	
196		5	9/14/19	28	196	101	100	2389	1207	417.5	21.09	21.07
197					197	101	101	2373	1181	419.0	21.06	
198					198	102	100	2383	1180	338.5	16.76	
199		10	9/14/19	28	199	100	100	2376	1194	334.4	16.80	17.15
200					200	101	100	2382	1179	327.9	16.23	
201					201	103	100	2395	1157	381.4	18.42	
202		15	9/14/19	28	202	101	100	2368	1161	303.4	14.87	15.24
203					203	100	100	2375	1170	306.9	15.12	
204					204	101	100	2380	1155	323.9	15.72	
205	24	0	9/14/19	28	205	100	100	2458	1199	443.2	21.62	21.84
206					206	100	100	2450	1189	454.6	22.07	
207					207	102	100	2488	1178	319.5	15.13	
208		5	9/14/19	28	208	102	102	2472	1142	389.3	18.35	18.42
209					209	103	102	2476	1128	410.9	19.09	
210					210	102	101	2453	1134	381.6	17.82	
211		10	9/15/19	28	211	101	101	2400	1115	245.8	11.53	12.86
212					212	102	102	2488	1128	278.4	12.87	
213					213	101	102	2397	1092	304.7	14.16	
214		15	9/15/19	28	214	104	103	2451	1069	263.4	11.84	12.51
215					215	104	102	2452	1075	286.2	12.80	
216					216	104	102	2432	1061	289.7	12.90	
217	72	0	9/16/19	28	217	102	101	2438	1091	436.6	19.73	19.80
218					218	102	102	2421	1067	424.9	19.11	
219					219	102	101	2467	1093	459.1	20.55	
220		5	9/16/19	28	220	102	102	2463	1076	354.8	15.81	16.62
221					221	104	101	2464	1061	393.7	17.13	
222					222	101	102	2460	1076	379.6	16.93	
223		10	9/17/19	28	223	102	103	2485	1061	222.4	9.78	14.17
224					224	103	105	2455	1013	322.8	13.99	
225					225	103	103	2475	1037	332.4	14.34	
226		15	9/17/19	28	226	103	104	2424	1001	234.1	10.06	9.63
227					227	102	103	2453	1029	262.3	11.33	
228					228	103	102	2414	1008	176.0	7.49	
229	28 Days	0	9/29/19		229	100	100	2402	1049	393.1	17.17	17.12
230					230	100	100	2380	1035	388.8	16.90	
231					231	100	100	2401	1039	399.6	17.30	
232		5	9/29/19		232	100	100	2393	1031	265.0	11.42	11.56
233					233	100	100	2399	1030	325.7	13.98	
234					234	100	100	2430	1038	217.3	9.29	
235		10	9/29/19		235	100	100	2423	1031	224.6	9.56	9.48
236					236	100	100	2370	1004	210.7	8.93	
237					237	100	100	2413	1018	235.6	9.94	
238		15	9/29/19		238	100	100	2417	1016	225.5	9.47	9.52
239					239	100	100	2408	1008	228.3	9.55	
240					240	100	100	2410	1004	228.8	9.53	

Table A. 20: Results for grade C25/30 soaked in XA2

Grade C25/30 Concrete soaked in XA2 Solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
241	6	0	9/14/19	28	100	101	102	2395	2325	422.7	41.85	43.21
242					104	101	100	2413	2297	468.2	44.57	
243					100	103	102	2450	2332	480.8	46.68	
244		5	9/14/19	28	101	101	101	2492	2418	300.8	29.49	36.53
245					100	102	102	2449	2354	370.4	36.31	
246					101	102	101	2442	2347	378.5	36.74	
247		10	9/14/19	28	101	102	101	2449	2354	255.3	24.78	27.06
248					101	102	101	2466	2370	283.9	27.56	
249					105	100	102	2476	2312	278.8	26.55	
250		15	9/14/19	28	100	102	101	2373	2303	346.9	34.01	33.63
251					100	104	100	2419	2326	337.6	32.46	
252					100	104	100	2404	2312	357.8	34.40	
253	24	0	9/14/19	28	103	102	101	2454	2313	468.1	44.56	43.78
254					101	101	101	2460	2388	438.9	43.03	
255					102	104	101	2466	2302	464.3	43.77	
256		5	9/14/19	28	102	103	102	2468	2303	308.4	29.35	35.89
257					103	100	102	2480	2361	378.7	36.77	
258					104	100	101	2462	2344	364.2	35.02	
259		10	9/15/19	28	102	103	101	2394	2256	218.4	20.79	24.63
260					103	104	103	2501	2267	304.9	28.46	
261					103	104	102	2464	2255	277.4	25.90	
262		15	9/15/19	28	103	101	103	2421	2259	288.9	27.77	26.76
263					102	102	102	2434	2294	281.5	27.06	
264					102	104	103	2432	2226	269.9	25.44	
265	72	0	9/16/19	28	101	103	101	2448	2330	442.1	42.50	43.06
266					102	103	102	2445	2282	458.3	43.62	
267					103	101	101	2473	2354	449.5	43.21	
268		5	9/16/19	28	101	101	102	2476	2380	376.5	36.91	34.61
269					104	102	102	2482	2294	368.5	34.74	
270					104	102	102	2467	2280	341.5	32.19	
271		10	9/17/19	28	102	102	103	2395	2235	279.3	26.85	27.91
272					102	103	104	2461	2252	288.4	27.45	
273					102	105	104	2471	2218	315.3	29.44	
274		15	9/17/19	28	102	102	104	2455	2269	244.5	23.50	24.99
275					102	102	104	2459	2273	258.1	24.81	
276					102	103	103	2426	2242	280.1	26.66	
277	28 Days	0	9/29/19		100	100	100	2384	2384	359.4	35.94	37.48
278					100	100	100	2403	2403	374.4	37.44	
279					100	100	100	2392	2392	375.1	37.51	
280		5	9/29/19		100	100	100	2453	335	376.5	37.65	37.25
281					100	100	100	2465	303	368.5	36.85	
282					100	100	100	2408	330	341.5	34.15	
283		10	9/29/19		100	100	100	2393	2393	231.7	23.17	27.58
284					100	100	100	2361	2361	266.9	26.69	
285					100	100	100	2381	2381	284.6	28.46	
286		15	9/29/19		100	100	100	2303	2303	210.5	21.05	21.15
287					100	100	100	2380	2380	212.4	21.24	
288					100	100	100	2420	2420	251.4	25.14	

Table A. 21: Results for grade C30/37 soaked in XA1

Grade C30/37 Concrete soaked in XA1 Solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
289	6	0	8/30/19	28	153	150	151	8120	2343	970.7	42.30	42.36
290					154	150	150	8125	2345	979.9	42.42	
291					150	150	150	8032	2380	1101.4	48.95	
292		5	8/30/19	28	103	101	101	2396	2280	351.3	33.77	32.24
293					100	100	100	2397	2397	317.7	31.77	
294					103	100	100	2382	2313	321.3	31.19	
295		10	8/31/19	28	100	101	100	2374	2351	302.1	29.91	28.85
296					103	103	102	2380	2199	294.9	27.80	
297					152	150	150	7974	2332	899.6	39.46	
298		15	8/31/19	28	101	100	100	2344	2321	282.6	27.98	25.23
299					100	100	101	2358	2335	224.7	22.47	
300					101	100	100	2334	2311	330.2	32.69	
301	24	0	8/31/19	28	150	153	150	7945	2308	906.4	39.49	40.23
302					150	152	150	7978	2333	933.9	40.96	
303					150	153	150	8061	2342	1022.3	44.54	
304		5	1/31/19	28	101	100	104	2477	2358	263.8	26.12	26.87
305					100	100	102	2396	2349	276.3	27.63	
306					100	101	100	2491	2466	233.1	23.08	
307		10	2/1/19	28	101	100	101	2422	2374	253.0	25.05	25.61
308					100	101	100	2412	2388	264.4	26.18	
309					102	101	100	2398	2327	290.9	28.24	
310		15	9/1/19	28	101	100	100	2394	2370	273.5	27.08	26.20
311					100	100	99	2382	2406	271.5	27.15	
312					100	100	100	2394	2394	243.7	24.37	
313	72	0	9/2/19	28	102	100	100	2426	2379	339.2	33.25	33.90
314					100	100	102	2433	2385	345.4	34.54	
315					100	100	103	2452	2381	287.4	28.74	
316		5	9/2/19	28	100	101	102	2454	2382	274.3	27.16	27.82
317					104	100	100	2484	2388	296.3	28.49	
318					102	100	100	2460	2412	357.0	35.00	
319		10	9/3/19	28	100	100	101	2392	2369	243.5	24.35	25.36
320					100	100	100	2416	2416	263.7	26.37	
321					100	101	100	2406	2382	306.2	30.32	
322		15	9/3/19	28	100	100	101	2383	2360	284.3	28.43	27.37
323					100	100	100	2392	2392	256.4	25.64	
324					100	100	100	2395	2395	280.3	28.03	
325	28 Days	0	9/29/19		100	100	100	2440	2440	358.0	35.80	35.23
326					100	100	100	2432	2432	348.2	34.82	
327					100	100	100	2446	2446	350.6	35.06	
328		5	9/29/19		100	100	100	2466	2466	294.3	29.43	29.69
329					100	100	100	2421	2421	299.0	29.90	
330					100	100	100	2436	2436	297.4	29.74	
331		10	9/29/19		150	150	150	7914	2345	687.5	30.56	29.91
332					150	150	150	7837	2322	674.1	29.96	
333					150	150	150	7888	2337	657.4	29.22	
334		15	9/29/19		150	150	150	7811	2314	579.5	25.76	25.18
335					150	150	150	7855	2327	554.4	24.64	
336					150	150	150	7796	2310	565.5	25.13	

Table A. 22: Results for grade C30/37 soaked in XA2

Grade Class C30/37 Concrete soaked in XA2 Solution												
Cube No.	Age at Soaking (Hrs)	SDA Content (%)	Date Tested	Duration of Soaking	Cube Dimensions (mm)			Mass in Air (g)	Density (Kg/m^3)	Crushing Load (kN)	Compressive strength (MPa)	Average Compressive strength (MPa)
					Length	Width	Height					
337	6	0	8/30/19	28	150	150	150	8077	2393	1003.5	44.60	43.53
338					152	150	150	8016	2344	968.3	42.47	
339					150	150	150	7902	2341	692.9	30.80	
340		5	8/30/19	28	102	100	100	2388	2341	318.4	31.22	31.29
341					102	100	100	2404	2357	320.0	31.37	
342					102	100	101	2384	2314	360.3	35.32	
343		10	8/31/19	28	150	153	152	7559	2167	735.0	32.03	32.13
344					150	153	150	1921	558	739.9	32.24	
345					150	150	151	7989	2352	393.3	17.48	
346		15	8/31/19	28	100	100	101	2352	2328	238.4	23.84	28.36
347					100	100	101	2342	2319	291.3	29.13	
348					100	100	101	2315	2292	275.8	27.58	
349	24	0	1/31/19	28	153	150	150	8085	2349	911.7	39.73	33.59
350					150	153	150	8010	2327	629.9	27.45	
351					150	150	155	8096	2321	528.3	23.48	
352		5	8/31/19	28	100	100	102	2382	2336	263.0	26.30	26.35
353					100	100	102	2418	2371	264.0	26.40	
354					102	101	105	2485	2298	237.1	23.01	
355		10	9/1/19	28	100	101	101	2416	2368	259.6	25.70	25.92
356					101	100	100	2431	2407	264.0	26.14	
357					101	100	100	2469	2444	333.0	32.97	
358		15	9/1/19	28	100	100	100	2376	2376	291.6	29.16	26.82
359					101	101	100	2397	2349	256.9	25.18	
360					103	100	100	2405	2335	268.9	26.11	
361	72	0	9/2/19	28	100	105	100	293.6	280	279.6	26.63	31.65
362					100	102	101	324.5	315	315.0	30.88	
363					100	100	104	337.2	324	324.2	32.42	
364		5	9/2/19	28	100	102	100	2473	2425	273.0	26.76	26.82
365					102	100	100	2446	2398	274.1	26.87	
366					100	104	103	2465	2301	232.7	22.38	
367		10	9/3/19	28	100	100	100	2388	2388	254.6	25.46	29.55
368					150	150	150	7921	2347	666.3	29.61	
369					150	150	151	7933	2335	663.3	29.48	
370		15	9/3/19	28	100	101	101	2342	2296	274.4	27.17	26.68
371					100	101	101	2434	2386	258.4	25.58	
372					100	101	100	2429	2405	275.6	27.29	
373	28 Days	0	9/29/19		100	100	100	2432	2432	312.5	31.25	31.78
374					100	100	100	2437	2437	325.4	32.54	
375					100	100	100	2427	2427	315.4	31.54	
376		5	9/29/19		100	102	100	2470	2422	272.6	26.73	25.74
377					100	104	103	2440	2278	253.5	24.38	
378					102	100	100	2444	2396	266.5	26.13	
379		10	9/29/19		150	150	150	7954	2357	583.3	25.92	26.68
380					150	150	150	8082	2395	628.9	27.95	
381					150	150	150	7985	2366	588.8	26.17	
382		15	9/29/19		100	100	100	2423	2423	167.5	16.75	16.98
383					100	100	100	2398	2398	176.3	17.63	
384					100	100	100	2394	2394	165.5	16.55	