# STRENGTH AND DURABILITY PROPERTIES OF CONCRETE BLENDED WITH PUMICE AND SCORIA UNDER COMBINED ATTACK OF SULPHATE AND CHLORIDE

**Safiel Tumaini Chambua**

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# ABSTRACT

Concrete structures suffer serious deterioration under corrosive environment. Consequently, the safety of these concrete structures is decreased. The influence of natural pumice (NP) and natural scoria (NS) as supplementing cementing materials of concrete exposed to sulphate, chloride and combined effect of sulphate and chloride is studied. Portland cement (PLC) was replaced with NP or NS at a substitution level of 10%. Concrete samples were submerged in portable water for 28 days. Afterwards, the specimens were immersed in 5% sodium sulphate ($Na_2SO_4$), 5% sodium chloride (NaCl) and combined sodium sulphate and chloride solutions for 28, 56 and 90 days. The results were compared between concrete mixes with NP or NS and control mix (CT) with PLC. The effects of sulphate, chloride and combined sulphate and chloride were evaluated in terms of change in weight, variation in compressive strength and degree of damage. The compressive strength was not compromised at 10% substitution level. It was observed that, concrete containing NP and NS have compressive strength of 46 MPa (7.7%) and 44 MPa (3.04%) higher than 42.7 MPa of CT submerged in water for 90 days respectively. Concrete samples immersed in 5% $Na_2SO_4$ solution, NP and NS has a compressive strength around 45.5 MPa (15.4%) and 44.8 MPa (13.6%) higher than 39.4 MPa of CT mix at 90 days, respectively. However, under 5% NaCl solution the compressive strength of concrete containing NP and NS decreased up to 34.2 MPa (7.5%) and 32.5 MPa (7.2%) for 90 days cured samples. Moreover, under combined effect of 5% $Na_2SO_4$ and 5% NaCl concrete containing NP and NS has a compressive strength around 29.8 MPa (8%) and 29.2 MPa (7.3%) higher than 27.4 MPa of control mix at the exposure period of 90 days. It can be concluded that NP and NS have extraordinary potential to be utilized as a cementitious material in concrete.

## DECLARATION

I, Safiel Tumaini Chambua do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Safiel Tumaini Chambua

______________________________ ______________________

Name and signature of candidate Date

The above declaration is confirmed

Dr. Yusufu Abeid Chande Jande

______________________________ ______________________

Name and signature of supervisor 1 Date

Prof. Revocatus Lazaro Machunda

______________________________ ______________________

Name and signature of supervisor 2 Date

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## CERTIFICATION

The undersigned certifies that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology a dissertation titled *"Strength and Durability Properties of Concrete Blended with Pumice and Scoria Under Combined Attack of Sulphate and Chlorides"* and recommend for examination in partial fulfillment of the requirements for the degree of Master's in Materials Science and Engineering of the Nelson Mandela African Institution of Science and Technology.

Dr. Yusufu Abeid Chande Jande

____________________________ ____________________

Name and signature of supervisor 1 Date

Prof. Revocatus Lazaro Machunda

____________________________ ____________________

Name and signature of supervisor 2 Date

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# DEDICATION

The work is dedicated to my family, friends who have always been there for support throughout my study and Department of Materials Science and Engineering of the Nelson Mandela African Institution of Science and Technology (NM-AIST).

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## LIST OF ABBREVATIONS AND SYMBOLS

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| BET | Brunauer-Emmett-Teller |
| BS | British Standard |
| $C_2S$ | Dicalcium Silicate |
| $C_3A$ | Tricalcium Aluminate |
| $C_3S$ | Tricalcium Silicate |
| CA | Coarse Aggregates |
| CH | Calcium Hydroxide |
| C–S–H | Calcium–Silicate–Hydrates |
| FA | Fly Ash |
| FA | Fine Aggregates |
| FM | Fineness Modulus |
| GGBFS | Ground Granulated Blast Furnace Slag |
| HPC | High Performance Concrete |
| LWC | Light Weight Concrete |
| MK | Metakaolin |
| NP | Natural Pumice |
| NS | Natural Scoria |
| NSHA | Neem Seed Husk Ashes |
| NSLWC | Non-Structured Light Weight Concrete |
| OPC | Ordinary Portland Cement |
| PAI | Pozzolanic Activity Index |
| PC | Portland Cement |
| PLC | Portland Limestone Cement |
| RHA | Rice Husk Ashes |
| SCBA | Sugar Cane Bagasse Ashes |
| SCC | Self–Compacting Concrete |
| SCMs | Supplementary Cementing Materials |
| SF | Silica Fume |
| SG | Specific Gravity |
| TBS | Tanzanian Bureau of Standard |
| XRF | X–Ray Fluorescence |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the Problem

Cement concrete is a composite material made of aggregates and paste which comprises Portland cement and water. The aggregates are comprised with sand, gravel or crushed stones (Antoni *et al.*, 2012). The cement concrete reinforced with steel bars is known as reinforced concrete. The reinforcements are used to improve properties and to satisfy wide range of application (Bhushan *et al.,* 2017).

The increase in degradation and environmental problems have led the researches to modify concrete ingredients such as cement to overcome these problem (Mlinárik & Kopecskó, 2013). Concrete structures such as tunnels, bridges or buildings suffers serious deterioration across the globe. Moreover, the cost of repairing and maintaining these structures are costfully. Also, the service life of these structures after maintenance and repair is not guaranteed (Mlinárik & Kopecskó, 2013).

Additionally, cement manufacture industries produce $CO_2$ which is 7% of the global carbon dioxide. Manufacturing one of tone of cement produce one tone of carbon dioxide (Thomas, 2018). Usually, concrete modification is adopted to improve concrete properties at its fresh and hardened state (Antoni *et al.*, 2012; Noor ul, 2012) together with aiming to produce green house and sustainable concrete to overcome environmental problems (Scrivener, 2014).

The concrete durability becomes a major concern since the capacity to withstand imposed load decrease with time. Moreover, the cost of repair and replacement of deteriorated structures becomes astronomical (Hartell *et al.*, 2011; Niu *et al.*, 2013). Nowadays, there is prevailing interest to reduce cement content and enhance concrete strength and durability by using Supplementary Cementing Materials (SCMs) and make more durable and sustainable concrete with good structural properties (Aksoğan *et al.*, 2016; Mboya *et al.*, 2019). Properties of fresh and hardened concrete are improved by addition of SCMs regardless of reducing cement content (Mboya *et al.*, 2019). The SCMs addition improves workability and flow (Mboya *et al.,* 2019), produce less porous and denser concrete which increase resistance to chemical attack (Merida & Kharchi, 2015), shock absorbing ability is enhanced (Bogas & Cunha, 2017; Onoue *et al.*, 2015), and compressive and flexural strength is enhanced (Mboya *et al.*, 2019).

Cement is preferred material in concrete structures but structures made of Ordinary Portland Cement (OPC) tend to weaken faster when exposed to extreme conditions. Structure exposed to extreme conditions are like waste water treatment plants and marine structures (Jin *et al.*, 2016). Domestic and overseas researchers have studied the durability of concrete under different extreme conditions (Al-Swaidani & Aliyan, 2015; Aldred & Castel, 2014; Barbhuiya & Kumala, 2017; Gu *et al.*, 2019; Holt *et al.*, 2015; Zeyad *et al.*, 2020). It was singled out that, sulphate, chloride and acidic attack are utmost issues for concrete properties (Al-Swaidani & Aliyan, 2015; Kępniak *et al.*, 2019; Ming *et al.*, 2016).

Natural pumice (NP) and natural scoria (NS) are natural material that can be used as eco-friendly material in construction industry. Their utilization reduce energy consumption and $CO_2$ during cement manufacture (Lemougna *et al.*, 2018; Mboya *et al.*, 2019). Natural pumice and Natural scoria are pyroclastic material rich in silica, alumina and iron oxide (Lemougna *et al.,* 2018). Around the world, NP and NS have been utilized as fine and coarse aggregate in concrete production, building blocks (Mboya *et al.,* 2019). Top *et al.* (2018) investigated the utility of NP as course aggregate in light weight geopolymer concrete. Then again, NP and NS have been used as fine and coarse aggregate for non-structural concrete and mortar (Bogas & Cunha, 2017; Tchamdjou *et al.*, 2018; Tchamdjou *et al.*, 2017).

However, based on previous studies, there is lack of literature on the properties of concrete containing NP and NS as supplementary cementitious material under combined exposure of sulphate and chloride. Moreover, the earlier inputs by Mboya et al. (2019) validated that the strength properties of concrete incorporated with NP and NS were satisfactory at a 10% substitution level. The 10% substitution level as recommended is adopted. Therefore work presented, explore the application of NP and NS as SCMs in concrete under combined effect of sulphate and chloride solution exposure conditions. Strength, change in weight, degree of damage are evaluated.

## 1.2 Statement of the Problem

Approximately 75% of the cement powder is utilized to produce Calcium-silicate hydrate (C-S-H) during cement hydration of Portland cement. The aggregates are bounded together by C-S-H and remaining 25% is portlandite (Calcium hydroxide-CH) as a byproduct that have a negative effects on concrete properties under corrosive environment. Pozzolans have been reported to be best SCMs to consume CH. There is growing interest to produce green and durable concrete from natural materials. Pumice and Scoria are among natural materials that are utilized as pozzolans that are rich in silica and alkali with high fineness. Researchers have been investigating the properties of containing Pumice and Scoria (Al-Swaidani, 2018; Al-Swaidani & Aliyan, 2015; Al-Swaidani *et al.*, 2016; Granata, 2015; Mboya *et al.,* 2019). However, no studies have reported on the concrete properties containing Pumice and Scoria under combined attack of sulphate and chloride. The experimental work is therefore aiming to evaluate the mechanical and durability properties of concrete containing Pumice and Scoria under combined attack of sulphate and chloride for short exposure time.

## 1.3 Rationale of the Study

The rationale of this study is to increase the service life of concrete by strengthen the strength and durability in sulphate and chloride environment by mixing cement with natural Pozzolans. This will lead to strong and stable structures which are more resistant to aggressive environment. Furthermore, green and sustainable concrete will be produced.

## 1.4 Objectives

### 1.4.1 Main Objective

To investigate the strength and durability properties of concrete incorporated with Scoria and Pumice as cement supplement materials under combined attack of sulphate and chloride.

### 1.4.2 Specific Objectives

(i) To assess the properties of concrete ingredients and proportioning.

(ii) To assess the strength and durability properties of Pumice and Scoria based concrete under combined attack of sulphate and chloride.

(iii) To evaluate the influence of Pumice and Scoria on the hydration of cement.

## 1.5 Research Questions

(i) Do the properties of aggregates and binders suitable to be used in production of concrete?

(ii) What is the impact of Pumice and Scoria on the resistance of concrete under combined attack of sulphate and chloride?

## 1.6 Significance of the Study

Safety and economic factors are major aspect to be considered during concrete structure design. It is advised to explore materials before they are endorsed for certain applications. This study is aiming to provide understanding on the behavior of concrete incorporated with Pumice and Scoria when exposed to combined attack of sulphate and chloride. This will attract application of Pumice and Scoria in the construction industry in order to produce durable and sustainable concrete and also the accessibility of raw materials for cement production will be increased.

## 1.7 Delineation of the Study

The focus of this study is to investigate the properties of concrete containing pumice and scoria as supplementary cementing materials exposed to combined attack of sulphate and chloride. The materials used are Pumice from Mbeya and Scoria from Uchira-Moshi. The first part of the study was based in producing Pumice and Scoria powder by using a disc miller and milled to have a fineness like cement for which the elemental analysis was done. The additional part of this study based on studying the properties of concrete incorporated with pumice and scoria exposed to combined attack of sulphate and chloride. Mechanical and durability properties were evaluated after exposure period of 28 days, 56 days and 90 days. The mass of concrete samples were recorded before and after exposure time was reached. The mass loss was calculated as the mass difference by considering each exposure condition. The compressive strength and degree of damage were determined for all concrete samples considered.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Cement

Cement is a common material in construction industry. In the presence of water it binds sand and gravel. The compact structure id formed after hydration process. Due to their ability of setting and hardens in presence of water, Portland cements (PC) are used as hydraulic cement. PC has four main phases, which are alite (50-70% tricalcium silicate - $Ca_3SiO_5$) belite (15-30% di-calcium silicate - $Ca_2SiO_4$) aluminate (5-10% tri-calcium aluminate - $Ca_3Al_2O_6$) and ferrite (5-15% tetra-calcium aluminoferrite -$CaAlFeO_5$). Raw materials which are rich in silicates, aluminates and iron oxides are used to manufacture them (Hewlett & Liska, 2019; Neville & Brooks, 2010). Manufacturing of PC requires high energy and also has high emission of $CO_2$.

The process of mixing PC with inorganic materials gives a composite cement. Organic materials blended together with cement gives additional strength and contribute to hydration process of cement. (Neville & Brooks, 2010). The collective term of these material is supplementary cementing materials (SCMs). They exhibit properties like pozzolanic and latent hydraulic properties. The reason of using composite cement is to improve properties of mortar, concrete, environment conservation reason, reducing energy consumption (Alp *et al.*, 2009; Sabir *et al.*, 2001).

The compositions of hydraulic cement is between those of pozzolanic materials and PC. It is mixed with pozzolanic material to improve mortar and concrete properties such as strength, durability and permeability. Addition of pozzolanic materials lower the cost of cement (Al-Chaar *et al.*, 2011; Nair *et al.*, 2006). The pozzolanic materials has advantages in construction industries and in cement manufacture industries in terms of cost, energy saving and natural resources conservation. The pozzolanic materials are produced by blending PC with Ground Granulated Blast Furnace Slag (GGBFS) or fly ash (FA) (Neville & Brooks, 2010). Moreover, it was found that calcination of clays such as kaolinite has greater potential as artificial pozzolanic material due to their availability around the world (Al-Ajeel *et al.*, 2012).

## 2.2 Cement Hydration

The process by which the main compounds of cement chemically react with water to yield calcium silicate hydrate (C-S-H) gel and calcium hydroxide (CH) is termed as hydration. Various solid phases are formed when the main cement minerals hydrate at different rates. The phases formed are the ones influencing the strength of the formed cement paste (Gartner *et al.*, 2002). The hydration process of the calcium silicate minerals present in the Ordinary Portland Cement (OPC) highly influences the strength of formed cement paste. The early concrete strength is an outcome of the hydration of $C_3S$, which is the most plentiful and important mineral in OPC. The hydration of $C_2S$ has little influence on the early strength (Gambhir, 2013). As presented in Equation (1) and (2), the hydration of $C_3S$ and $C_2S$ yield C-S-H gel and C-H. However, the rate of solubility of $C_3S$ is relative high compared to $C_2S$ which yield high amount of free lime (CH) (Scrivener *et al.*, 2015).

$$3C_3S + 9H \rightarrow 3C - S - H + 6CH \quad (1)$$

$$2C_2S + 4H \rightarrow 2C - S - H + 2CH \quad (2)$$

About 75% of cement paste are converted to calcium silicate hydrate (C-S-H) due to hydration reactions of cement. The aggregates are bounded together by C-S-H. The 25% of cement paste remaining is mainly composed with calcium hydroxide (CH) as byproduct. Accumulation of CH in concrete has negative effect on steel reinforcement, increase alkalinity or acidity. Calcium hydroxide accelerates the alkali silica reaction in the presence of reactive aggregates which affect the compatibility of the concrete (Davidovits, 1994). In the presence of water, pozzolans react with portlandite (CH).

## 2.3 Pozzolanic Reaction

Pozzolans materials are alumino-silicate materials which can be natural or man-made and can be used as supplement to cement. These materials react with calcium hydroxide produced during hydration of cement to produce a highly cementitious product, C-S-H gel (Aprianti *et al.*, 2015). The reaction occurs at ordinary temperature. Commonly materials used as pozzolans to supplement cement are Silica fume and Fly ashes. The main chemical components of pozzolans are the oxides of silicon and aluminium metals. The C618 of the American Society for Testing and Materials (ASTM) specifies the chemical requirements of pozzolans as shown in Table 1.

**Table 1: ASTM C618 Chemical requirements of pozzolans**

| Chemical composition | Class | | |
|---|---|---|---|
| | N | F | C |
| Silicon dioxide ($SiO_2$) plus aluminum oxide ($Al_2O_3$) plus iron oxide ($Fe_2O_3$), min % | 70 | 70 | 50 |
| Sulfur trioxide ($SO_3$), max % | 4.0 | 5.0 | 5.0 |
| Moisture content, max % | 3.0 | 3.0 | 3.0 |
| Loss on Ignition (LoI), max % | 10.0 | 6.0 | 6.0 |

The CH produced in Equation (1) has no significant importance on improving concrete strength but has negative effect on the concrete durability properties. Pozzolans have high amount of silicon dioxide which upon their addition to cement with Ca $(OH)_2$ to yield excess C-S-H gel, as the main binding material in cement as described in Equation (3). Incorporation of pozzolans can result into green concrete products at a relatively low cost. Moreover, utilization of pozzolans to supplement cement reduce environment pollution by reducing the rate of $CO_2$ emissions.

$$3Ca_3SiO_5 + 7H_2O \rightarrow 3CaO.2SiO_2.4H_2O + 3Ca(OH)_2 \quad (3)$$

## 2.4 Concrete Aggregates

Aggregates occupies about three-quarters of the total volume of normal concrete. The properties of aggregates influence the properties of concrete at fresh and hardened state. The concrete performance is affected through their properties such as chemical, thermal and physical properties. Aggregates used in concrete or mortar are classified depending on their size and nature of their availability (Antoni *et al.*, 2012).

### 2.4.1 Effect of Aggregates

The concrete properties are mostly affected by aggregates properties. Aggregates properties like surface texture affects the aggregates bonds matrix which influence the strength of the concrete and affect the workability of the concrete. Crushed aggregates are most preferred in concrete production because of their angular surface textures which gives satisfactory concrete properties (Gambhir, 2013).

### 2.4.2 Classification and Grading of Aggregates

The aggregates used in concrete production are usually classified buy considering their size, unit weight and source. Based on unit weight or source, aggregates are classified as coarse aggregates (CA) on fine aggregates (FA). Based on size, the aggregates which their size is between 5 to 150 mm are known as CA and usually retained in 4.75 mm sieve. However, due to structural requirement and safety CA with a maximum size of 25 mm are widely used in construction industry. Fine aggregates particles sizes range between 4.75 mm and 75 µm sieve (BS 882:1992).

The number of voids which are present in aggregates affects the workability of the concrete at it fresh state. The volume occupied by voids are to be filled with equivalent volume of the cement paste (Neville & Brooks, 2010), hence proper selection of aggregates to be used in concrete production, the grading of aggregates is done by sieve analysis method. The grading curve is used to select suitable material for concrete production. Table 2 presents the commonly used sieves.

**Table 2: Sieve size designation and their sizes**

| Sieve designation | Nominal size of sieve opened |
|---|---|
| 6 in. | 150 mm |
| 3 in. | 75 mm |
| 1.5 in. | 37.5 mm |
| 3/4 in, | 19 mm |
| 3/8 in | 9.5 mm |
| No.4 | 4.75 mm |
| No.8 | 2.36 mm |
| No.16 | 1.18 mm |
| No.30 | 600 µm |
| No.50 | 300 µm |
| No.100 | 150 µm |
| No.200 | 75 µm |

The Fig. 1 demonstrate the aggregates distribution curve. It is well known that aggregates which are well graded with wide range of sizes and dense are recommended to be used in construction of concrete structures. The distribution curve is for both fine and coarse aggregate.

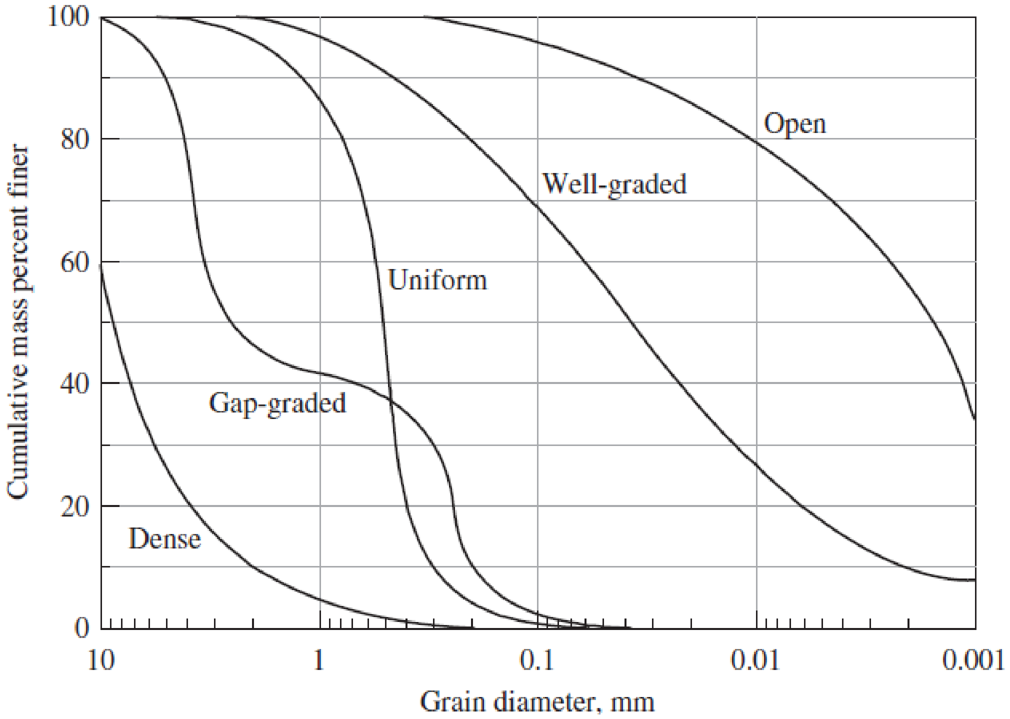


**Figure 1: Five types of aggregate gradation (Neville & Brooks, 2010)**

Under gap graded distribution it shows that aggregates falling in this category are missing some intermediary sizes and it's well-recognized due to the region that is nearly horizontally along the curve. The materials which are falling in uniform, gap-graded and open curve are missing certain range of sizes and materials falling in these categories are unsatisfactory and are not recommended to be used in construction activities. They will lead to weak structures (Gambhir, 2013; Neville & Brooks, 2010).

### 2.4.3 Fineness Modulus

The extent on how the aggregates are course or fine is given by fineness modulus (FM). The Fineness Modulus is basically calculated from a series of sieves from 6 in to No: 100 as given in Table 2. For the fine aggregates, the FM lies between 2.3 and 3.1. Large number indicate that the material is coarser one. The low the fineness modulus, the more the paste is required to produce the workable concrete. The FM is necessary parameter to be determined as it used to proportion aggregates and also influence the workability of the concrete (Duggal, 2008).

## 2.5 Water

Water occupies about 15 to 25 % of the total volume of concrete. The properties of concrete at fresh and hardened state are influenced by water (Gambhir, 2013; Kurdowski, 2014). Water is used for mixing, curing and washing of aggregates in concrete production as outlined below:

### 2.5.1 Mixing Water

The amount of water which is added to interact with cement to form a paste. The amount of water added reacts with cement to form the hydration products which binds the aggregates together. The water added affects the workability of the concrete and strength properties. Mixing water is therefore recommended to be free from chemical contamination and also should be safe for human consumption (Gambhir, 2013).

### 2.5.2 Water for Curing of Concrete

Water for curing of concrete has no restriction because concrete is cured in short period of time but will depending on the quality of the concrete required. Water containing organic and in organic matters can be used for curing of concrete. However, water containing corrosive species may cause disturbance on the growth of concrete strength. Accumulation of impurities is there recommended to be at acceptable limit water (Kurdowski, 2014).

### 2.5.3 Water for Washing Aggregate

Normally, aggregates are washed to remove unwanted organic matters and also materials coated on their surface which when not removed will affect the bonds between cement paste and aggregates. Water suitable for washing aggregates should not have a capability on forming films or coasts after washing the aggregates and should be free from chemical species which have detrimental effects (Duggal, 2008).

## 2.6 Supplementary Cementitious Materials

Around the global, researchers are extensively explore suitable and affordable materials to replace certain amount of cement for structural and non-structural use. The aim is to replace certain amount of cement in mortar and concrete without compromising properties of concrete at fresh and hardened state. Pozzolan appeared to be best supplementary cementing material. Pozzolans which are used to supplement cement react with the CH during cement hydration process (Frías *et al.*, 2005). Supplementary Cement Materials (SCMs) are utilized to improve concrete and mortar (Taylor *et al.*, 2012). Moreover, they are used as admixture in concrete production to improve properties like strength, chemical resistance and permeability (Al-Chaar *et al.*, 2013). Also, their utilization conserve environment, reduce $CO_2$ emission and promote economic benefits (Sabir *et al.,* 2001; Sajedi & Razak, 2010). Around the world, pozzolans have been used as materials to control cracking and heat resistant materials (Mehta, 2006).

## 2.7 Pozzolanic Materials

Pozzolan are natural materials composed of aluminosilicates mineral that react with CH at ambient temperature. They can be either from volcanic materials or calcined materials. They reacts chemically with lime to form a cementing compounds. These pozzolans are classified as natural or artificial pozzolans. Natural pozzolans do not need further treatment like heat treatment, they can be grinded to obtain a fine powder and used to supplement cement. Volcanic ashes and metakaolin are defined as natural pozzolans. Artificial pozzolans needs further treatment like heat treatment to increase their reactivity (Aiswarya *et al.*, 2013).

Mostly used pozzolans are volcanic ashes, GGBFS, Fly ashes, Silica fume, GGBFS. Fly ash are inorganic pozzolans. Organic pozzolans are agricultural byproducts for example Neem Seed Husk Ashes (NSHA), Rice Husk Ashes (RHA) (Aiswarya *et al.*, 2013; Akande *et al.*, 2011). The most reactive components of pozzolans are amorphous or semi-amorphous siliceous or aluminous (Naceri & Chikouche, 2008). The Fly ash, Silica fume, GGBFS and RHA are mostly utilized pozzolans.

### 2.7.1 Silica Fume

Silica fume (SF) byproduct of manufacture of silicon or silicon alloy. It's a non-crystalline material. Table 3 shows the basic oxides of silica fume and the particles have average diameter of 0.1 to 0.2 μm. Silica fume (SF) is best pozzolanic material due to its silica content and high fineness (Aldred *et al.*, 2006). Addition of silica fume as supplement to cement improves properties of cement and concrete at fresh and hardened state because of its high fineness (20000 $m^2$/kg) and pozzolanic activity. Addition SF reduce bleeding, permeability and increase durability by refine pore size and distribution with-in cement paste-aggregates. The parking effects increase concrete density thus increases its compressive strength (Al-Chaar *et al.*, 2011).

**Table 3: Chemical composition of some pozzolans**

| Oxide | MK | SF | FA | RHA | GGBFS | Scoria | Pumice |
|---|---|---|---|---|---|---|---|
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| $SiO_2$ | 54.1 | 93.55 | 27.88 – 59.68 | 94.95 | 31.2 | 45 – 50 | 60.82 |
| $Al_2O_3$ | 16.7 | 0.56 | 5.23 – 33.99 | 0.39 | 12.96 | 13 – 15 | 16.71 |
| $Fe_2O_3$ | 10.1 | 0.17 | 1.21 – 29.63 | 0.26 | 0.87 | 7 – 8 | 7.04 |
| CaO | 1.0 | 1.13 | 0.37 – 27.68 | 0.54 | 41.43 | 5 – 8 | 4.44 |
| MgO | 2.9 | 0.75 | 0.422 – 8.79 | 0.90 | 4.27 | 4 – 6 | 1.94 |
| $K_2O$ | 1.8 | 1.05 | 0.64 – 6.68 | 0.94 | 0.31 | 4 – 6 | 2.25 |
| $Na_2O$ | 0.5 | 0.14 | 0.20 – 6.90 | 0.25 | 0.11 | | 5.42 |
| $SO_3$ | 0.4 | 1.01 | 0.04 – 4.71 | | 0.04 | 0.01-0.02 | 0.14 |
| $TiO_2$ | 2.0 | 0.002 | 0.24 – 1.73 | 0.02 | 0.49 | | |
| LoI | 9.88 | 1.16 | 0.21 – 28.37 | 0.85 | 6.00 | 1.25 – 1.5 | 1.52 |

### 2.7.2 Fly Ash

Fly ash (FA) are acquired from combustion of pulverized coal in electrical power plant. FA is also used as supplement to cement to increase properties of cement and concrete. Fly ashes are class F and C ashes in nature (Aldred *et al.*, 2006). The maximum level of substation for class F fly ash 15 - 25% and 15 - 40% for class C fly ash. Fly ash class F are fine powder with good pozzolanic properties and care composed with reactive alumina and silica. Fly ash class C have fairly coarser particle rich in oxides of iron and calcium (Aldred *et al.*, 2006). Table 3 shows the basic oxides of fly ash.

### 2.7.3 Ground Granulated Blast Furnace Slag

The Ground Granulated Blast Furnace Slag (GGBFS) is a byproduct of the manufacture of iron, which is mostly composed of silica and alumina combined with oxides of iron and limestone. Ground Granulated Blast Furnace Slag possesses both hydraulic and pozzolanic properties and improves resistance against chloride ions protect steel reinforcements, low permeability and improves resistance against sulphate corrosion of cement-blended materials. Table 3 shows the basic oxides of GGBFS and fineness influence their properties as pozzolanic material. Due to their pozzolanic properties of GGBFS, the heavy structures such as dams and offshore structure are constructed by incorporate GGBFS blended (Al-Chaar *et al.*, 2013).

### 2.7.4 Metakaolin

Calcination of kaolinite at a temperature between 600 and 900 ºC gives metakaolin (MK). The MK is rich in silica as shown in Table 3 and because of its reactivity it is used as pozzolanic material to supplement cement in mortar and concrete. MK has high pozzolanic activity which influence early strength and long term strength when supplement cement. Shayma'a *et al.* (2012) reveal that kaolin calcinated at a temperature of clay as 700 ºC gives MK with good pozzolanic properties.

### 2.7.5 Rice Husk Ash

Rice husks are applied in different field of science such as fertilizer and in production of bio-fuel. Calcination of rice husks under controlled supply of oxygen produce rice husk ashes (RHA). Upon addition of calcination temperature, the reactive silica increases. Nair *et al.* (2006) reveal that in order to have a RHA with reactivity, the calcination temperature should range between 500 - 700 °C. Calcination of RHA at 700 ºC gives 94.95 percentage of silica as shown in Table 3. Varying of burning temperature and limited supply of oxygen give variations in silica contents. It was reported that RHA can replace cement up to 40% without compromising concrete or mortar strength (Della *et al.*, 2002).

### 2.7.6 Scoria

Scoria is natural rock material found on the earth surface after volcanic eruption (Hossain, (2006). Scoria is rich in iron which is seen through its red colored fragments and possess vesicular and crystalline structure (Mboya *et al.*, 2017). Scoria is rich in alumina, silica and iron oxide respectively as shown in Table 3. Around the world, Scoria has been used in production of lightweight concrete. With this regards, huge deposit of Scoria are found the world when processed could be used as supplement to cement and reduce the cost of cement.

### 2.7.7 Pumice

Pumice is a natural rock material found on the earth surface after volcanic eruption (Mboya *et al.,* 2017). These rock materials are light colored and are rich in Silica and Aluminium as shown in Table 3. (Green *et al.*, 2011). The chemical composition are varying from one deposit to another due to mineralogical features and petrography of the volcanic lava, temperature and rate of cooling, ASTM C 618 stipulates that for Pumice to qualify as pozzolans, the sum of basic oxides ($SiO_2$, $Al_2O_3$ and $Fe_2O_3$) must be greater than 70 %. The easiness of processing and accessibility of Pumice makes it an ideal SCM.

## 2.8 Properties of Concrete Containig Pumice and Scoria

The investigation by Mboya *et al.* (2019) investigated the impact of Pumice and Scoria as inorganic binders to supplement cement in concrete. The concrete was cured under normal water curing for curing peiod of 3, 7 and 28 days. The optimum level of substitution was 10%. Up to that level of substitution the concrete properties were are not compromise. Additionaly, the thermal stability of these materials were studied and showed that, the concrete retained its strength upto exposure temperature of $600^0$ C.

Mboya *et al.* (2017) is another study that studied the quality of Pumice, Rice Husk Ashes (RHA) and Scoria as SMCs. The Scoria, Pumice and RHA achieved a ultimate mean compressive strength of 42.5, 44.8 and 43 MPa after 28 days of curing respectively. Pozzolanic activity index (PAI) was 87.8, 70.7 and 82.7 % at 7 days and 88.9, 85.5 and 89.0% at 28 days for RHA, Pumice and Scoria respectively. This is the indication that NP, NS and RHA ae good SCMs. Additionally, it was revealed that fineness of SCMs is more important for pozzolanic reaction to take place easily.

Ardalan *et al.* (2017) studied the properties of Self-Compacting Concrete (SCC) where cement was replaced with Pumice powder and Silica Fume (SF). The substitution level ranged between 10% and 50% . Properties of SCC such as slump flow, V-funnel flow, U-box and J-ring flow and compressive strength was investigated. The optimum level of substitution was observed to be 30% and at this level the concrete incoporated with pumice showed a promising result than that of control concrete. It was revealed that, the incoporation of pozzolanic materials enhanced the properties of concrete.

Kurt *et al.* (2016) investigated the properties of light weight concrete (LWC) incoporated with Pumice powder. Concrete properties were evaluated under normal water curing conditions. The flow diameters, T50 times, paste volumes, 28-day compressive strengths, dry unit weights, thermal conductivities and ultrasonic pulse velocity of self-compacting lightweight aggregate concrete were obtained in the range of 560–800 mm, 2–11 s, 435–558 $l/m^3$, 10.5–65.0 MPa, 840–2278 $kg/m^3$, 0.347–1.694 W/mK and 2611–4770 m/s respectively. The 28 days coompressive strength was 65 Mpa. The results proved the pontentality of utlizing pumice as pozzolanic material.

Granata (2015) investigated the properties of SCC incoporated with Pumice powder as filler. Self compacting concrete with Pumice filler is compared with other mixtures contains Silica fume and Marble powder as fillers through tests on properties of concretee. Rheological and mechanical properties such as compressive and tensile strength of SCC was investigated after 28 days of curing . It was concluded that addition of pumice in SCC has a positive impact on mechanical properties after 28 days of curing.

Onoue *et al.* (2015) investigated the properties of LWC by using volcanic pumice aggregates on their shock- absorbing capacity. In the impact test, a falling weight tester was employed with placing buffer layer concrete on base layer concrete. Statistical analysis results indicated that the LWC is by averages of 28% and 41% more effective in reducing the maximum impact load than the control concrete, under the impact velocities of 1.5 m/s and 4.5 m/s, respectively. This indicates that, volcanic pumice aggreates can be used in LWC to improve structural properties of concrete structures.

Bogas and Cunha (2017) studied the properties of Non-Structured Light Weight Concrete (NSLWC) incoporated with volcanic scoria. Mechanical and physical properties of building floors were evealuated where the abrasion resistance, compressive and tensile strength, shrinkage , behaviour at high temperatures of different NSLWC fill solutions were analyzed. The results showed the potential of using volcanic scoria to improve concrete properies. Compared to control concrete, NSLWC with volcanic scoria showed similar mechanical strength, less shrinkage, higher punching strength.

### 2.9 Effect of Corrossive Species on Compressive Strength of Concrete

The durability study by Barbhuiya and Kumala (2017) studied the effects of 3% sulphuric acid and 1.5% nitric acid on the properties of sustainable concrete. The level of substitution was 30% for fly ash and 10% for ultra-fine fly ash. Concrete mixes submerged in 3% sulphuric acid showed a high resistance against degradation when the cement was replaced with 30% fly ash and 10% ultra-fine fly ash. Moreover, concrete mixes submerged in nitric acid have higher compressive strength when the substitution level was 30% for fly ash and 10% for ultra-fine fly ash.

De Sensale (2010) investigated the influence of mortar incorporated with Rice Husk Ash (RHA) to resist acid. The 1% hydrochloric acid was used as corrosive environment and mortar specimens were submerged on it. The durability properties of mortar were evaluated. The incorporation of RHA reduces the mass loss of specimens when exposed to hydrochloric acid solutions and reduces the expansion due to sulphate attack and alkali-silica reaction. The acid resistance of mortar specimens increases with increase in substitution level of RHA.

Kannan and Ganesan (2014) investigated strength and durability performance of SCC incorporated with self- combusted RHA and MK. The level of substitution was between 0% to 30% for individual replacement of MK or RHA respectively and 0% to 40% for combination of MK and RHA. The durability and strength properties were investigated. The 15% RHA, 10% MK and 10% RHA + 10% MK b mixers of SCC showed improved properties and resistance to aggressive environment attack.

Chindaprasirt *et al.* (2007) investigated the sulphate resistance of OPC incorporated with RHA. The slump flow, V- Funnel, U-box, L-Flow and hardened properties such as mechanical strength (compressive and split tensile) and durability properties (porosity and rapid chloride permeability test) at 7, 28 and 56 days were investigated. Concrete specimens were prepared with 0, 10, 15 and 20% RHA replacing cement. Replacing cement with 20% RHA showed minimum specified workability. The increase of compressive strength was observed to be 25%, 33% and 36% at 7, 28 and 56 days respectively when RHA content was 15% compared to control mix. Maximum split tensile strength was 3.8 $N/mm^2$ at 28 days and 4.0 $N/mm^2$ at 56 days for 15% RHA replacement.

Merida and Kharchi (2015) investigated the sulphate resistance of high performance concrete (HPC) incorporated with Algerian natural pozzolan of volcanic origin extracted from the deposit Beni-saf. The strengthen of strength was noticed for concrete samples immersed in water where the control samples has developed as strength from 34 MPa to 45MPa and HPC has developed a compressive strength of 56 MPa to 73 MPa after curing in water respectively for 28 days. Both samples cured in sulphate environment showed the decrease in strength, where the compressive strength of control concrete decreased by 17.77% and that of HPC decreased by 5.48%.

Al-Swaidani & Aliyan (2015) considered Scoria as SCMs for concrete exposed to aggressive acidic environment, sulphate resistance mortars were submerged in 5% $Na_2SO_4$ solution for 52 weeks. After 28 and 90 days of curing, the rapid chloride penetration test was done and declared that, chloride penetration resistance of concrete increases with the increase in substitution level.

Additionally, the acid resistance of mortars increase with increase in addition of Scoria at early age.

However, based on aforementioned studies, no any study has been reported on concrete containing NP and NS as SCMs under combined exposure of sulphate and chloride. Moreover, the earlier inputs by (Mboya *et al.,* 2019) validated that the compressive strength of concrete incorporated with NP and NS were satisfactory at a 10% substitution level. The 10% substitution level of cement with NP and NS has been adopted.

## CHAPTER THREE

## MATERIALS AND METHODS

### 3.1 General Overview

This chapter explains the specified materials used and their properties and laboratory testing that were carried in this study. For better understanding tables and figures were used to describe the methodology employed.

### 3.2 Materials

#### 3.2.1 Cement

In this study, Portland Limestone Cement type II (Twiga plus) class 42.5 N compatible with Tanzanian standard TZS 727:2002 which comply with British standard, BS 12:1996 13. PLC was purchased in the city (Arusha). Type II cement was chosen because it has finer particle than type I cement. This makes it to be more reactive and higher surface area allows more hydration. The mineralogical composition of the cement employed are shown in Table 7 in result section.

#### 3.2.2 Coarse Aggregates

The coarse aggregates with nominal size of 20 mm were utilized. The coarse aggregate were ordered from Mohamed builders in Arusha region. Figure 2 shows a visual description of coarse aggregate that were used.

**Figure 2: Coarse aggregates**

### 3.2.3 Fine Aggregates

Natural river sand purchased from local dealers was used as fine aggregates with ultimate 4.75 mm size. Figure 3 shows a visual description a natural river sand used.

**Figure 3: Fine aggregates**

### 3.2.4 Water for mixing concrete ingredients and curing of concrete samples

Portable drinking water was used for washing aggregates, mixing of concrete ingredients and curing of concrete.

### 3.2.5 Pumice and Scoria

Scoria and Pumice stone was milled by using a disc miller to produce a fine powder of Scoria and Pumice marked S and P respectively. The rate of milling was 2 kg/h. The 75 µm sieve conforming to British standard (1986) was used for sieving and analyzed to obtain their physical and chemical properties. The Pumice and Scoria powder produced was used as the mineral admixture in the study. Figure 4 shows a visual description of the Pumice and Scoria powder that was employed in this study.

(a) (b)

**Figure 4: (a) Pumice and (b) Scoria powder**

### 3.3 Experimental Procedures

#### 3.3.1 Characterization of Pumice, Scoria and Cement

The chemical composition of pumice, scoria and cement were determined by using X-ray fluorescence (XRF) and Brunauer-Emmett-Teller (BET) method was employed to determine the surface area of pumice, scoria and cement.

#### 3.3.2 Properties of Aggregates

The aggregates properties were established before concrete mix design process since they play important role in proportioning of ingredients that will help to attain the targeted properties of concrete at its fresh and hardened state. The aggregates properties carried out are described below:

**(i) Moisture Content**

Moisture content is the amount of water stored by the aggregates. This amount of water is stored in the pores of aggregates and it is easily reduced by drying in an oven for a period of 3hrs at a maximum temperature of 110 ℃. Equation (4) was used to compute the moisture content.

$$w = \left( \frac{m_2 - m_3}{m_3 - m_1} \right) x100\% \tag{4}$$

where $m_1$ is the container weight (g); $m_2$ is the weight of wet soil and container (g); and $m_3$ is the weight of dry soil and container (g).

### (ii) Water Absorption

Water absorption is the ability of aggregates to absorb water and hold it. The aggregates having higher absorption values are mostly deemed unsuitable since their crushing value are higher and their abrasion resistance are low. Water absorption ($w_{ab}$) was determined as per BS 812-2:1995 by using Equation 5.

$$w_{ab} = \left( \frac{w_1 - w_2}{w_2} \right) x100\% \tag{5}$$

where $w_1$ is the saturated aggregates weight (g), and i $w_2$ is the weight of dried aggregates.

### (iii) Specific Gravity

Specific gravity ($G_S$) is the fraction of the weight of aggregate to the weight of an equivalent volume of water". The strength quality is measured by using specific gravity. The pycnometer was used to find the specific gravity of aggregates and Equation (6) was used to calculate the specific gravity in accordance with (American Society for Testing Materials [ASTM]. 2001).

$$G_s = \frac{W_2 - W_1}{[(W_4 - W_1) - (W_3 - W_2)]} \tag{6}$$

where; $W_1$ is the pycnometer weight in air (g), $W_2$ aggregates and pycnometer weight (g), $W_3$ is the weight of aggregates, pycnometer, and water (g) and $W_4$ is the weight of water and pycnometer in the air (g).

## 3.4 Sieve Analysis

The sieves outlined in Table 2 was used to carry out sieve analysis of fine and coarse aggregates. The main aim is to find the particle size distribution of fine and coarse aggregates. The laboratory procedure are outlined below:

(i) The representative mass of fine and coarse aggregates were dried in oven at 110 ºC for 3 hours, then allowed to cool for 1 hour.

(ii) Sieves were arranged from largest to smallest and air-cooled aggregates were put on the sieve.

(iii) The sieving process was done for 3 minutes until no particles passed through. The shaken of sieve tray was done in all directions. Sieve trays were then de-attached.

(iv) Then after, the aggregates weight retained in each sieve was measured.

(v) The mass of aggregates passing each sieve was also calculated.

(vi) The results obtained were used to calculate the fineness modulus.

### 3.5 Mix Design for Concrete

BS 1881 - 125:1986 (British standard, 1986) was used for proportioning and mixing of concrete ingredient. Series of steps followed are outlined below:

(i) The target mean strength was estimated as a function of the specified characteristics strength based on the required control level.

(ii) Water/cement ratio was chosen depending on strength and durability requirement.

(iii) Water content was selected depending on the workability of the concrete to be produced from water/cement ratio selected in step (ii), cement content was calculated.

(iv) Proportioning of aggregates was done depending on previously determined properties.

(v) Materials for trial mix was proportioned.

(vi) The trial mix was tested for compressive strength and possible modification was made to attain desired mix proportion.

### 3.6 Concrete Mix Proportions

The 25 MPa was used as target mean strength and the slump of 60 – 180 mm was selected. 20 mm was selected as maximum nominal size of coarse aggregate. Table 6 represents the properties of aggregates which were used to proportion concrete mix. It is previous suggested that up to 10% replacement of cement by Pumice and Scoria improve the performance of concrete (Mboya et *al.,* 2019). The samples were prepared by replacing cement with Pumice and Scoria as tabulated in Table 4. The mix was 1:1.3:3 for cement, fine aggregates and coarse aggregates respectively. The Appendix 6 shows the procedures outlined in BS 8110 for concrete mix design process.

**Table 4: Mix design of concrete adopted**

| Components ($kg/m^3$) | Percent of PLC replacement (wt. %) | |
|---|---|---|
| | 0 | 10 |
| Cement | 380 | 342 |
| NP/NS | 0 | 38 |
| Fine aggregate | 552 | 552 |
| Coarse aggregate | 1243 | 1243 |
| Water | 205 | 205 |

### 3.7 Production of Concrete

British standard of concrete mixing BSI, (British standard, 1986) was used as guidance during production of concrete, the electric concrete mixer was used to mix concrete ingredients as shown in Fig. 5. The weighed aggregates (fine and coarse) and cement were put into the concrete mixer. The proportions were mixed before adding water. Afterward, water, cement, P and N was added simultaneously and thoroughly mixed for 3 minutes. Natural pumice (NP) and Natural scoria (NS) was used to prepare concrete samples by replacing cement. During the laboratory work, three streams were established for preparing the concrete sample. The first stream considered 0% replacement of cement, the remaining two stream considered replacing cement at 10% with both NP and NS. The workability test was carried out before casting of concrete.

**Figure 5: Concrete production**

### 3.7.1 Workability of Concrete

After mixing concrete ingredients, the workability of the concrete was measured by using slump test method. Workability of the concrete affects its final properties. Moreover, it described the easiness of transporting, casting and compaction of the concrete or mortar. The slump method test was used to measure the concrete workability. The apparatus has a rod, measurement scale and slump cone comprises of slump cone. The cone height is 300 mm, base diameter of 200 mm and top opening diameter of 100 mm.

The workability was measured by following steps as mentioned in BS: 1199-1959:

(i) The apparati were cleaned before placing them on the flat surface.

(a)

(b)

(c)

(d)

**Figure 6: Slump testing: (a) standard cone (b) temping (c) slumping (d) slump measurement**

(ii) The cone was placed on the flat surface shown in Fig. 7(a), filled with concrete in three layers.

(iii) Each layer was compacted by temping it 25 times using a 16 mm standard diameter steel rod as shown in Fig. 7(b).

(iv) The top surface of the concrete was leveled.

(v) After leveling, the cone was carefully removed and the concrete was allowed to fall as shown in Fig. 7(c).

(vi) The slump value of the concrete was measured as shown in Fig. 7(d).

### 3.7.2 Preparation of Concrete Samples

Concrete cubes with standard size of 150 mm were used to prepare concrete cubes samples. Three cubes from each system were prepared. A total number of One hundred and eight cubes were cast and kept at room temperature of 25 ± 3 ℃ to set for 24 hrs. After 24 hours, demolding was carefully done and then concrete samples were submerged in water. After 7 and 28 days of curing in water, samples were dried in natural air for 24 hours under controlled environment conditions before submerging them to sulphate, chloride and combination of sulphate and chloride solutions. Samples preparation process are shown in Fig. 7 and sample details are provided in Table 5.

**Table 5: Concrete sample details**

| Sample details | Curing(days) | Immersed under | | | |
|---|---|---|---|---|---|
| | | Water | 5% $Na_2SO_4$ | 5% NaCl | 5% $Na_2SO_4$+5% NaCl |
| Control mix (CT) | 28 | 3 | 3 | 3 | 3 |
| | 56 | 3 | 3 | 3 | 3 |
| | 90 | 3 | 3 | 3 | 3 |
| Concrete with 10% NP(S1) | 28 | 3 | 3 | 3 | 3 |
| | 56 | 3 | 3 | 3 | 3 |
| | 90 | 3 | 3 | 3 | 3 |
| Concrete with 10% NS (S2) | 28 | 3 | 3 | 3 | 3 |
| | 56 | 3 | 3 | 3 | 3 |
| | 90 | 3 | 3 | 3 | 3 |
| Sub total | | 27 | 27 | 27 | 27 |
| Total number of specimens | | 108 | | | |

(a)

(b)

(c)

(d)

**Figure 7: Concrete sample preparation: (a) molds; (b) casting; (c) demolding; and (d) curing**

### 3.8 Treatment in Sulphate and Chloride Solution

A methodology similar to earlier study was adopted (Mangi *et al.*, 2019), where 9 specimens of CT, 9 specimens of NP and 9 specimens of NS were immersed in 5% $Na_2SO_4$, 5% NaCl and 5% $Na_2SO_4$ + 5 % NaCl for 28, 56 and 90 days. The control samples were cured in water for addition curing of 28, 56 and 90 days. Preparation and testing equipment used complied with British standard (2000) and British standard (1983).

### 3.9 Testing of Concrete Specimen

By means of digital balance, the mass loss of concrete specimen was assessed. The maximum capacity of digital balance was 10000 g. Control specimens were weighed and initial mass was recorded as $M_1$ without submerging the specimen either in sulphate, chloride or combination of sulphate and chloride solution. The weight of specimen after submerging in sulphate, chloride or combination of both sulphate and chloride solution was recorded as $M_2$. The weights, $M_1$ and $M_2$ were used to determine overall mass change. The change in weight at each submerging time was determined by using Equation (7).

$$M_{change} = \frac{M_2 - M_1}{M_2} \tag{7}$$

A compressive testing machine with a full load of 3000 kN was used to determine the strength of concrete specimens as shown in Fig. 8. Concrete specimens were crushed at a loading rate of 100 kN/min. The concrete samples were loaded to the point of failure and crushing load was obtained as described in British standard. (1983). The crushing was done at loading rate of 100 kN/min. As described in British standard. (2003), the samples were loaded up to the point of failure where the crushing load was recorded.


**Figure 8: Compressive strength testing machine**

The compressive strength ($f_c$) was computed as the ratio crushing load, F (N) and surface area of the cubes, A ($mm^2$) using the Equation (8). Three concrete cubes were considered and their average compressive strength was taken as ultimate compressive strength.

$$f_c = \frac{F}{A} \tag{8}$$

The degree of damage of concrete specimen was calculated by using Equation (9) and it was previously obtained by Niu *et al.* (2013). The degree of damage measures the extent of deterioration of concrete.

$$D_i = 1 - \frac{\sigma_i}{\sigma_0} \tag{9}$$

where, $D_i$ is the extent of deterioration after treatment time; $\sigma_i$ is the compressive strength of concrete after treatment time; and $\sigma_0$ is the compressive strength of control concrete specimens at 28 days. In the current study, $\sigma_0$ is the compressive strength value of CT, S1 and S2 at the age of 28 days after immersed in water.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Properties of Aggregates

Properties of fine and coarse aggregates used in the study are presented in Table 6. The properties presented in Table 6 were determined by using BS 882:1992 (British standard, 1992). Fine and coarse aggregates were classified and combined together to obtain the correct proportions in order to have anticipated properties at fresh and hardened state of concrete (British standard, 1992). The proportions of fine to coarse aggregates was 33% to 67% respectively. The fineness modulus (FM) was 5.1 and specific gravity (SG) was 2.6 for the combined aggregates. The SG of aggregates was observed to lay between 2.4 and 2.8 which suggest that the aggregates used were normal weight aggregates (Mboya *et al.,* 2019).

**Table 6: Measured properties of coarse and fine aggregates**

| Properties | Coarse aggregates | Fine aggregates |
|---|---|---|
| Maximum size (mm) | 20 | 4.75 |
| Water absorption (%) | 0.8 | 1.3 |
| Specific gravity | 2.96 | 2.65 |
| Bulk density (kg/m$^3$) | 2956 | 2649 |
| Moisture content (%) | 3.5 | 4.57 |
| Fineness modulus | 6.6 | 2.2 |

Absorption capacity measures aggregates capacity to withstand degradation. Water contents measures the amount of water held in the pores of the concrete. The porosity level is measured by water stored in aggregate pores. Moisture content defines the amount of water stored in the pores of aggregate. The amount of water to be added or reduced is controlled by these properties.

A set of sieves described in Table 2 was used for grading of aggregates used in the study. Particle size distribution are shown in Fig. 9. From the Fig. 9, the grading curve indicates that the aggregates particles are well distributed and meets the standards to be used as aggregate in concrete production.

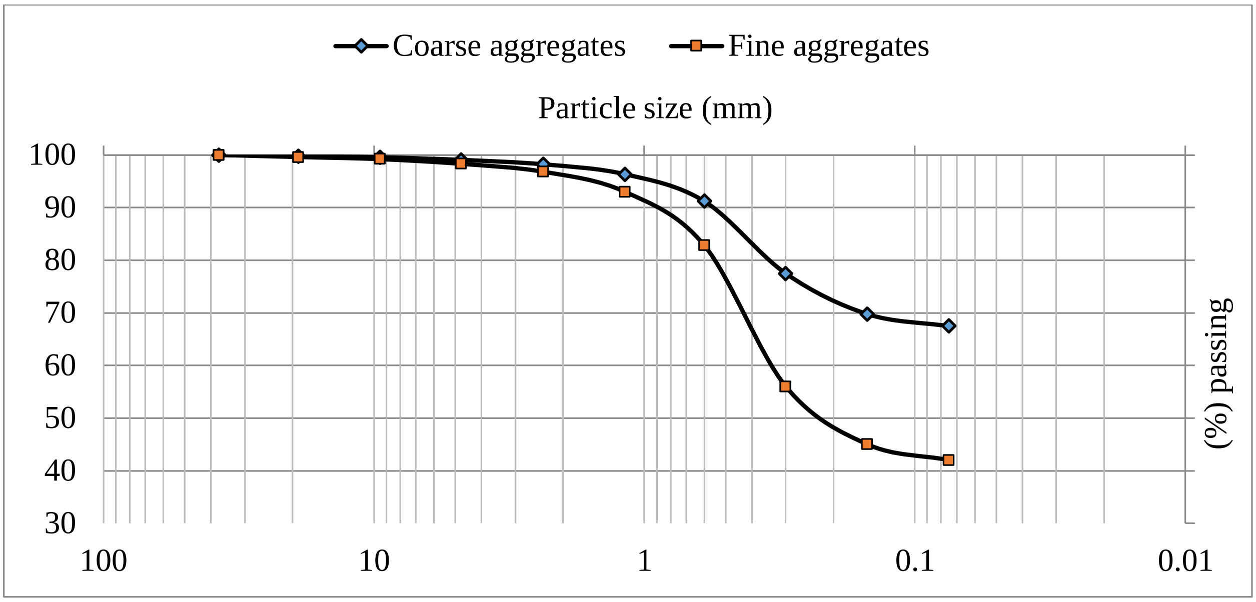


**Figure 9: Particle size distribution of the used aggregates**

## 4.2 Characterization of Natural Pumice, Natural Scoria and Portland Limestone Cement

X-ray Fluorescence (XRF) was used to analyze chemical composition of NP, NS and PLC. The results are tabulated in Table 7. The physical properties are presented in Table 8. Total silica, aluminum oxide and iron oxide was found to be 67 and 76% for NS and NP respectively. The allowable loss on ignition for class N fly ash as stipulated in ASTM C618 is 10%. The loss on ignition for NP and NS were less than 10%. This prove that NP and NS meets the requirement stipulated in ASTM (2005).

**Table 7: Chemical properties of Portland limestone cement, natural pumice and natural scoria**

| Chemical Properties | Material | | |
|---|---|---|---|
| | PLC | NP | NS |
| $SiO_2$ | 17.9 | 55.91 | 39.07 |
| CaO | 60.9 | 0.52 | 10.32 |
| $Al_2O_3$ | 5.5 | 14.55 | 12.80 |
| $Fe_2O_3$ | 2.9 | 4.30 | 15.47 |
| MgO | 0.5 | 0.21 | 4.82 |
| $TiO_2$ | | 0.55 | 3.84 |
| $K_2O$ | 0.22 | 5.01 | 0.62 |
| MnO | 0.36 | 0.36 | 0.22 |
| $Na_2O$ | | 4.95 | 0.40 |
| Loss on Ignition | 8.4 | 8.79 | 10.73 |

**Table 8: Physical Properties of portland limestone cement, natural pumice and natural scoria**

| Physical Properties | Material | | |
|---|---|---|---|
| | PLC | NP | NS |
| Density ( kg/m$^3$) | 3010 | 2390s | 2930 |
| Blaine-specific surface area (m$^2$/kg) | 431 | 507 | 575 |
| Initial setting time (minutes) | 148 | | |
| soundness (mm) | 1.5 | | |
| Compressive strength 28 days (MPa) | 45 | | |

## 4.3 Properties of Fresh Concrete

The workability of the concrete was evaluated by using slump cone method with accordance of ASTM C143 (British standard, 2015). Workability results of concrete mix CT (control mix), S1 (concrete containing NP) and S2 (concrete containing NS) are shown in Table 9. The slump results reveal that, slump decrease due to increases silicon concentration which increases water demand in order to produce workable concrete (Adesanya & Raheem, 2009). This results are also confirmed by (Mboya *et al.*, 2019) and (Adesanya & Raheem, 2009) when SCMs are used as substitution of cement in concrete production.

**Table 9: Concrete workability**

| Concrete Mix | Slump value (mm) |
|---|---|
| Control mix (CT) | 68 |
| Concrete S1-10% NP | 58 |
| Concrete S2-10% NS | 60 |

## 4.4 Properties of Hardened Concrete

### 4.4.1 Weight Loss

The weight of concrete specimen was taken before and after immersing the specimen in water, sulphate, chloride and combination of sulphate and chloride solution. The detailed results of mass loss are provided in Fig. 10. The result reveals that there is no weight change of all specimens immersed in water. The significant change in weight is noted when both types of specimens are immersed in 5% $Na_2SO_4$, 5% NaCl and the combination of both. At 56 days, CT was observed to have uppermost weight gain while the lowest is observed in both S1 and S2 when exposed 5% $Na_2SO_4$. Concrete with NP and NS has lower values compared to control mix because of the denser structure which reduces salts penetration.

It was also agreed by (Xu *et al.*, 2013) that higher amount of sulphate ions, gypsum and ettringite are influenced by more hydration product which provides growth in weight of specimen which containing 30% fly ash in 5% $Na_2SO_4$ (Mangi *et al.*, 2019). Under combined sulphate and chloride, there is significant mass increase from 28 days up-to 90 days and CT concrete is more affected and this is mainly attributed by formation of more ettringite and gypsum. This concur with the finding of Maes and De Belie (Maes & De Belie, 2014) where the investigation was done to evaluate the effect of combined attack of chloride and sulphate on concrete and mortar.

Incorporation of NP and NS reduces the hydration process, moreover reduces the penetration of salt in concrete thus no significant increase in weight in (S1 and S2). This assure that incorporation of SCMs in concrete (S1 and S2) could reduce the permeability of corrosive species which cause corrosion in reinforced structures and failure of structure (Jaya *et al.*, 2011; Ramadhansyah *et al.*, 2011). It is concluded that, addition of NP and NS increase the overall performance of concrete thus it is adequate under 5% NaCl and 5% $Na_2SO_4$ and combination of both 5% NaCl and 5% $Na_2SO_4$.

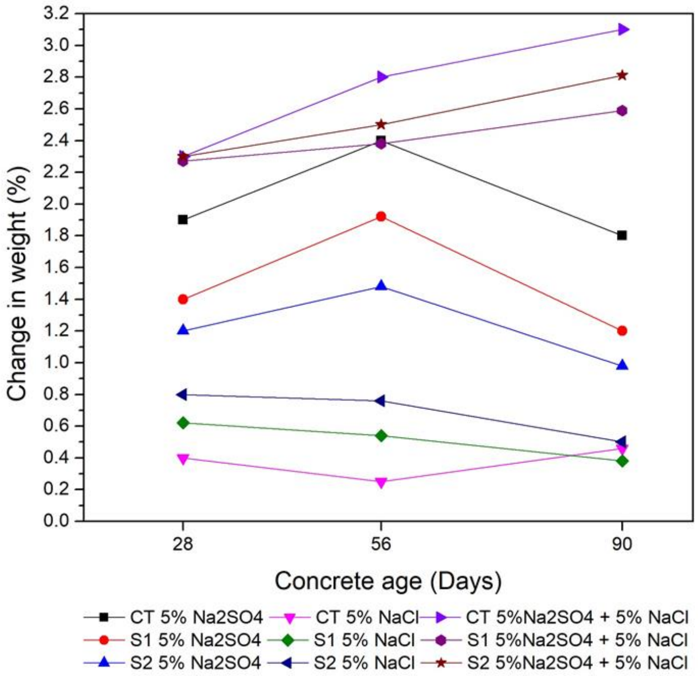


**Figure 10: Weight of concrete CT, S1 and S2 sample in sulphate, chloride and combined sulphate and chloride solution**

### 4.4.2 Compressive Strength of the Specimens Immersed in Portable Water

The compressive strength for the dried samples was determined after immersion test. The compressive strength of 28, 56 and 90 days immersed samples in portable water are presented in Fig 12. The results demonstrate that the performance of concrete samples S1 (34.3MPa) and S2 (33.4 MPa) is higher than the CT (31.9 MPa) at 28 days when immersed in water, this indicates that the pozzolanic reaction initiated the growth of strength in concrete samples S1 and S2. For instance, the compressive strength of S1 is 40.9 MPa (12.11%) and 46 MPa (7.7%) as compared to 36.5 MPa and 42.7 MPa of CT at 56 and 90 days respectively. S2 compressive strength is 38.8 MPa (6.3%) and 44 MPa (3.04%) as compared to 36.5 MPa and 42.7 MPa of CT at 56 and 90 days respectively. It was noted, under presence of pumice and scoria the pozzolanic reaction took place after 28 days and kept on increasing with concrete age.

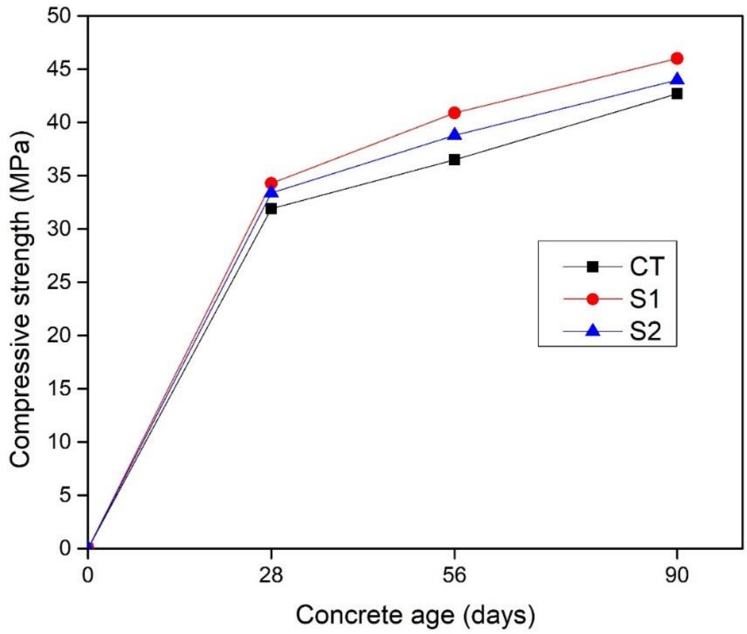


**Figure 11: Compressive strength CT, SI and S2 sample in portable water**

### 4.4.3 Compressive Strength of the Specimens Immersed in 5% Sodium Sulphate Curing

The compressive strength of samples immersed in 5% sodium sulphate curing for different exposure time are presented in Fig. 13 and the physical characteristics are presented in Table 10.

**Table 10: Physical characteristics of concrete mixes after exposure to sulphate solution-slight peeling of the surface visible**

| Sample | Curing days | | |
|---|---|---|---|
| | 28 | 56 | 90 |
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

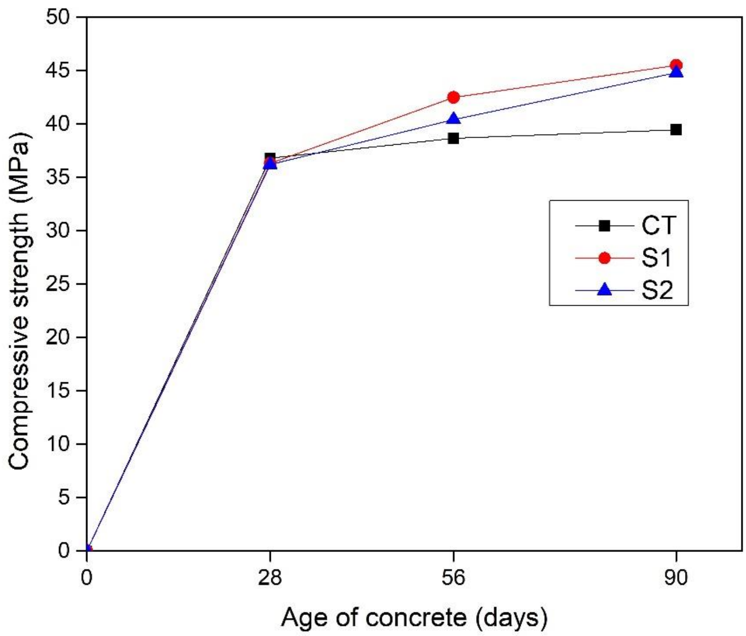


**Figure 12: Compressive strength of CT, S1 and S2 sample in sulphate**

From Fig. 13 concrete samples under 5% $Na_2SO_4$ exposure condition show that the performance of concrete samples containing pumice (S1) and scoria (S2) was found to be comparable with concrete without pumice and scoria (CT) at 28 days of immersion. It was noted that concrete samples with and without pumice and scoria after exposure to sulphate solution there is no significant damage caused for short-term exposure. The compressive strength of S1 was found to be 42.5 MPa (9.9%) and 45.5 MPa (15.4%) compared to 38.67 MPa and 39.44 MPa of CT at 56 and 90 days respectively. The same trend is observed in S2 where strength was 40.4 MPa (4.6%) and 44.8 (13.6%) at 56 and 90 days respectively. This concur with findings observed from Mangi et al. (2019) as they investigated on OPC concrete with coal bottom ashes exposed to sulphate solution for 90 days exposure time.

Moreover, Demir *et al.* (2018) reported the same findings which coincide with the current study where OPC mortar with blast-furnace slag, bottom ash and fly ash as SMCs were investigated where mortar samples were immersed in $Na_2SO_4$ solution for 360 days and strength performance of blended mortar was 2% superior to OPC mortar. It was previously declared that samples immersed in lower proportions of $Na_2SO_4$ (0.27-1.8%) for 300 days no significant damage is caused on mortar properties.

It was also acknowledged that diffusion of sulphate ions in pores of the concrete accelerate the chemical reaction between cement hydration products. The chemical reaction of $Na_2SO_4$ and sulphate ions with Ca $(OH)_2$ and mono-sulphate gives gypsum and ettringite (crystal needle) in concrete pores (Aköz *et al.*, 1999; Saribas & Cakir, 2017). Addition of pozzolanic materials makes the concrete denser by decreasing Ca $(OH)_2$ content at the same time development of corrosive species becomes hard to grow (Association, 2001). Pumice and scoria remove lime liberated during cement hydration and $C_3A$ dilution (Al-Swaidani & Aliyan, 2015). It was experimentally found that pumice and scoria blended concrete has better performance and found to resist the effect of $Na_2SO_4$ solution. The performance of pumice and scoria blended concrete is attributed by refinement of pore sizes that limits ingress of sulfate ions (Djobo *et al.*, 2016; Granata, 2015).

### 4.4.4 Compressive Strength of the Samples Immersed in 5% Sodium Chloride Curing

The compressive strength of samples immersed in 5% sodium chloride curing for different exposure time are presented in Fig 14 and the physical characteristics are presented in Table 11.

**Table 11: Physical characteristics of concrete mixes after exposure to chloride solution-without significant surface damage**

| Sample | Curing days | | |
|---|---|---|---|
| | 28 | 56 | 90 |
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

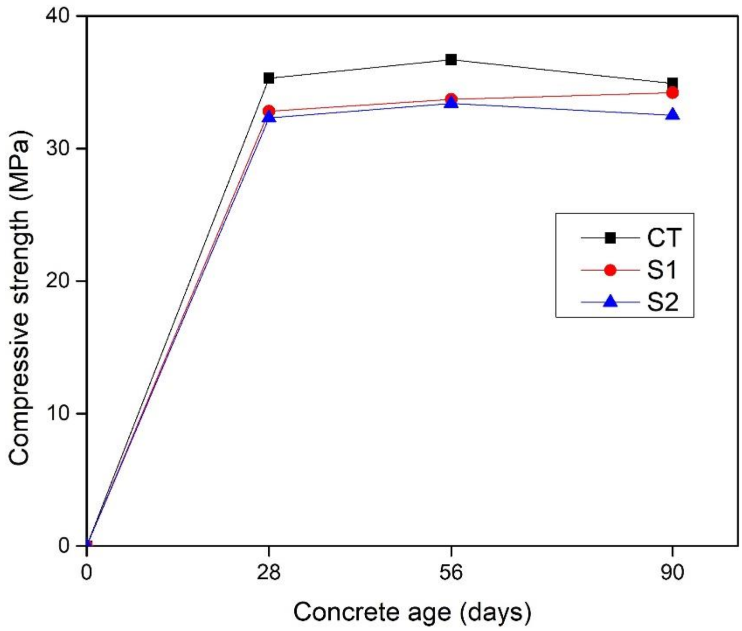


**Figure 13: Compressive strength of concrete CT, S1 and S2 sample in chloride**

The strength development of S1 and S2 was found to be lower than CT in NaCl exposure environment. The same trend have been found in the concrete containing 5% coal bottom ashes

(Mangi *et al.*, 2019) and concrete containing 5% rice husk ashes (Abalaka & Babalaga, 2011). The chloro-aluminate produced in chloride solution is the reason for strength deterioration and by de-calcifications the deterioration took place and the deterioration is notable at later ages (Santhanam *et al.*, 2006; Yuan *et al.*, 2009). At the same time, leaching of calcium hydroxide, permeable C-S-H gel formation and the de-calcification effects of NaCl, takes place in concrete (Abalaka & Babalaga, 2011).

It is also known that chlorides promotes the leaching of Ca $(OH)_2$ and promotes the formation of porous C-S-H involving complex reactions (Lee *et al.*, 2000). Physical appearance of concrete is affected due to disturbance created in the hydration process by the presence of chlorides which affect the pore sizes. From experimental results, CT in 5% NaCl solution, gain its strength up to 56 days and the strength decline after 90 days of immersion time. The performance of S1 and S2 was found to be lower than CT but it was noted that there is continual growth of strength in S1 and S2. It was acknowledged that under 5% NaCl, the pozzolanic reaction becomes slow and takes more time to recover (Mangi *et al.*, 2019). Thus, the performance of S1 and S2 was unsatisfactory under sodium chloride.

### 4.4.5 Compressive Strength of Samples Immersed in 5% Sodium Sulphate and Chloride Curing

The compressive strength of samples immersed in 5% sodium sulphate and chloride curing for different exposure times are presented in Fig. 15 and physical characteristics of concrete mixes after exposure to sulphate and chloride solution are presented in Table 12. Under combined exposure of sodium chloride and sulphate, the concrete blended with pumice (S1) and scoria (S2) performed better than the control mix at exposure period of 28, 56 and 90 days. At 28 days the compressive strength of S1 and S2 was 31.67 MPa (4.5%) and 31.2 MPa (1.3%) greater than 29.9 MPa of CT respectively. A superior performance is observed at early ages. The compressive strength of S1 concrete was 30.78 MPa (3.3%) and 29.8 MPa (8%) greater than 29.4 MPa and 27.4 MPa of CT at 56 and 90 days respectively. Its counterpart, S2 have a compressive strength of 30.5 MPa (2.3%) and 29.2 MPa (7.3%) at 56 and 90 days respectively.

The decline in compressive strength of CT, S1 and S2 can be explained as follows, both sulphate and chloride binds with $C_3A$ to form ettringite, gypsum and sometimes Friedel's salt. However, Friedel's salt, chlorides reaction product is not stable under sodium sulphate solution (Brown & Badger, 2000), as time of immersion is increased Friedel's salt will disappear, more ettringite and gypsum will form and deterioration will occur at later ages. Moreover, ettringite may induce expansion in concrete which may cause a certain cracking in concrete (Jin *et al.*, 2016). This cracking leads to increase of chloride penetrability in concrete. The sample S1 and S2 performance was influenced by dense microstructure due to pozzolanic reaction of pumice and scoria so that the penetration of chloride ions becomes less.

**Table 12: Physical characteristics of concrete mixes after exposure to sulphate and chloride solution-large peeling of the surface visible**

| Sample | Curing days | | |
|---|---|---|---|
| | 28 | 56 | 90 |
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

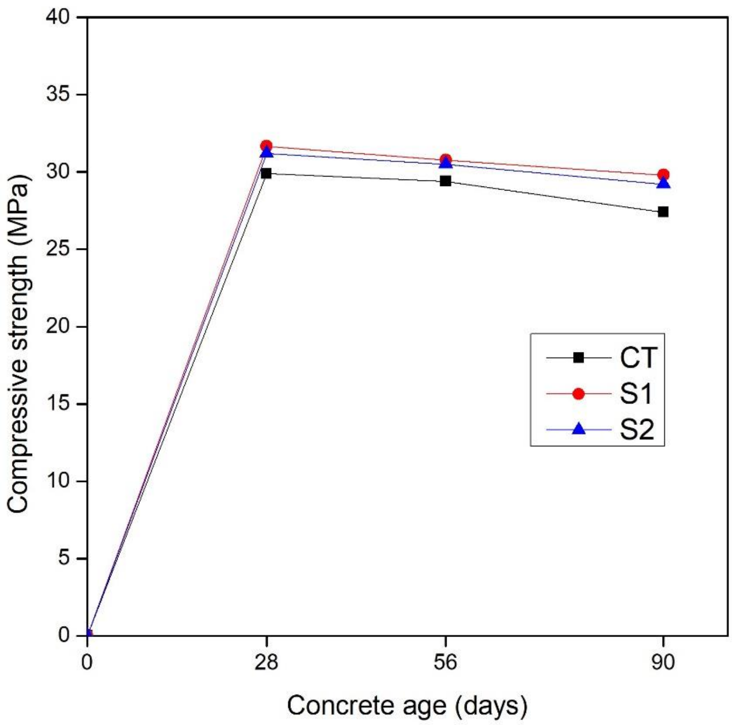


**Figure 14: Compressive strength of CT, S1 and S2 sample in combined solution of sulphate and chloride**

### 4.4.6 Compressive Strength Variation

The strength assessment between concrete with natural pumice (S1), concrete with natural scoria (S2) with reference to CT (concrete without natural pumice and scoria) under altered exposure environments at the age of 28, 56 and 90 days was used to assess the variation in strength properties. At early age of 28 days, the growth in strength was slowly for S1 (concrete containing NP) and S2 (concrete containing NS) when immersed in 5% $Na_2SO_4$ solution but significant development of strength is noticeable at the age of 56 and 90 days.

The concrete samples, S1 (mix containing NP) and S2 (mix containing NS) under 5% NaCl has significant reduction of strength. Moreover, similar observation is noticed in concrete specimens exposed in combined 5% $Na_2SO_4$ and NaCl solution. Concrete samples immersed in water and $Na_2SO_4$ solution has a superior performance than other mixes immersed in 5% NaCl and combined 5% $Na_2SO_4$ and NaCl solution. At 56 days, the concrete containing pumice (S1) has a developed a strength around 12.11% in water and 9.9 % in 5% $Na_2SO_4$ solution than CT, while concrete containing scoria (S2) has developed a strength around 6.3% in water and 4.6% in 5% $Na_2SO_4$ solution. For 90 days cured samples, concrete containing pumice (S1) has developed a strength around 7.7% in water and 15.4% in 5% $Na_2SO_4$ solution, while concrete containing scoria (S2) has 3.04% in water and 13.6% in 5% $Na_2SO_4$ solution..

The concrete containing pumice (S1) and scoria (S2) showed the drop of strength under 5% NaCl exposure condition. Under the combination of both 5% $Na_2SO_4$ and NaCl solution, concrete containing pumice (S1) has developed a strength around 8% and concrete containing scoria (S2) has developed a strength around 7.3% higher than control mix (CT) at immersed period of 90 days. Figure 15 demonstrate the differential in compressive of concrete specimens S1 and S2 under $Na_2SO_4$ and NaCl solution at different concrete ages.

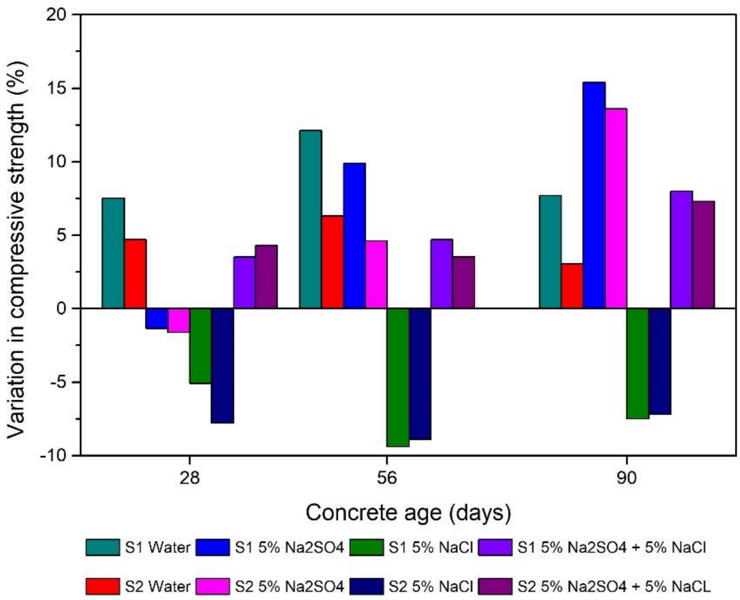


**Figure 15: Compressive strength variation of CT, S1 and S2 sample in water, sulphate and chloride**

### 4.4.7 Degree of Damage

The degree of damage measures the extent of deterioration of concrete. The Equation 9 was used to evaluate the degree of damage as described by Mangi *et al.* (2019).

The extent of deterioration of concrete specimens immersed in water, sulphate and chloride was obtained by using Equation 9 and presented in Fig. 16-19. The results reveal that the extent of deterioration of control mix (CT) is highest at all exposure conditions except for sodium chloride exposure where the degree of damage is lowest. Moreover, the concrete containing pumice (S1) and scoria (S2) has less degree of damage at all exposure conditions except for sodium chloride exposure.

However, the higher were noticed in CT concrete 0.02, 0.04 and 0.11 under combined exposure of sulphate and chloride for 28, 56 and 90 days respectively. The sample S1 has 0.01, 0.04, 0.08 under combined exposure of sulphate and chloride for 28, 56 and 90 days respectively, while S2 has 0.02, 0.04 and 0.7 of 28, 56 and 90 days respectively. The degree of damage was highest in control mix (CT) because of the porous structure formed due to chemical corrosion. Sulphate and chloride penetrate easily into interior due to increased permeability hence increased porosity and decreasing of effective area (Ming *et al.*, 2016). The increase in degree of damage reduce the bearing capacity of concrete structures and it will reach a time the concrete structure will collapse completely (Ramadhansyah *et al.*, 2012). As the degree of damage is lowered, the more the structure is durable.

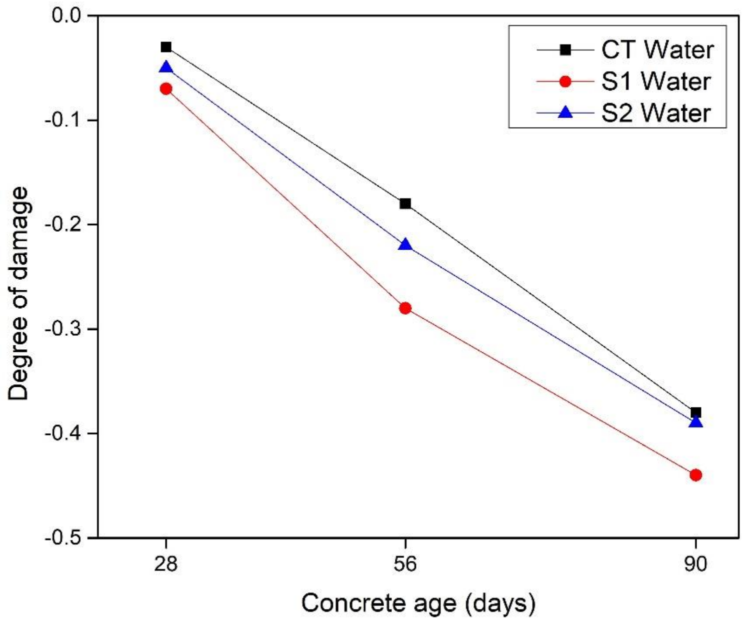


**Figure 16: Degree of damage of concrete with and without pumice and scoria sample in water**

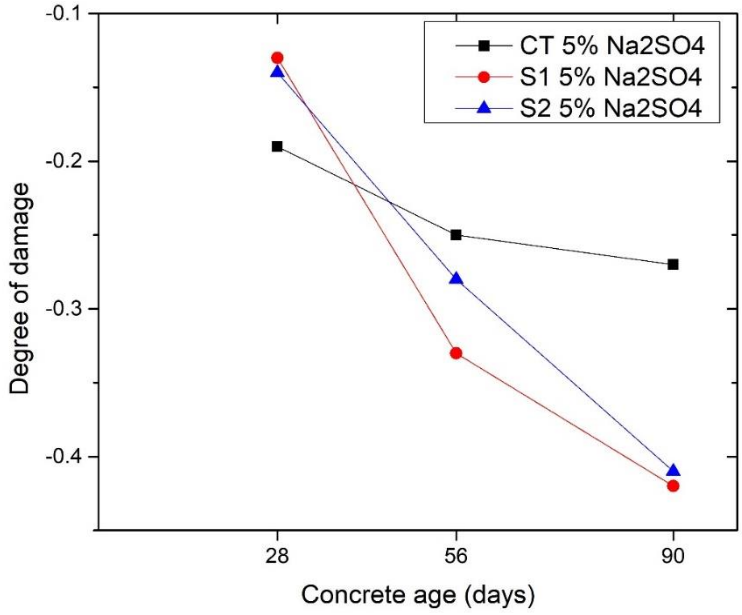


**Figure 17: Degree of damage of concrete with and without pumice and scoria sample in sulphate solution**

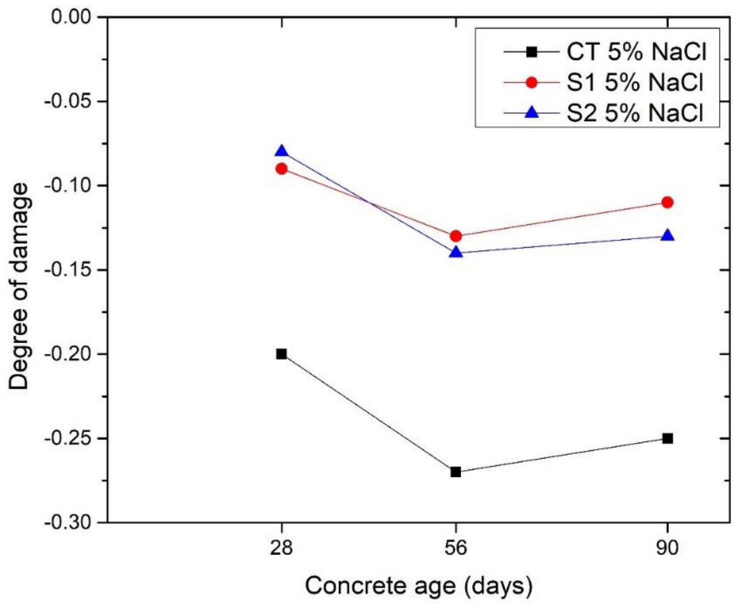


**Figure 18: Degree of damage of concrete with and without pumice and scoria sample in chloride solution**

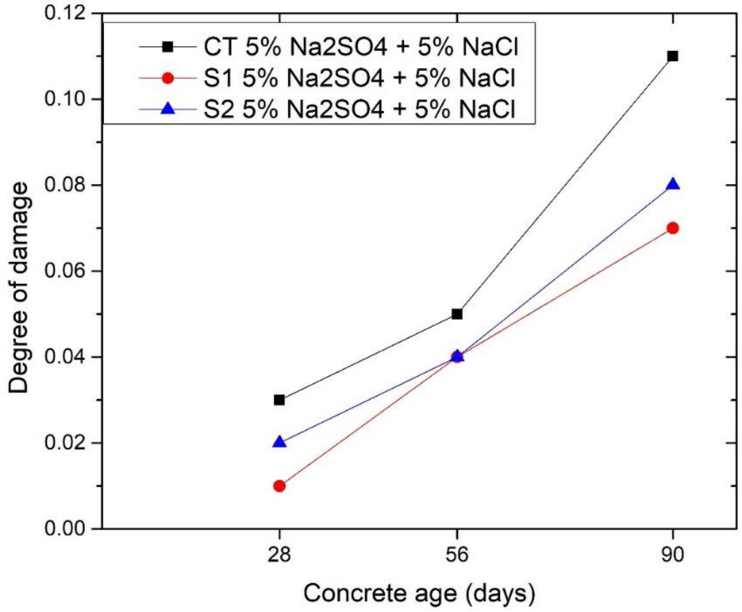


**Figure 19: Degree of damage of concrete with and without pumice and scoria immersed in combined sulphate and chloride solution**

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

The present study investigated the compressive strength, degree of damage, physical properties of the cement-NP/NS mixed normal concrete (with design strength of 25 MPa) subjected sodium sulphate and sodium chloride solution. The blended concrete mixes containing 10% NP/NS showed a greater compressive strength than the control mixes, implying that the inclusion of NP/NS led to better-quality concrete at both ordinary and aggressive environment. The blended concrete performed better than the normal concrete when immersed in both sodium sulphate and combination of both solutions (sodium sulphate and sodium chloride). The significant loss of strength was observed when concrete blended with 10% NP/NS was immersed in sodium chloride solution. Following are the conclusion drawn on the presented experimental results as follows:

(i) The study indicated the successfulness of pumice and scoria as SCMs to replacement OPC in concrete under normal and aggressive environment.

(ii) Under normal water curing, concrete mixes do not change its weight. It was observed that the changes in weight occurs when all type of mixes, CT, S1, S2 are exposed in 5% Na2SO4, 5% NaCl and 5% Na2SO4 + 5% NaCl solution. Control mixes (CT) were observed to have highest weight gain. However, concrete mixes S1 and S2 has less weight gain when exposed to 5% Na2SO4, 5% NaCl due to reduced hydration process and decreased salt penetrability. Moreover, under combination of both 5% Na2SO4 + 5% NaCl highest weight gain is observed in CT and less in S1 and S2 which was influenced by dense microstructure due to pozzolanic reaction of pumice and scoria.

(iii) The compressive strength of S1 and S2 was higher than CT under water curing at 28 days. This indicates that the pozzolanic reaction started at early age. The compressive strength of S1 was 40.9 MPa (12.11%) and 46 MPa (7.7%) higher than 36.5 MPa and 42.7 MPa of CT at 56 and 90 days respectively, S2 was 38.8 MPa (6.3%) and 44 MPa (3.04%) higher than 36.5 MPa and 42.7 MPa of CT at 56 and 90 days respectively.

(iv) The performance of S1 and S2 when exposed to 5% $Na_2SO_4$ solution was found to be superior to control mix (CT). S1 and S2 has higher strength of 45.5 MPa (15.4%) and 44.8 MPa (13.6%) than 39.44 MPa CT at 90 days.

(v) The performance of S1 and S2 when exposed to 5% NaCl solution was unsatisfactory than that of CT, however, strength development was noticed in S1 and S2. Moreover, it was observed that control mix (CT) gain its strength up to 56 days and strength decline upon further exposure.

(vi) Under 5% $Na_2SO_4$ + 5% NaCl solution, the performance of S1 (concrete with pumice) and S2 (concrete with scoria) was found to be superior to CT (concrete without pumice and scoria). Compressive strength of S1 and S2 was 29.8 MPa (8%) and 29.2 MPa (7.3%) higher than 27.4 MPa of CT at 90 days respectively.

(vii) Application of pumice and scoria conveys satisfactory performances of concrete exposed to sulphate, chloride and combination of sulphate and chloride environment.

## 5.2 Recommendations

In view of the findings, analysis of the results and conclusion arrived, the following recommendations are made regarding to Pumice and Scoria as supplementary cementitious materials:

(i) The current study was carried out in steady condition. Future study is therefore recommended to carry the durability studies on stressed conditions since the structures will not only suffers from attack by chemical substances but also may suffer from high stresses induced by underground water in the overlaying soil and surrounding rocks.

(ii) The durability studies were carried out for short exposure time up to 90 days, future studies is recommended to evaluate durability properties on long exposure period of 180 and 360 days.

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# APPENDICES

## Appendix 1: Moisture content of aggregates

| Sample reference | Unit | Coarse aggregates | Fine aggregates |
|---|---|---|---|
| Mass if wet sample +container | g | 385.19 | 369.83 |
| Mass of dry sample+ container | g | 374.54 | 356.74 |
| Mass of container | g | 70.34 | 70.34 |
| Mass of moisture | g | 10.65 | 13.09 |
| Mass of dry sample | g | 304.2 | 286.4 |
| MOISTURE CONTENT | % | 3.5 | 4.57 |

**Appendix 2: Water absorption of aggregates**

| Sample reference | Unit | Coarse aggregates | Fine aggregates |
|---|---|---|---|
| Mass of saturated surface dry aggregates in air | g | 310.9 | 332.7 |
| Mass of oven-dry aggregate in air | g | 308.4 | 328.4 |
| WATER ABSORPTION | g | 0.81 | 1.31 |

**Appendix 3: Specific gravity of aggregates**

| Sample reference | Unit | Coarse aggregates | Fine aggregates |
|---|---|---|---|
| Weight of empty pycnometer, $W_1$ | g | 619.7 | 619.7 |
| Weight of pycnometer half filled with aggregates, $W_2$ | g | 1348.3 | 1349.8 |
| Weight of pycnometer filled with half aggregate and half water, $W_3$ | g | 2172.0 | 2143.3 |
| Weight of pycnometer filled with water, $W_4$ | g | 1688.8 | 1688.8 |
| Specific gravity, $G_S$ | | 2.96 | 2.65 |

**Appendix 4: Particle size distribution of coarse aggregates**

| | Coarse aggregates | | Fine aggregates | |
|---|---|---|---|---|
| Sieve size (mm) | Cumulative mass retained (g) | % Passing | Cumulative mass retained (g) | % Passing |
| 37.5 | 0 | 100 | 0 | 100 |
| 19 | 16.7 | 99.87 | 0 | 100 |
| 9.5 | 1379.43 | 98.99 | 30.23 | 99.38 |
| 4.75 | 2957.63 | 97.2 | 94.73 | 98.08 |
| 2.36 | 4539.83 | 94.3 | 195.96 | 96.02 |
| 1.18 | 6132.43 | 88.99 | 387.06 | 92.13 |
| 0.6 | 7726.33 | 76.39 | 827.23 | 83.18 |
| 0.3 | 9325.86 | 63.76 | 1909.36 | 61.18 |
| 0.15 | 10923.66 | 51.04 | 3373.76 | 31.4 |
| 0.075 | 12523.46 | 38.31 | 4918.89 | 0 |

**Appendix 5: Concrete mix design calculation**

**Step 1: water/cement ratio selection**

The compressive strength for the concrete made of OPC and W/C of 0.50 after 28 days is 49 MPa. Appendix 6 outlined that, to achieve a compressive strength of 49 MPa, W/C is 0.58, and for this case average value is adopted.

Considering 5% defectiveness and for less than 20 samples per batch, the margin strength can be calculated as follows;

Margin strength = standard deviation (from Fig. 21) × appropriate defectiveness value

= 3 × 1.64

= 4.92 MPa

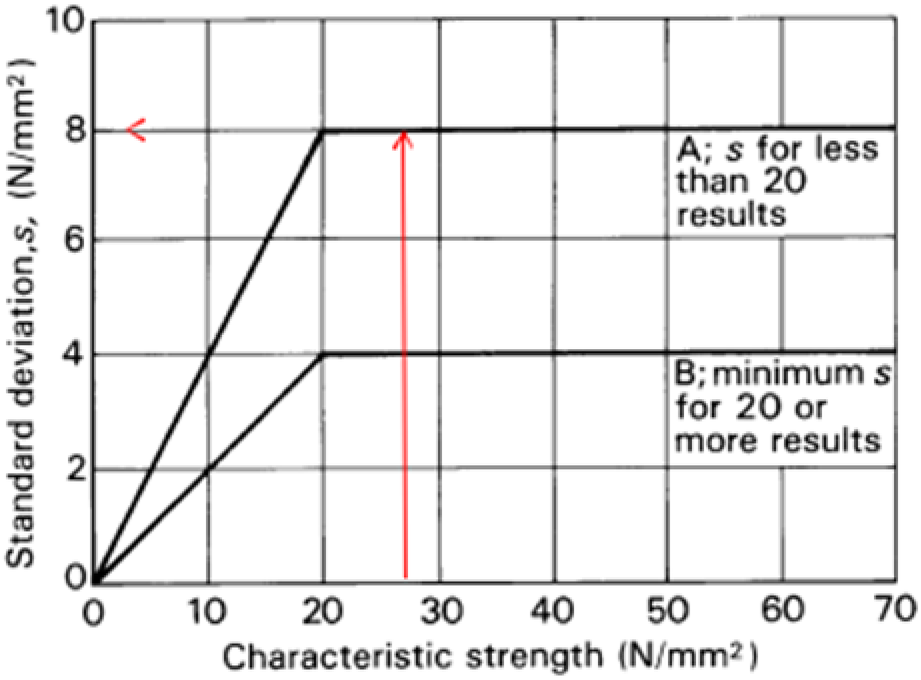
The target mean strength = specified mean strength + the margin

= 25 + 4.92 = 29.92 MPa

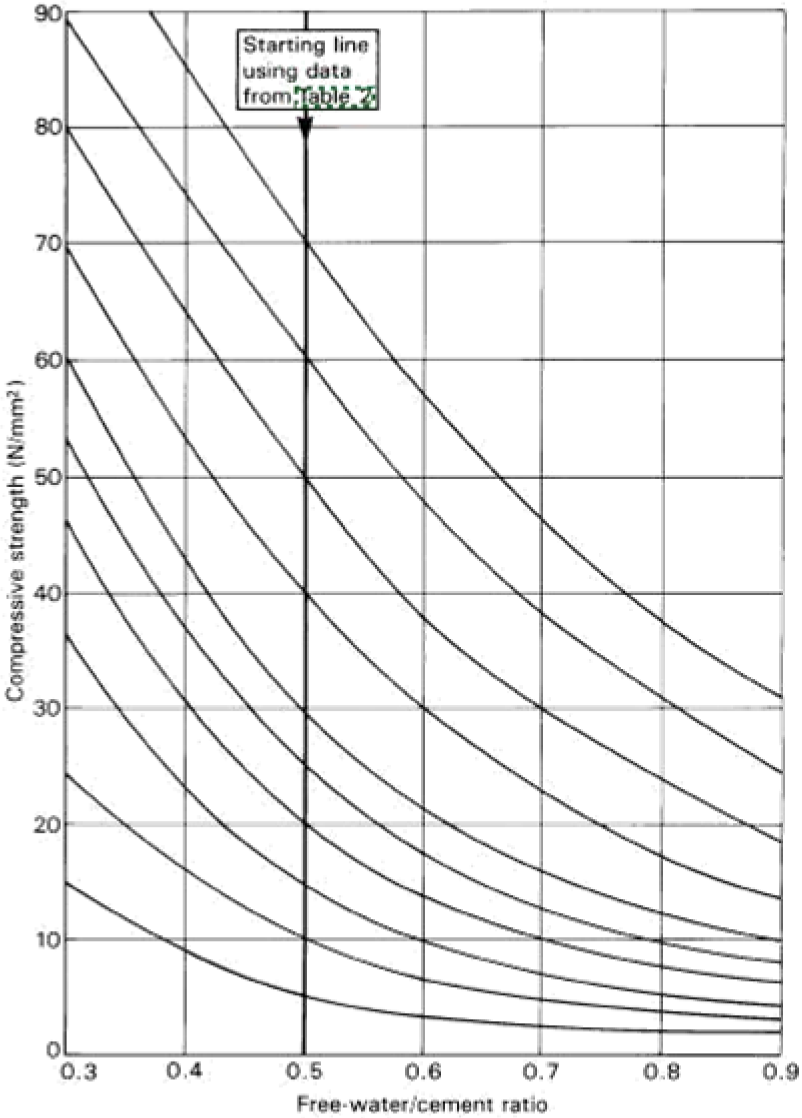
**Appendix 6: Approximate compressive strengths ($N/mm^2$) of concrete mixes made with a free water/cement ratio of 0.5**

| Cement strength class | Type of coarse aggregates | Compressive strength ($N/mm^2$) Age (days) | | | |
|---|---|---|---|---|---|
| | | 3 | 7 | 28 | 91 |
| 42.5 | Uncrushed | 22 | 30 | 42 | 49 |
| | Crushed | 27 | 36 | 49 | 56 |
| 52.5 | Uncrushed | 29 | 37 | 48 | 54 |
| | Crushed | 34 | 43 | 55 | 61 |

**Appendix 7: Relationship between standard deviation and characteristic strength; BSI (1986)**



**Appendix 8: Determination of water to cement ratio depending on design strength: BSI (1986)**




**Step 2: Water content determination**

The slump value selected is between 60 - 180 mm. For the uncrushed fine aggregates and coarse aggregates with a nominal size of 20 mm, that the amount of free water required is 205 $kg/m^3$ of concrete.

**Appendix 9: Amount of free- water contents (kg/m$^3$) required for different slump**

| Slump (mm)<br>Vebe time (S)<br>Maximum size of aggregates | <br><br>Type of aggregate | 0-10<br>> 12 | 10-30<br>6-12 | 30-60<br>3-6 | 60-180<br>0-3 |
|---|---|---|---|---|---|
| 10 | Uncrushed | 150 | 180 | 205 | 225 |
| | Crushed | 180 | 205 | 230 | 250 |
| 20 | Uncrushed | 135 | 160 | 180 | 195 |
| | Crushed | 170 | 190 | 210 | 225 |
| 40 | Uncrushed | 115 | 140 | 160 | 175 |
| | Crushed | 155 | 175 | 190 | 205 |

**Step 3: Cement content determination**

The amount of cement is equal to 205/0.54 = 380 kg/m3 of concrete. According to Table 11, the minimum required cement content for moderate exposure conditions is 240 kg/m3 of concrete. Thus, our estimated cement content is satisfactory

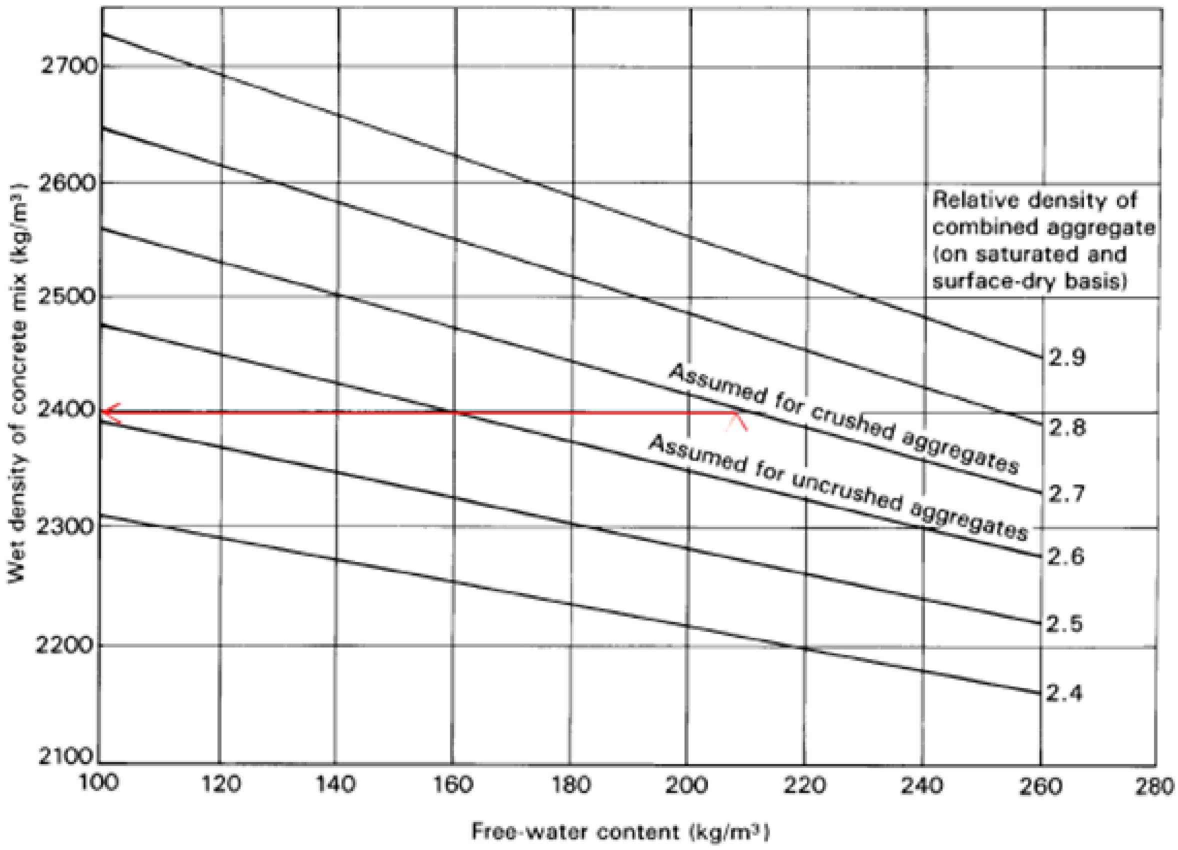
**Appendix 10: Minimum cement content requirement**

| | Plain concrete | | | Reinforced concrete | | |
|---|---|---|---|---|---|---|
| Exposure | Minimum cement content (kg/m$^3$) | Maximum free water-cement ratio | Minimum grade of concrete | Minimum cement content (kg/m$^3$) | Maximum free-water cement ratio | Minimum grade of concrete |
| Mild | 220 | 0.60 | - | 300 | 0.55 | M20 |
| Moderate | 240 | 0.60 | M15 | 300 | 0.50 | M25 |
| Severe | 230 | 0.50 | M20 | 320 | 0.45 | M30 |
| Very severe | 260 | 0.45 | M20 | 340 | 0.45 | M35 |
| extreme | 280 | 0.40 | M25 | 360 | 0.40 | M40 |

**Step 4: Determination of total aggregate content**

For the aggregates having the SG of 2.5 and free water content of 205 kg/m$^3$, the wet density of concrete is 2380 kg/m$^3$ from Fig. 22. The total aggregate content is 2380 – (205 + 380) =1795 kg/m$^3$ of concrete

**Appendix 11: Estimated wet density of fully compacted concrete; BSI (1986)**




**Step 5: Determination of fine and coarse aggregates contents**

From table 21, the ratio of FA/CA is 0.31/0.69, therefore: fine aggregate content is 1795x0.308= 552.9 kg/m$^3$ and coarse aggregate is 1795-553=1242kg/m$^3$.

**Appendix 12: Combination of fine and coarse aggregates**

| Sieve size | mm | `0.15 | 0.30 | 0.60 | 1.18 | 2.36 | 4.75 | 9.50 | 19.00 | 37.50 |
|---|---|---|---|---|---|---|---|---|---|---|
| FA | 0.31 | 5.98 | 30.50 | 72.12 | 87.73 | 93.50 | 95.86 | 98.06 | 100.00 | 100.00 |
| | | 1.84 | 9.39 | 22.21 | 27.02 | 28.80 | 29.53 | 30.20 | 30.80 | 30.80 |
| CA | 0.69 | 0.40 | 0.54 | 0.65 | 0.70 | 0.87 | 1.62 | 15.05 | 98.96 | 100.00 |
| | | 0.28 | 0.37 | 0.45 | 0.49 | 0.60 | 1.12 | 10.42 | 68.48 | 69.20 |
| Resultant | 1.00 | 2.12 | 9.77 | 22.66 | 27.51 | 29.40 | 30.65 | 40.62 | 99.28 | 100.00 |
| Target | | 4 | 7 | 13 | 20 | 28 | 40 | 62 | 88 | 100 |

The calculated quantities in kg/m$^3$ are summarized as follows;

| | |
|---|---|
| Cement: | 380 |
| Fine aggregate: | 552 |
| Coarse aggregate: | 1243 |
| Water: | 205 |
| Total: | 2380 |

## RESEARCH OUTPUT

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*Research Article*

# Strength and Durability Properties of Concrete Containing Pumice and Scoria as Supplementary Cementitious Material

**Safiel Tumaini Chambua**,[1,2] **Yusufu Abeid Chande Jande**,[1,2] **and Revocatus Lazaro Machunda**[2,3]

[1]*Department of Materials and Energy Sciences and Engineering, The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania*
[2]*Water Infrastructure and Sustainable Energy Futures, The Nelson Mandela African Institution of Science and Technology, P.O. Box 9124, Arusha, Tanzania*
[3]*Department of Water and Environmental Science and Engineering, The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania*

Correspondence should be addressed to Safiel Tumaini Chambua; chambuas@nm-aist.ac.tz

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Concrete structures suffer serious deterioration under a corrosive environment. Consequently, the service life of these concrete structures is decreased and deteriorates under combined attack of sulphate and chlorides. Most studies confined on single deteriorating factor such as sulphate attack only or chloride attack only but the current study focused on the influence of natural pumice (NP) and natural scoria (NS) on the strength performance of concrete exposed to the combined attack of sulphate and chloride. Portland cement (PLC) was replaced with NP or NS at a substitution level of 10%. Concrete samples were cured in water for the curing period of 28 days. Afterwards, the specimens were immersed in 5% sodium sulphate ($Na_2SO_4$), 5% sodium chloride (NaCl), and combined sodium sulphate and chloride solutions for additional curing of 28, 56, and 90 days. The results were compared between concrete mixes with NP or NS and control mix (CT) with PLC. The effects of sulphate, chloride, and combined sulphate and chloride were evaluated in terms of change in weight, variation in compressive strength, and degree of damage. Conclusively, the application of NP and NS has extraordinary potential to be utilized as a cementitious material in concrete to increase the resistance against aggressive salts.

## 1. Introduction

Concrete has been a dominant construction material for the infrastructure around the globe [1]. It is estimated that the global production is over 10000 million tons [2]. The development in concrete technology has led the material to be the choice for the construction of structures which are exposed to extreme conditions [3]. Despite concrete being the chief construction material, the concrete structures made with Ordinary Portland cement (OPC) tend to depreciate faster when exposed to extreme conditions.

Structures exposed to extreme conditions are such as waste water treatment plants and marine structures [4]. Researchers have studied the durability of concrete under different extreme conditions [5–10]. It was singled out that sulphate, chloride, and their associated cations are the most aggressive chemicals affecting concrete durability. The concrete durability becomes a major concern since the capacity to withstand imposed load decreases with time. Moreover, the cost of repair and replacement of deteriorated structures becomes astronomical [11, 12].

Nowadays, there is prevailing interest to reduce the cement content and enhance concrete strength and durability by using Supplementary Cementing Materials (SCMs) and make more durable and sustainable concrete with good structural properties [13, 14]. The properties of fresh and hardened concrete are improved by addition of SCMs, and the cement content is reduced simultaneously [13]. Downrightly, the SCMs' addition improves workability and flow [13], produces less porous and denser concrete which increase resistance to chemical attack [15], shock absorbing ability is enhanced [16, 17], and compressive and flexural strengths are enhanced [13].

Furthermore, SCMs produce the additional Calcium-silicate-hydrate (C-S-H) gel from the pozzolanic reaction between the calcium hydroxide (C-H) that forms from the cement hydration [13]. The C-S-H gel together with the packing effect of fine and coarse aggregate increases compatibility of concrete, thus reducing permeability and protection of steel reinforcement against corrosion [18, 19]. Different research studies have been investigating the concrete with SCMs immersed in the sulphate and chloride environment as follows.

Kannan and Ganesan [20] investigated the chemical and chloride resistance of self-compacting concrete incorporated with rice husk and metakaolin and declared that concrete incorporated with metakaolin and rice husk leads to improvement in the strength and reducing permeability when compared to the control mix.

Mangi et al. [1] investigated the effects of sodium and chloride attack on concrete blended with coal bottom ashes for the exposure period of 90 days, and it was found that incorporation of coal bottom ashes reduces the negative effects of sulphate and chloride salts and increases the concrete resistance against the aggressive environment.

Aksogan et al. [14] investigated the durability performance of concrete where the fine aggregate was replaced by calemanite and barite and cement by corn stalk, wheat straw, and sunflower stalk ashes immersed in 5% $Na_2SO_4$ for 180 days and stated that, upon addition of corn stalk, wheat straw, and sunflower stalk ashes, the chemical resistance of concrete was improved.

Demir et al. [21] replaced cement with the combination of fly ash, bottom ashes, and blast-furnace slag and evaluated the performance of Ordinary Portland Cement (OPC) mortars under 5% $Na_2SO_4$ solution for 360 days. It was found the blended cement mortar has a compressive strength of 2% greater than that of OPC when cement is replaced with 5% fly ash, 5% blast-furnace slag, and 5% bottom ash.

Othman et al. [22] investigated the sulphate resistance of foamed concrete containing processed spent bleaching earth (PSBE) as the cement replacement. The sulphate resistance was evaluated in terms of expansion, loss in mass, and loss in compressive strength after 52 weeks of immersion time. It was found that concrete containing 30% PSBE is more durable than the control specimen after immersion in 5% sodium sulphate. However, the investigation was based on single attack only.

Al-Swaidani and Aliyan [7] investigated the sulphate resistance of mortars by partially replacing cement with scoria. The sulphate resistance of mortars was performed by immersing the mortar samples in 5% Na2SO4 solution for 52 weeks and declared that, upon addition of scoria, the sulphate resistance of mortars is improved. The investigation was done only on single deteriorating factor, that is, sulphate attack only.

Jaya et al. [23] investigated the potential of using rice husk ashes (RHA) as the cement replacement in concrete under seawater attack by wetting and drying cycles. Cement was replaced with RHA at the substitution level of 0%, 10%, 20%, 30%, and 40%. Compressive strength and chloride ion permeability were evaluated. Incorporation of RHA was found to reduce calcium hydroxide formation during hydration seawater attack. The investigation was based on single attack only.

Natural pumice (NP) and natural scoria (NS) are natural materials that can be used as eco-friendly materials in the construction industry. Cement production requires energy, and much $CO_2$ is released but utilization of NS and NS reduces energy demand and $CO_2$ [13, 24]. NP and NS are pyroclastic materials rich in silica, alumina, and iron oxide [24]. Around the globe, NP and NS have been utilized as fine and coarse aggregates in concrete production and building blocks [13]. Top and Vapur investigated the utility of NP as course aggregates in light-weight geopolymer concrete [25]. Then again, NP and NS have been used as fine and coarse aggregates for nonstructural concrete and mortar [17, 26, 27].

Mboya et al. [13] indicated that NP and NS as the cement replacement can enhance the strength and durability of concrete but studies on concrete containing NP and NS under the combined exposure of sulphate and chloride are rarely reported. In addition, no research has evaluated the properties of concrete NP and NS under the combined exposure of sulphate and chloride solutions. Moreover, the earlier inputs by Mboya et al. [13] validated that the compressive strength of concrete incorporated with NP and NS was satisfactory at a 10% substitution level. The 10% substitution level of cement with NP and NS has been adopted. Therefore, the work presented explores the application of NP and NS as SCMs in concrete under the combined effect of sulphate and chloride solution exposure conditions. Strength, change in weight, and degree of damage are evaluated.

## 2. Materials and Methods

### *2.1. Materials*

*2.1.1. Binder.* In the current study, Portland Limestone Cement (PLC) type II (Twiga plus) class 42.5 N conforming to Tanzanian standard TZS727:2002 in accordance with the British standard BS 12:1996 13 and SS-EN 197-1 CEM II/A-L was used [28]. PLC was obtained from local dealers around Arusha city, Tanzania.

Pumice stone with white colored fragments was collected from Ikuti in Mbeya region, and scoria stone with red colored fragments was collected from Uchira in Kilimanjaro region. Both were collected in Tanzania. A disc mill model 4A100L6T1 SN 535277 was used to mill pumice and scoria stones to produce a fine powder of pumice and scoria marked NP and NS, respectively, at a rate of 2 kg/h and sieved through 75 $\mu$m in accordance with BS 410 [29], visually presented in Figure 1, and analyzed to determine

(a) (b)

Figure 1: Pumice and scoria powder used in the study.

chemical and physical properties. Automatic Blaine Apparatus (AIM-391-3) SN 2001 from Aimil Ltd., India was used to determine fineness of the NP and NS powder [30]. The density of PLC, NP, and NS was determined according to SS-EN 197-1 and ASTM D 854 [31, 32]. The chemical and physical properties of binders are outlined under the result section.

*2.1.2. Aggregates.* Fine and coarse aggregates were obtained from local dealers. Properties of fine and coarse aggregates such as specific gravity and water absorption were determined, guided by the standard. ASTM C127 [33] and ASTM C128 [34] were employed to determine aforementioned properties, respectively. Particle size requirement for aggregates was done to conform to BS EN 933-1:2012 [35]. Grading and blending of fine and coarse aggregates were done to conform with PD 6682-1 and BS 12620 specifications [36, 37].

The particle size distribution and properties of fine and coarse aggregates used in the study are shown in Figure 2 and Table 1, respectively. To achieve desired properties of fresh and hardened concrete, fine and coarse aggregates were graded and blended together to obtain the right proportions [36]. BS EN 12620 was used to blend coarse and fine aggregates in proportions of 33% to 67% fine to coarse aggregates [36]. The blended aggregates showed fineness modulus (FM) of 5.1 and specific gravity (SG) of 2.6. The specific gravity of aggregates was found to be between 2.4 and 2.8 which suggest that the aggregates used were normal weight aggregates [13].

*2.1.3. Water.* Potable tap water was used for washing aggregates and mixing and curing of concrete. Water used was free from suspended particles, and the pH value was 6. The amount of water added during mixing reacts with cement to form the hydration products which bind the aggregates together, which also affect the workability of the concrete and strength properties. Mixing water was free from chemical contamination and safe for human consumption [38].

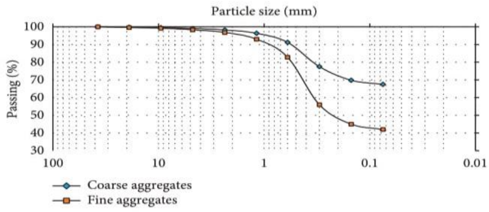


Figure 2: The particle size distribution of aggregates used in the study.

*2.2. Mix Proportioning.* Concrete grade M25 was adopted in this study, and the concrete samples were made by partially replacing cement with NP or NS. BS 1881-116 [39], BS EN 12390-2 [40], and BS EN 206 [41] were used as guidelines for concrete mixing, casting, and testing of fresh and hardened properties of concrete, respectively. Three streams of test specimens were under consideration; the first stream was the concrete made with only Portland cement (0% replacement) (hereafter, referred as CT), the second stream was the concrete made with partial replacement of cement by NP, and the third stream was the concrete made with partial replacement of cement with NS. Cement was replaced by 10% in second and third streams, as illustrated in Table 2.

*2.3. Sample Preparation.* Concrete mixes were prepared by using an electric mixer. The weighed PLC and fine and coarse aggregates were all together put into the concrete mixer and mixed thorough, followed by addition of NP and NS and mixed through. Weighed water was added and mixed throughout to have a homogeneous mixture. Standard cubes of 150 mm size were used to prepare concrete cubes with and without NP and NS. A total of 108 specimens were prepared, and three cubes from each stream were selected for testing in the corrosive environment. Concrete specimens were left to allow setting at a room temperature of $25 \pm 3^{\circ}C$ after casting. The

Table 1: Properties of aggregates used in the study.

| Properties | Coarse aggregates | Fine aggregates |
|---|---|---|
| Maximum size (mm) | 20 | 4.75 |
| Water absorption (%) | 0.8 | 1.3 |
| Specific gravity | 2.96 | 2.65 |
| Bulk density (kg/m$^3$) | 2956 | 2649 |
| Moisture content (%) | 3.5 | 4.57 |
| Fineness modulus | 6.6 | 2.2 |

Table 2: Concrete mix design.

| Components (kg/m$^3$) | Percent of PLC replacement (wt. %) | |
|---|---|---|
| | 0 | 10 |
| Cement | 380 | 342 |
| NP/NS | 0 | 38 |
| Fine aggregate | 552 | 552 |
| Coarse aggregate | 1243 | 1243 |
| Water | 205 | 205 |

demoulding of cubes was done after 24 h, and then, the specimens were cured in water for 7 and 28 days to obtain the designed strength. Specimens were taken out of the water tank after 7 and 28 days and left out for 24 h to allow drying under controlled laboratory conditions. Compaction and curing equipment used complied with BS EN 12390-2 [40] and BS 1881-116 [39].

*2.4. Continuous Immersion Test.* A methodology similar to earlier studies [1, 4] was adopted, where 9 specimens of CT, 9 specimens of S1, and 9 specimens of S2 were immersed in 5% $Na_2SO_4$, 5% NaCl, and combination 5% $Na_2SO_4$ and 5% NaCl for 28, 56, and 90 days, respectively. The remaining specimens were submerged in water for additional curing of 28, 56, and 90 days.

*2.5. Testing.* The CT specimens were weighed and tested without immersing them into the corrosive environment. Before submerging concrete mixes in the corrosive environment, all specimens were weighed. After the continuous immersion test of samples in the corrosive environment, the samples were weighed again. The mass loss was assessed by using the recorded weights at each exposure condition. The compressive strength testing machine conforming to BS EN 12390-2 [40] and BS 1881-116 [39] was used to measure the strength of concrete samples. The crushing loads were obtained in accordance with BS EN 12390-3:2019 [42]. Their degree of damage was evaluated by using equation (1) as described by Mangi et al. [1]:

$$D_i = 1 - \frac{\sigma_i}{\sigma_0}, \quad (1)$$

where $D_i$ is the degree of damage after certain immersing period, $\sigma_i$ is the compressive strength of concrete after certain immersing time, and $\sigma_0$ is the initial compressive strength of concrete. In the current study, the $\sigma_0$ value represents the compressive strength of CT, S1, and S2 at the age of 28 days before being shifted into sulphate and chloride solutions.

## 3. Results and Discussion

*3.1. Physical and Chemical Properties of PLC, NP, and NS.* X-ray Fluorescence (XRF) was used to analyze chemical composition of PLC, NP, and NS. The results are presented in Table 3. The total of silica, aluminum oxide, and iron oxide was found to be 74.76% and 67.34% for NP and NS, respectively. This implies that NS and NP meet the standard criteria to be considered as pozzolanic materials according to ASTM C618 [43]. Physical properties of PLC, NP, and NS are presented in Table 4.

*3.2. Workability.* Slump cone method was used to evaluate the workability of concrete with accordance to ASTM C143 [44]. Workability results of the concrete mix CT (control mix), S1 (concrete containing NP), and S2 (concrete containing NS) are shown in Table 5. The slump results reveal that slump decreases with increase of cement replacement, and this is due to the presence of NP and NS which upon their addition, increases silicon concentration which increases water demand in order to produce workable concrete [45]. This result was also observed by Mboya et al. [13] and Adesanya and Raheem [45] when SCMs were used as partial substitution of cement in concrete production.

*3.3. Weight Loss.* The weight of the concrete specimen was taken before and after immersing the specimen in water, sulphate, chloride, and combination of sulphate and chloride solution. The detailed results of mass loss are provided in Figure 3. The result reveals that both types of concrete do not change their weight when immersed in water. The significant change in weight is noted when both types of specimens are immersed in 5% $Na_2SO_4$, 5% NaCl, and the combination of both. The highest weight loss was noticed in CT at 56 days, while the lowest was observed in both S1 and S2 when exposed to 5% $Na_2SO_4$. Concrete with NP and NS has lower values compared to the control mix because of the denser structure which reduces salts' penetration.

It was also agreed by Xu et al. [46] that higher amounts of sulphate ions, gypsum, and ettringite are influenced by more hydration products which provide growth in weight of the specimen containing 30% fly ash in 5% $Na_2SO_4$ [1]. Under combined sulphate and chloride, there is significant mass loss from 28 days up to 90 days, and CT concrete is more affected, and this is mainly attributed by formation of more ettringite and gypsum. This concurs with the findings of Maes and De Belie [47] where the investigation was performed to evaluate the effect of combined attack of chloride and sulphate on concrete and mortar.

Incorporation of NP and NS reduces the hydration process; moreover, it reduces the penetration of salt in concrete, thus no significant loss in weight in S1 and S2. This assures that incorporation of SCMs in concrete (S1 and S2) could reduce the permeability of corrosive species which cause corrosion in reinforced structures and failure of

Table 3: Chemical properties of PLC, NP, and NS.

| Chemical properties | Material | | |
|---|---|---|---|
| | PLC | NP | NS |
| $SiO_2$ | 17.9 | 55.91 | 39.07 |
| CaO | 60.9 | 0.52 | 10.32 |
| $Al_2O_3$ | 5.5 | 14.55 | 12.80 |
| $Fe_2O_3$ | 2.9 | 4.30 | 15.47 |
| MgO | 0.5 | 0.21 | 4.82 |
| $TiO_2$ | — | 0.55 | 3.84 |
| $K_2O$ | 0.22 | 5.01 | 0.62 |
| MnO | 0.36 | 0.36 | 0.22 |
| $Na_2O$ | — | 4.95 | 0.40 |
| Loss on ignition | 8.4 | 8.79 | 10.73 |

Table 4: Physical properties of PLC, NP, and NS.

| Physical properties | Material | | |
|---|---|---|---|
| | PLC | NP | NS |
| Density (kg/m$^3$) | 3010 | 2390 | 2930 |
| Blaine-specific surface area (m$^2$/kg) | 431 | 507 | 575 |
| Initial setting time (minutes) | 148 | — | — |
| Soundness (mm) | 1.5 | — | — |
| Compressive strength 28 days (MPa) | 45 | — | — |

Table 5: Concrete workability.

| Concrete mix | Slump value (mm) |
|---|---|
| Control mix (CT) | 68 |
| Concrete with 10% NP (S1) | 60 |
| Concrete with 10% NS (S2) | 60 |

structure [48, 49]. Thus suggesting that incorporation of NP and NS prohibits penetration of aggressive salts making concrete adequate under 5% NaCl and 5% $Na_2SO_4$ and combination of both 5% NaCl and 5% $Na_2SO_4$.

*3.4. Compressive Strength Variation.* The strength comparison between concrete with natural pumice (S1) and concrete with natural scoria (S2) with reference to CT (concrete without natural pumice and scoria) under different exposure conditions at the age of 28, 56, and 90 days was used to assess the variation in compressive strength. At the early age of 28 days, the increase in compressive strength was slow for S1 (concrete containing NP) and S2 (concrete containing NS) when immersed in 5% $Na_2SO_4$ solution but significant increase in compressive strength is noticeable at the age of 56 and 90 days.

The concrete samples S1 (concrete containing NP) and S2 (concrete containing NS) under 5% NaCl have significant reduction of strength. Moreover, similar observation is noticed in concrete specimens exposed in the combined 5% $Na_2SO_4$ and NaCl solution. The performance of concrete was superior under water and $Na_2SO_4$ solution. Concrete containing pumice (S1) has 12.11% and 9.9% higher strength than the control mix (CT) in water and in 5% $Na_2SO_4$ solution, respectively, at the age 56 days, and concrete containing scoria (S2) has 6.3% and 4.6% higher strength than the control mix (CT) in water and 5% $Na_2SO_4$ solution, respectively, at the age of 56 days. For 90 days cured samples, concrete containing pumice has 7.7% and 15.4% in water and 5% $Na_2SO_4$ solution, respectively, while concrete containing scoria has 3.04% and 13.6% in water and 5% $Na_2SO_4$ solution, respectively.

The concrete containing pumice (S1) and scoria (S2) showed the drop of strength under 5% NaCl exposure condition. Under the combination of both 5% $Na_2SO_4$ and NaCl solution, concrete containing pumice has 8% and concrete containing scoria has 7.3% higher strength than the control mix (CT) at the age of 90 days. Figure 4 demonstrates the differential in compressive of concrete specimens S1 and S2 under $Na_2SO_4$ and NaCl solutions at different concrete ages.

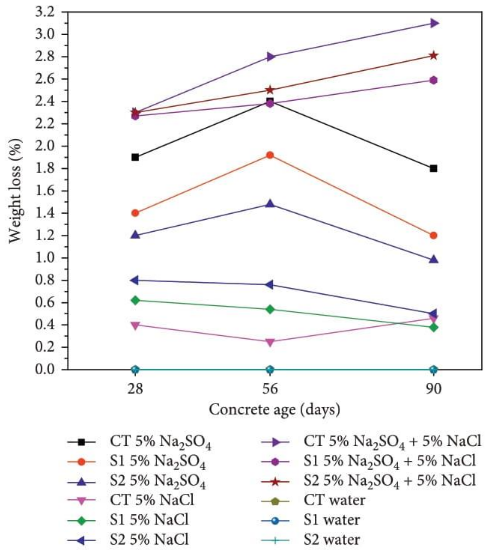


Figure 3: Weight loss of CT, S1, and S2 immersed in sulphate, chloride, and combined sulphate and chloride solution.

*3.5. Compressive Strength of the Specimens under Water, Sulphate, and Chloride Solutions.* The compressive strength for the dried samples was determined after the immersion test. The compressive strength of 28, 56, and 90 days immersed samples in potable water is presented in Figure 5. The results demonstrate that the performance of concrete samples S1 (34.3 MPa) and S2 (33.4) is higher than the CT (31.9 MPa) at 28 days when immersed in water; this indicates that the pozzolanic reaction initiated the growth of strength in concrete samples S1 and S2. For instance, the compressive strength of S1 is higher by 12.11% and 7.7% as compared to CT at 56 and 90 days, respectively. S2 compressive strength is higher by 6.3% and 3.04% as compared to CT at 56 and 90 days, respectively. It was noted that, under the presence of

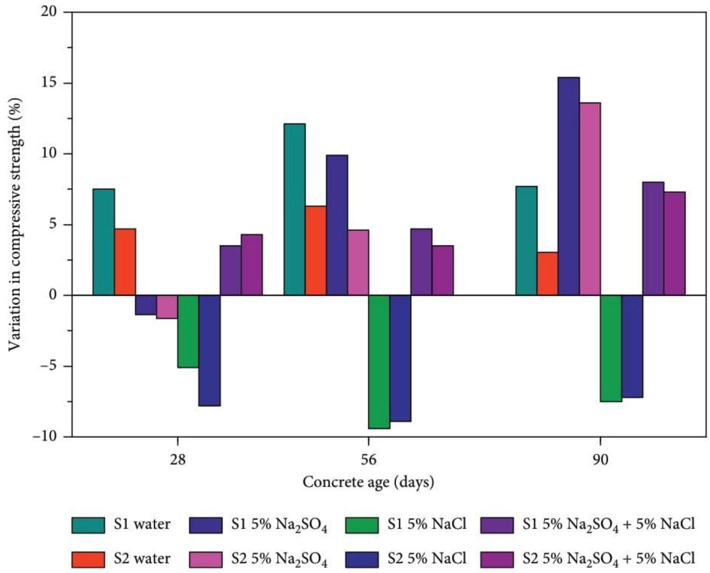


Figure 4: Compressive strength variation of CT, S1, and S2 immersed in water, sulphate, and chloride at different concrete ages.

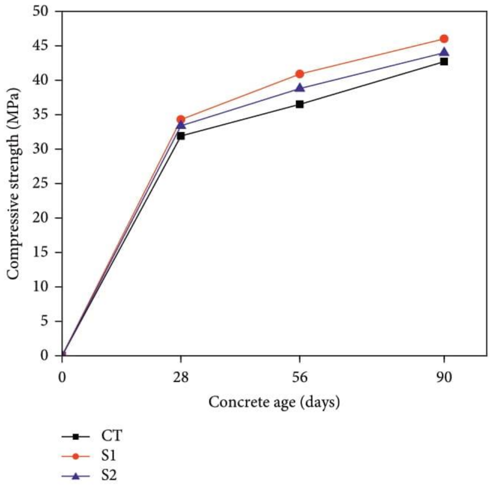


Figure 5: Compressive strength of CT, S1, and S2 immersed in potable water.

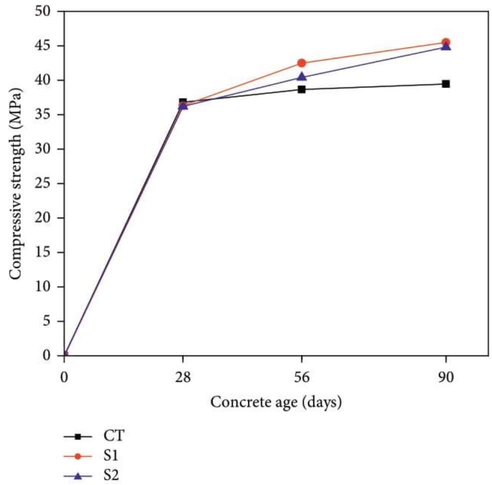


Figure 6: Compressive strength of CT, S1, and S2 immersed in the sulphate solution.

pumice and scoria, the pozzolanic reaction took place after 28 days and kept on increasing with the concrete age.

The compressive strength of samples immersed in 5% sodium sulphate curing for different exposure time is presented in Figure 6, and the physical characteristics are presented in Table 6. From Figure 6, concrete samples under the 5% $Na_2SO_4$ exposure condition show that the performance of concrete samples containing pumice (S1) and scoria (S2) was found to be comparable with concrete without pumice and scoria (CT) at 28 days of immersion. It was noted that concrete samples with and without pumice and scoria after exposure to the sulphate solution have no significant damage caused for the short-term exposure. The compressive strength of S1 was found to be outstanding as

Table 6: Physical characteristics of concrete mixes after exposure to the sulphate solution: slight peeling of the surface is visible.

| Sample | Curing days 28 | 56 | 90 |
|---|---|---|---|
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

compared to CT by 9.9% and 15.4% at 56 and 90 days, respectively. The same trend is observed in S2 where strength was superior as compared to CT by 4.6% and 13.6% at 56 and 90 days, respectively. This concurs with the findings observed by Mangi et al. [1] as they investigated on OPC concrete with coal bottom ashes exposed to the sulphate solution for 90 days exposure time.

Moreover, the findings in the current study concur with the findings reported by Demir et al. [21] where OPC mortar with blast-furnace slag, bottom ash, and fly ash as SMCs was investigated where mortar samples were immersed in the $Na_2SO_4$ solution for 360 days and strength performance of blended mortar was 2% greater than that of OPC mortar. It was previously declared that samples immersed in lower proportions of $Na_2SO_4$ (0.27–1.8%) for 300 days had no significant damage caused on mortar properties.

It was also acknowledged that diffusion of sulphate ions in pores of the concrete accelerates the chemical reaction between cement hydration products. The chemical reaction of $Na_2SO_4$ and sulphate ions with Ca $(OH)_2$ and monosulphate gives gypsum and ettringite (crystal needle) in concrete pores [50, 51]. Addition of pozzolanic materials makes the concrete denser by decreasing the Ca $(OH)_2$ content; at the same time, development of corrosive species becomes hard to grow [52]. Pumice and scoria remove lime liberated during cement hydration and $C_3A$ dilution [7]. It was experimentally found that pumice and scoria-blended concrete has better performance and was found to resist the effect of the $Na_2SO_4$ solution. The performance of pumice and scoria-blended concrete is attributed by refinement of pore sizes that limits ingress of sulphate ions [53, 54].

The compressive strength of samples immersed in 5% sodium chloride curing for different exposure time is presented in Figure 7, and the physical characteristics are presented in Table 7. The strength development of S1 and S2 was found to be lower than CT in the NaCl exposure environment. The same trend has been found in the concrete containing 5% coal bottom ashes [1] and concrete containing 5% rice husk ashes [55]. The chloro-aluminate produced in the chloride solution is the reason for strength deterioration, and the deterioration took place by de-calcifications, and the deterioration is notable at later ages [56, 57]. At the same time, leaching of calcium hydroxide, permeable C-S-H gel formation, and de-calcification effects of NaCl take place in concrete [55].

It is also known that chlorides promote the leaching of Ca $(OH)_2$ and the formation of porous C-S-H involving complex reactions [58]. Physical appearance of concrete is affected due to disturbance created in the hydration process by the presence of chlorides which affect the pore sizes. From experimental results, CT in 5% NaCl solution gains its strength up to 56 days, and the strength declines after 90 days of immersion time. The performance of S1 and S2 was found to be lower than CT but it was noted that there is continual growth of strength in S1 and S2. It was acknowledged that, under 5% NaCl, the pozzolanic reaction becomes slow and takes more time to recover [1]. Thus, the performance of S1 and S2 was unsatisfactory under sodium chloride.

The compressive strength of samples immersed in 5% sodium sulphate and chloride curing for different exposure times is presented in Figure 8, and physical characteristics of concrete mixes after exposure to the sulphate and chloride

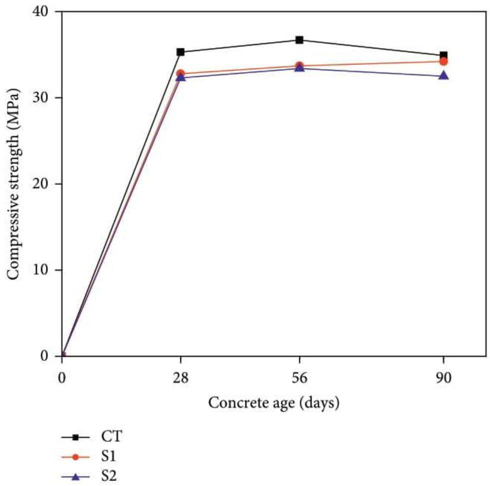


Figure 7: Compressive strength of concrete CT, S1, and S2 immersed in the chloride solution.

Table 7: Physical characteristics of concrete mixes after exposure to the chloride solution: without significant surface damage.

| Sample | Curing days | | |
|---|---|---|---|
| | 28 | 56 | 90 |
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

solution are presented in Table 8. Under the combined exposure of sodium chloride and sulphate, the concrete blended with pumice (S1) and scoria (S2) performed better than the control mix at exposure periods of 28, 56, and 90 days. At 28 days, the performance of S1 and S2 was 4.5% and 1.3% greater than CT, respectively. A superior performance is observed at early ages. The compressive strength of S1 concrete is 3.3% and 8% greater than the CT at 56 and 90 days, respectively. Its counterpart, S2 has 2.3% and 7.3% at 56 and 90 days, respectively.

The decline in compressive strength of CT, S1, and S2 can be explained as follows; both sulphate and chloride bind with $C_3A$ to form ettringite, gypsum, and, sometimes, Friedel's salt. However, for Friedel's salt, chlorides' reaction product is not stable under the sodium sulphate solution [59]; as time of immersion is increased, Friedel's

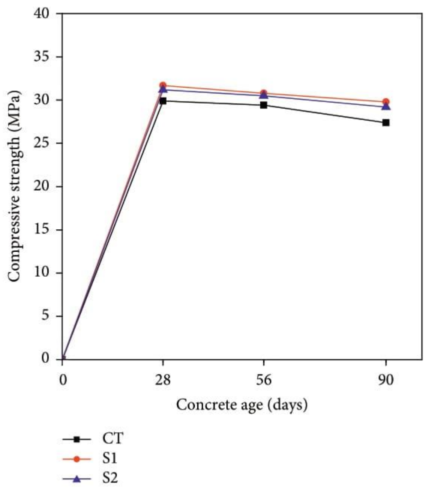


Figure 8: Compressive strength of CT, S1, and S2 immersed in the combined solution of sulphate and chloride.

Table 8: Physical characteristics of concrete mixes after exposure to sulphate and chloride solution: large peeling of the surface visible.

| Sample | Curing days | | |
|---|---|---|---|
| | 28 | 56 | 90 |
| CT |  |  |  |
| S1 |  |  |  |
| S2 |  |  |  |

salt will disappear, more ettringite and gypsum will form, and deterioration will occur at later ages. Moreover, ettringite may induce expansion in concrete which may cause a certain cracking in concrete [4]. This cracking leads to increase of chloride penetrability in concrete. The S1 and S2 performance was influenced by the dense microstructure due to the pozzolanic reaction of pumice and scoria so that the penetration of chloride ions becomes less.

*3.6. Degree of Damage.* The extent of deterioration of concrete specimens immersed in water, sulphate, and chloride was obtained by using equation (1) and graphically

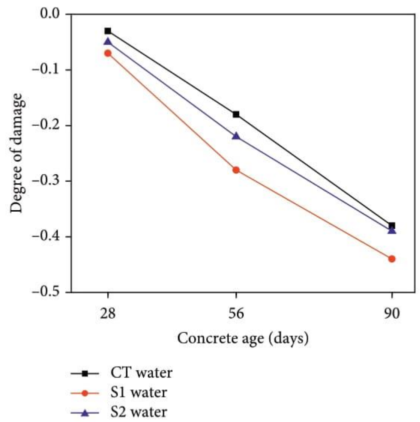


Figure 9: Degree of damage CT, S1, and S2 scoria immersed in water.

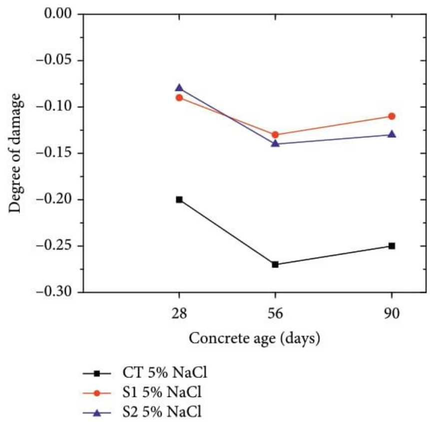


Figure 11: Degree of damage of CT, S1, and S2 immersed in the chloride solution.

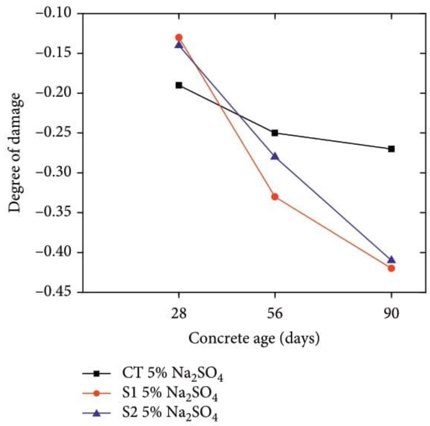


Figure 10: Degree of damage of CT, S1, and S2 immersed in the sulphate solution.

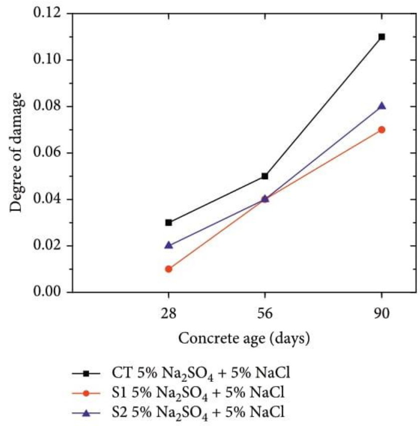


Figure 12: Degree of damage of CT, S1, and S2 immersed in the combined sulphate and chloride solution.

presented in Figures 9–12. The results reveal that the degree of damage of the control mix (CT) is highest at all exposure conditions except for the sodium chloride exposure where the degree of damage is highest. Moreover, the concrete containing pumice (S1) and scoria (S2) has less degree of damage at all exposure conditions except for the sodium chloride exposure.

However, the higher were noticed in CT concrete 0.02, 0.04, and 0.11 under the combined exposure of sulphate and chloride for 28, 56, and 90 days, respectively. S1 has 0.01, 0.04, and 0.08 under the combined exposure of sulphate and chloride for 28, 56, and 90 days, respectively, while S2 has 0.02, 0.04, and 0.7 of 28, 56, and 90 days, respectively. The degree of damage was highest in the control mix (CT) because of the porous structure formed due to chemical corrosion. Due to increase of permeability, the sulphate and chloride solutions can more easily penetrate into interior of concrete; as a result, the porosity is increased, and the effective area is decreased. [3]. The increase in the degree of damage reduces the bearing capacity of concrete structures, and it will reach a degree, and the concrete structure will fail completely [60]. The lower the degree of damage, the higher is the strength and durability of concrete.

## 4. Conclusions

The present study investigated the compressive strength, degree of damage, and physical properties of the cement-NP/NS blended normal concrete (with design strength of 25 MPa) subjected to combined sodium sulphate and sodium chloride solutions. The blended concrete mixes containing 10% NP/NS showed a greater compressive strength than the control mixes, implying that the inclusion of NP/NS led to improved compressive strength both at the ordinary and aggressive environment. Following are the conclusions drawn on the presented experimental results:

(1) The study indicated the successfulness of pumice and scoria as SCMs to replacement of OPC in concrete under normal and aggressive environments
(2) The concrete S1 (concrete with pumice) and S2 (concrete with scoria) has outperformed concrete CT under sulphate, chloride, and combined sulphate and chloride solutions showing that incorporation of natural pumice and scoria has great potential of alleviating penetration of aggressive salts in concrete structures
(3) The degree of damage of concrete is reduced with the incorporation of natural pumice and scoria, and it is obvious concrete incorporated with natural pumice and scoria has less deterioration caused by aggressive salt solutions

## Data Availability

The data used to support the findings of this study are included within this article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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(ii) Poster Presentation

# STRENGTH AND DURABILITY PROPERTIES OF CONCRETE CONTAINING PUMICE AND SCORIA AS SUPPLEMENTARY CEMENTITIOUS MATERIAL

Safiel T Chambua [a, b], Revocatus L. Machunda [a, b, c], Yusufu A. C. Jande [a, b]

[a]Department of Materials and Energy Science and Engineering, Nelson Mandela African Institution of Science and Technology; P. O. Box 447, Arusha, Tanzania.
[b]Water Infrastructure and Sustainable Energy Futures, the Nelson Mandela African Institution of Science and Technology; P.O. Box 9124, Nelson Mandela, Arusha, Tanzania.
[c]Department of Water and Environmental Science and Engineering, the Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania

## Abstract

Concrete structures suffer serious deterioration under corrosive environment. Consequently, the service life of these concrete structures is decreased and deteriorate under combined attack of sulphate and chlorides. Most studies confined on single deteriorating factor such as sulphate attack only or chloride attack only but the current study focused on the influence of natural pumice (NP) and natural scoria (NS) on the strength performance of concrete exposed combined attack of sulphate and chloride. Portland cement (PLC) was replaced with NP or NS at a substitution level of 10%. Concrete samples were cured in water for the curing period of 28 days. Afterwards, the specimens were immersed in 5% sodium sulphate ($Na_2SO_4$), 5% sodium chloride (NaCl) and combined sodium sulphate and chloride solutions for additional curing of 28, 56 and 90 days. The effects of sulphate, chloride and combined sulphate and chloride were evaluated in terms of change in weight, variation in compressive strength and degree of damage. Conclusively, application of NP and NS have extraordinary potential to be utilized as a cementitious material in concrete to increase the resistance against aggressive salts.

## Introduction

- Concrete is one of the most widely used materials in the construction industry
- It was singled out that, sulphate, chloride and their associated cations are the most aggressive chemicals affecting concrete durability. The concrete durability becomes a major concern since the capacity to withstand imposed load decrease with time.
- Such changes lead to loss of strength, structural integrity and shortened service life (Manjunath & Dinakar, 2016)

## Pozzolanic Reaction

Cement chemically react with water to yield calcium silicate hydrate (C-S-H) gel and calcium hydroxide (CH)

$$2C_3S + 6H \rightarrow C-S-H + 3CH$$

The silicon dioxide from the pozzolans (NP or NS) react with $Ca(OH)_2$ to yield C-S-H gel, the principal binding agent

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow C-S-H\ gel$$

## Problem Statement

- Mboya et al., [Mboya et al., 2019] indicated that NP and NS as cement replacement can enhance the strength and durability of concrete but studies on concrete containing NP and NS under combined exposure of sulphate and chloride are rarely reported.
- In addition, no research has evaluated the properties of concrete NP and NS under combined exposure of sulphate and chloride solutions.

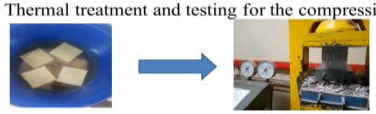
## Objectives

To investigate the strength and durability properties of concrete incorporated with Scoria and Pumice as cement supplement materials under combined attack of sulphate and chloride

## Materials and Methods

**i.** Producing the NP and NS and concrete samples preparation


**ii.** Thermal treatment and testing for the compressive strength



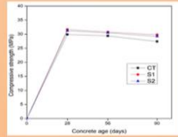
Treatment of the concrete samples in salts — Testing for compressive strength

## Results and Discussion

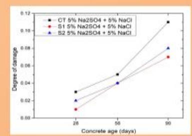
Elemental compositions for the mineral binders

| Chemical properties | % $SiO_2$ | % CaO | % $Al_2O_3$ | % $Fe_2O_3$ | % MgO | % $SO_3$ | LoI | surface area ($m^2/kg$) |
|---|---|---|---|---|---|---|---|---|
| NSHA | 45.2 | 2.6 | 22.6 | 3.4 | 3.3 | 0.8 | 5.6 | 544 |
| Cement | 17.4 | 57.4 | 4.9 | 3.0 | 0.5 | 2.7 | 9.9 | 431 |

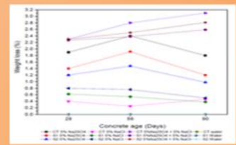
Physical characteristics of treated samples



Compressive strength results




Degree of damage



Mass loss

## Conclusion

- The study indicated the successfulness of pumice and scoria as SCMs to replacement OPC in concrete under normal and aggressive environment
- The concrete S1 (concrete with pumice) and S2 (concrete with scoria) has outperformed concrete CT under sulphate, chloride and combined sulphate and chloride solutions showing that incorporation of natural pumice and scoria has great potential of alleviating penetration of aggressive salts in concrete structures.

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