DEVELOPING A CONCRETE MIX DESIGN FOR A SIMULATED AGGRESSIVE ACIDIC SEWER ENVIRONMENT USING RICE HUSK ASH AS AN ADMIXTURE

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A thesis submitted to the School of Engineering and Built Environment in partial fulfillment of the requirements for the award of the Degree of Master of Science in Structural Engineering of Masinde Muliro University of Science and Technology

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DECLARATION

This thesis is my original work prepared with no other than the indicated sourcesand support and has not been presented elsewhere for a degree or any other award.

Signature... Date ....

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CSE/G/01-52474/2018

CERTIFICATION

The undersigned certify that they have read and hereby recommend for approval of Masinde Muliro University of Science and Technology a research thesis entitled **'Developing a Concrete Mix Design for A Simulated Aggressive Acidic Sewer Environment Using Rice Husk Ash as An Admixture'**

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DEDICATION

This work is dedicated to my mum, my wife Melline and to mydaughters Zully and Hope for their constant love.

ABSTRACT

When sewage flows through closed concrete pipes, sulphuric acid (H_2SO_4) generated from the sewage interacts with elements of concrete leading it to corrode. This leads to reduced durability and reduction of lifetime of sewer pipes and pumpingstations. Interventions that have been used to mitigate this phenomenon have been found to result into high maintenance costs, thus expensive and unsustainable. The study aimed to develop a concrete mix design for use in acidic sewer environments using Rice Husks Ash (RHA) as an admixture with minimum water cement ratio. The required characteristic strength for such environment according to BS 8500 Part I is $35N/mm^2$. Two variables, namely percentages of RHA and water to cement ratio (W/C) were used to alter the properties concrete. The properties evaluated were workability, compressive strength, surface texture, mass loss and porosity. The two water cement ratios 0.4 and 0.35 were used with 0%, 5%, 10%, 15% and 20% RHA in cement to produce concrete. Slump test was carried on fresh concrete for all the categories. The cubes were exposed toacidic solution, which was used to simulate the aggressive acidic sewer environment. The effect the acidic solution had on surface roughness, mass loss, porosity and compressive strength of the cubes was then evaluated. The presence of RHA diminishedthe workability of concrete as the slump values reduced with increased presence ofRHA in cement. Samples with 0.35 W/C were observed to have slightly more compressive strengths and also performed better in terms of surface texture, mass loss and porosity than those with 0.4 W/C. The highest compressive strengths, for the two water cement ratios, were achieved with 5% RHA in cement and thereafter the strengths reduced with increasing presence of RHA. The mass loss and porosities, for both water cement ratios, decreased with increasing presence of RHA in cement. As the various categories performed differently on the properties investigated, Analytic Hierarchy Process (AHP) was used to develop a scoring system to evaluate the performance of various percentages of RHA and thus determine the optimum % RHA replacement. The process determined a mix of 10% RHA and 0.35 W/C as the optimum with a compressive strength of $35.29N/mm^2$ slightly higher than the recommended characteristic strength by 0.8%. This translated to a mix proportion of cement, fine aggregates and coarse aggregates of 1: 0.98: 1.67, with 10% RHA as an admixture.

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LIST OF ABBREVIATIONS

ACEC: Aggressive Chemical Environment for Concrete

AHP: Analytical Hierarchy Process

ASTM: American Society for Testing and Materials

BOD: Biochemical Oxygen Demand

BRE: Building Research Establishment

BS: British Standard

CAC: Calcium Aluminate Cement

C-H: Calcium Hydrate

CH_4 : Ammonia

CO_2: Carbon Dioxide

DC class: Design Chemical Class

FA: Fly Ash

H_2S: Hydrogen Sulphide

H_2SO_4: Sulphuric Acid

HCl: Hydrochloric Acid

JICA: Japan International Cooperation Agency

KIWASCO Kisumu Water and Sanitation Company

$MgSO_4$: Magnesium Sulphate

NH_3: Ammonia

OPC: Ordinary Portland Cement

PC: Portland Cement

RHA: Rice Husk Ash

SF: Silica Fume

SOB: Sulphur Oxidizing Bacteria

SO_4: Sulphate

SRPC: Sulphate Resisting Portland Cement

VOCs: Volatile Organic Compounds

W/C: Water Cement Ratio

CHAPTER ONE:

INTRODUCTION

1.1 Background information

An efficient wastewater collection and disposal system is key in maintaining minimum sanitary standards of any civilized and growing urban set up. Inadequate functioning or the absence of wastewater infrastructure can result in the transmission of illnesses and the pollution of potable water, particularly prevalent in the developing nations.

Concrete has been and is still being used widely as a construction material worldwide due to its strength, flexibility in usage, durability, ease of production and moderate maintenance cost. It is used in general construction of among others; buildings, bridges, road works, water retaining structures, marine structures and wastewater conveyance and treatment plants. In Kisumu city the total mapped sewerage pipe network (according to a feasibility study report by JICA on Kisumu Water Supply and Sewerage System in 2010) is approximately 145km, 52% of which is concrete. The service provider KIWASCO is currently undertaking expansion of the sewerage reticulation network within the city most of which is concrete works as shown in figure 1.1.

However, even though concrete offers numerous benefits and versatility as a construction material and is extensively utilized, concrete structures in specific harsh conditions like sewer systems experience hastened degradation.

Figure 1. 1: Newly Constructed Concrete Sewer Pipe and Manholes

Corrosion of concrete within sewer systems has been recognized as a primary factor contributing to the deterioration of concrete structures in wastewater infrastructure on a global scale. This trend is progressively causing elevated maintenance expenses and posing significant health and environmental issues (Guangming, 2014)

Currently, concrete corrosion has been identified as affecting sewer systems in many cities of the world. Figure 1.2 shows a chamber showing peeled-off zones and exposed reinforcement due to corrosion. As a result of corrosion, the expected lifespan of this concrete pipe has been dramatically diminished, dropping from an initial projection of 75–100 years to less than two decades. In general, the anticipated lifespan of numerous sewer tunnels constructed during the 1960s and 1970s has seen a substantial reduction, decreasing from an initial estimate of 75–100 years to less than 50 years (Linping et al., 2018). Moreover, the production of hazardous gases, primarily hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and other volatile organic compounds (VOCs) linked to biogenic corrosion, poses a significant health hazard to both workers and operators within the wastewater system (Gutierrez et al., 2010)

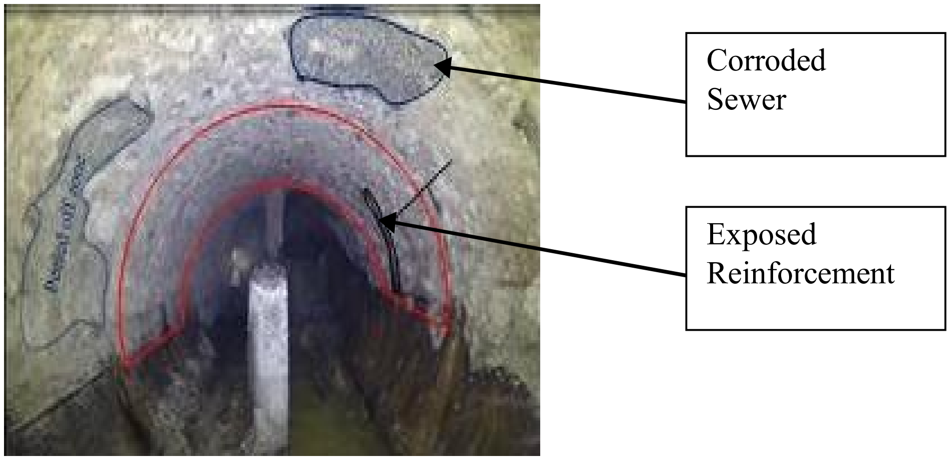

Figure 1. 2: Corrosion conditions in a sewer tunnel (Limping et al, 2018)

As early as 1945, it was determined that microorganisms actively initiate the process of degradation of inner chambers of concrete sewer pipes, and that the process was caused by the Sulphur cycle (Parker, 1945). In the absence of oxygen, sulphate reducing bacteria (SRB) generate hydrogen sulphide gas (H_2S) from Sulphur compounds.

Hydrogen sulfide gas (H_2S) is generated in conjunction with carbon dioxide (CO_2), methane (CH_4), and various other volatile gases, and it is partially released into the atmosphere within the wastewater piping system, wastewater treatment facilities, and/or pumping stations.

As H_2S is released into the chambers, it is involved in a chemical reaction to produce sulphur, and consequently to produce sulphuric acid (H_2SO_4) by sulphur oxidizing bacteria (SOB). This leads to formation of loose expansive whitish by products as shown in figures 1.3, 1.4 and 1.5 (Guangming, 2014).

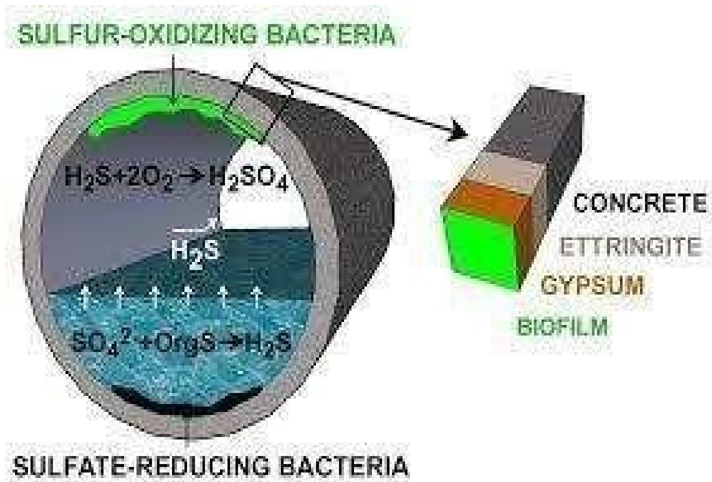

Figure 1. 3: Corrosion Process in a sewer (Wells, 2009)

Figure 1. 4: Internally Corroded Concrete Sewer Pipe (Guangming, 2014)

Figure 1. 5: Internally Corroded Concrete manholes (Guangming, 2014)

It has been proven that the more the generation of H_2S inside the chamber, the faster the concrete material starts to corrode. Using concrete coupons in an experiment, Guangming (2014) was able to demonstrate that a higher concentration of H_2S in the sewer chamber reduced the concrete corrosion initiation time significantly (Guangming, 2016).

Understanding the degradation processes outlined above in cementitious structures when exposed to such corrosive substances represents a crucial initial phase in advancing concrete mixes that exhibit enhanced performance in these conditions. This knowledge can contribute to extending the operational lifespan and enhancing the safety of various structures and facilities. Furthermore, an understanding of the chemical characteristics of concrete and their implications in corrosion can serve as the foundation for developing appropriate concrete formulations for long-lasting wastewatersystems

This research aimed to investigate the utilization of locally accessible additives, specifically Rice Husks Ash (RHA), for the purpose of formulating a concrete blend with suitable characteristics forpreventing corrosion.

RHA have been found to have pozzolanic properties and for a long time explored as an admixture. Water cement ratio (W/C) have also been shown to have significant impact on the physiochemical properties of concrete product such as strength, surface roughness and porosity.

The two variables, RHA and W/C, were used in this study to alter the physiochemical properties of concrete mix that can withstand corrosion. Concrete cubes were exposed to a simulated aggressive environment in form of acidic solution then the performance of various mixtures determined.

The objective of this research was to create an environmentally friendly concrete mix design suitable for challenging sewer conditions, while considering the chemical and physical attributes of concrete that govern its interaction with harmful substances. Prevention of ingress of aggressive chemicals into the concrete matrix and chemical reaction with cement paste was the primary step in inhibiting deterioration of concrete exposed to these environments.Concrete production basically entails two major processes that is concrete manufacturing and the hydration or curing process. Concrete manufacturing process involves design and controlled mix of relevant binder types, aggregates, water cement ratio and admixtures. Various types of concrete for specific applications have been produced after careful selection and mix of these input parameters. The physiochemical characteristics include pore structure, size & distribution, compressive strength, surface quality and texture and mineralogical composition. These characteristics, in view of the current study, are assumed to contribute to resistance of the final concrete product to corrosion

1.2 Problem Statement

The flexibility and ease of production of concrete as an engineering material has led it to be used in most of civil engineering structures among them sewer works. Like any other engineering materials, concrete needs to be designed for certain desirable properties for specific application or for specific environments.

Concrete in wastewater works undergo corrosion that affects the durability of the works leading to expensive repairs and replacement of damaged structures before their time. For instance, in the United States alone, sewer infrastructure was reported to suffer an annual economic loss estimated at approximately $14 billion due to corrosion (Brongers et al, 2002). Additionally, in some extreme cases, studies have revealed that the lifespan of sewer pipes and pumping stations has been reduced to less than a decade, as reported by Olmsted and Hamlin in 1900.In addition, the population in urban areas have been increasing mainly due to industrialization putting more pressure on existing sewer networks and the need by authorities to research on and develop new methods of developing lasting sewers. This has however proved to be costly and with logistical challenges as some roads have to be closed during construction works especially in crowded and busy urban centers.

There have been situations where concrete sewer pipes and manholes have collapsed and resulted in sewage flowing and flooding the streets. This is detrimental to both human health and the environmentdue to the release of hydrogen sulphide gas that is odorous and toxic. The leakage from these damaged pipes may also mix with ground water leading to contaminations.

A number of interventions have been proposed and tested to counter corrosion but to date none of the so far tested materials can withstand the aggressive environment over its design life. In addition, the interventions are costly in the long term. There is also no standard regulation which recognizes this specific type of attack. The conventional exposure classes in the BS 8500 also do not stipulate specific requirements for this kind of environment.

A concrete mix which incorporates readily available admixtures therefore need to be developed so as to achieve desired physiochemical concrete parameters that inhibit corrosion while in use in aggressive sewer environment. The study focusses on RHA that can readily be obtained from agricultural wastes.

1.3 Research Objectives

1.3.1 Main Objective

The main objective of this study was to develop a mix design for concrete exposed to a simulated aggressive acidic sewer environmentusing Rice Husk Ash as an admixture.

1.3.2 Specific Objectives

The specific objectives addressed in this study were

1. To determine the effect of rice husks ash (RHA) and Water Cement Ratio on the workability of concrete.
2. To determine the effect of RHA and Water Cement Ratio oncompressive strength of concrete exposed to a simulatedaggressive acidic sewer environment.
3. To determine the effect of rice husk ash (RHA) and Water Cement Ratio on the surface texture, mass loss, and porosity of concrete exposed to a simulated aggressive acidic environment.
4. To develop a concrete mix design with optimum RHA to inhibit corrosion by a simulated aggressive acidic sewerenvironment.

1.4 Research Questions

This research sought to address the following questions:

1. What is the effect of (RHA) and Water Cement Ratio on the workability of concrete?

2. What is the effect of (RHA) and Water Cement Ratio on the compressive strength of concrete exposed to a simulated aggressive acidic environment?
3. What is the effect of (RHA) and Water Cement Ratio on the surface texture, mass loss and porosity of concrete exposed to a simulated aggressive acidic environment?
4. What are the mix proportions of concrete incorporating RHA as an admixture that is optimum for inhibition of corrosion in a simulated aggressive acidic environment?

1.5 Significance of the Study

A good number of sewer systems in African cities which have been in operation for over forty years have undergone have undergone degradation caused by corrosion of concrete material. Replacement and rehabilitation of these systems have been a challenge due to associate high costs (Hewayde et al., 2006).

There have been improvements on cement manufacture the use of admixtures which have led to production of concrete with superior properties for application in aggressive environments like sewer works. (Alexander, 2014). These can contribute significantly to production of more durable concrete sewer pipes. However, this has been limited by cost and availability of these effective binder systems. A good technological advancement that is appropriate should utilize locally available materials to solve engineering problems.

Therefore, for practical applications by design engineers, binder systems and production technologies that lead to production of durable concrete sewer pipes should take into consideration utilization of locally available admixtures but effective in prevention of corrosion. This is the main contribution of the current study.

1.6 Scope and limitations of the study

Corrosion within concrete sewers is a complex process influenced by multiple factors present in the sewer environment. These factors encompass the chemical and physical attributes of the concrete, the composition of the sewerage, and the hydraulics of the sewer system.

Moreover, the physical and chemical characteristics are subject to variation based on the concrete constituents, including the type of binder, the aggregates used, the water-to-cement ratio, and the methods employed in concrete preparation and handling during production. While there are several admixtures known to possess diverse chemical qualities that contribute to distinct concrete properties, this study focused on investigating only one admixture due to limitations in the experimental setup. The study only explored the contribution of two variables in altering the physiochemical parameters of concrete:

a) Partial replacement of cement with burnt rice husks ash (RHA), being the admixture, at 0%, 5%, 10%, 15% and 20%. The rice husks were obtained from Lake Basin Development Company in Kisumu.

b) Two water cement ratios 0.35 and 0.4.

A simulated aggressive environment in form of an acidic solution was also used instead of a real sewerage due to time constrains. An acidic solution prepared from a commercially available sulphuric acid, with a concentration of 5%, was used to mimic the aggressive sewer environment which normally initiates corrosion after 15 months to 24 months of sewage flow. A 5% concentration which has a pH of below 5 is an adequate representation of the sewer environment where release of acidic substances and corrosion is initiated.

1.7 Outline of this thesis

This thesis consists of five chapters. Chapter one provides an introduction, which includes the study's context, the articulation of the research problem, the research objectives, the significance of the study (detailing its motivation and knowledge contribution), as well as the study's boundaries and constraints. Chapter Two provides an extensive literature review organized into seven main sections.

The first section focusses on the factors influencing concrete corrosion in sewer structures, with a particular focus on those factors that play a pivotal role in the generation of hydrogen sulfide (H_2S) within the sewer's headspaceand its subsequent transformation into sulfuric acid (H_2SO_4), which leads to concrete corrosion.

The second section focusses on the characteristics of Rice Husk Ash (RHA) when used as an additive. It covers the production process of RHA, the chemical byproducts formed during this process, and the advantages ofconsidering RHA as a pozzolanic material.

The third section assesses how RHA and the water-cement ratio impact the workability of fresh concrete, as determined by prior research.

The fourth section examines existing literature regarding the influence of RHA and the water-cement ratio on the compressive strength of concrete when exposed to aggressive acidic environments.

The fifth section explores the effects of RHA and the water-cement ratio on concrete properties like surface texture, mass loss, and porosity when subjected to aggressive acidic conditions—these are the specific properties under investigation in this study.

The sixth section reviews prior approaches to mitigating concrete corrosion in aggressive acidic sewer environments, focusing on measures that aim to control the corrosive sewer environment, protect the concrete surface from corrosion, and modify the physiochemical properties of concrete to inhibit corrosion. This section also discusses methods for safeguarding the surface of finished concrete products and altering the concrete mix to create corrosion-resistant concrete for aggressive environments.

The final section of this chapter examines the essential concrete properties required for use in aggressive environments.

Chapter Three outlines the materials used and the experimental procedures conducted in the research. The primary approach employed for experimentation was predominantly laboratory-based. They included preparation of concrete cubes incorporating RHA as part of the binder system, curing of cubes, and preparation of a simulated acidic aggressive sewer environment using commercially available sulphuric acid, exposure of the cubes in the acidic solution and evaluation of the performance of the variouscubes. The evaluation tests carried out were compressive strength, mass loss, porosity and evaluation of surfaces of degraded samples.

Chapter Four presents the results and analysis of experimental data obtained from the tests. It focusses on the influence of varying the RHA in cement withthe two water cement ratios, on the parameters under consideration that is strength, porosity mass loss and surface texture. The results on the performance of various samples incorporating different quantities of RHA are used with the Analytic Hierarchy Process tool to propose and optimum mix for concrete exposed in aggressive acidic environment.

Chapter Five presents the conclusions of the study on research objectives and the recommendations for further study. The conclusions are based on the set out specific objectives and on the main aim of developing a mix design for acidic sewer environment. In light of the results obtained and discussed in chapter four, it presents a conclusion in form of a concrete mix design incorporating RHA and a given W/C that the study developed as the optimum. The recommendations are proposals on possible further research areas.

Appendix I presents the gradation process for fine and coarse aggregates used in the experimental study.

Appendix II presents the concrete mix design for the two water cement ratiosbased on the British Research Establishment (BRE) method.

Appendix III Presents the individual and percentage weighted scores fordifferent categories of RHA present in cement, as determined using Analytical Hierarchy Process.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter first gives an understanding of aggressive sewer environment which the sewer pipes are exposed to as they convey sewage.

Secondly the chapter investigates the factors that influence the speed and initial period of concrete corrosion in sewer pipes. These variables, which have been previously identified by researchers, are discussed in this section with respect to their roles in the corrosion process.

The effects of Rice Husk Ash (RHA) and the Water-to-Cement ratio (W/C) on various aspects of concrete when exposed to aggressive acidic conditions are also reviewed. Specifically, their effects on workability, compressive strength, surface texture, mass loss, and porosity, as determined by previous studies are reviewed as determined by previous studies.

Additionally, the chapter provides an overview of the essential properties that concrete should possess when used in aggressive acidic environments. It also evaluates the strategies that have been employed to protect concrete in sewer systems from this type of deterioration, including efforts to design concrete mixes tailored for such environments.

Previous interventions to tackle concrete corrosion can be categorized into two: a) Managing the underlying causative environmental conditions and b) Altering material properties of concrete to enhance its resilience against corrosion (Tahereh et al., 2017). Managing underlying causative environmental conditions entails dosing chemicals into the waste water in order to control emission of gaseous products that transform into corrosive fluids. This intervention can be effective as it tackles corrosion at the primary stage where corrosive gaseous compounds are produced. Some chemicals used in this category are usually meant to reduce the concentration of H2S thus prolonging corrosion initiation time.

However, sewage generated in cities are millions of litters and neutralizing all these would in the long run be very costly and therefore not sustainable.

Altering material properties of concrete to improve its interaction with the aggressive fluids without degradation would be a more sustainable solution.

Concrete admixtures have for a long time been used to achieve different desired physiochemical properties of the concrete. Commercial admixtures have mostly been used.

Previous research has established that there are variations in the durability characteristics among different concrete types when exposed to harsh conditions. However, it's important to note that none of the materials tested in these studies were able to completely prevent corrosion, and all fell short of achieving their intended design lifespan (Alexander et al. 2013 and Herisson et al. 2013).

Different types of cements have demonstrated varying performance outcomes when exposed to harsh conditions, as indicated in studies by Alexander (2014). For instance, calcium aluminate cements (CAC) combined with carbonate aggregates have exhibited effectiveness up to six times greater than that of conventional Portland cement (OPC)-based concrete when subjected to identical aggressive environments (Alexander et al, 2014 and Kiliswa 2016).

2.2 Aggressive Acidic Sewer Environment

According to Guangming (2014) deterioration of wastewater infrastructure is related to the sulphur cycle in wastewater infrastructure. Under certain conditions, oxygen is consumed by some micro-organisms much faster than they can be replaced, changing the environment from an aerobic to an anaerobic system. Under anaerobic conditions, certain bacteria reduce Sulphur compounds to hydrogen sulphide gas (H2S). As H2S is released into the chambers, it is involved in a chemical reaction to produce Sulphur, and consequently to produce sulphuric acid (H2SO4) by Sulphur oxidizing bacteria (SOB). The acid reacts with the alkali components of the concrete binder thus corroding and reducing the thickness of the pipe. This process of production of gas and release of acid to attack the concrete defines the aggressive nature of the sewage.

2.3 Factors Influencing Concrete Corrosion in Sewerstructures

The rate at which concrete corrosion occurs and the moment when corrosion initiates in sewer systems are primarily determined by two key factors: the rate at which hydrogen sulfide (H_2S) is generated and the characteristics of the concrete sewer pipe material.

The production of H_2S, in turn, is influenced by the pH level of the sewer environment, the biodegradability and composition of the waste material (measured by BOD in the sewage), as well as the temperature and flow characteristics of the wastewater.

As noted by previous researchers, this process of corrosion commences with bacteria triggering a biological conversion of sulphates and sulphides into hydrogen sulphide (H_2S). As time elapses, the concrete's surface pH decreases due to the neutralization caused by hydrogen sulphide (Tahereh et al, 2017). The decrease in pH levels promotes the growth of sulfur-oxidizingbacteria (SOB) on the outer surface of concrete pipes during their growth phase. Ultimately, the activity of SOB, which entails the conversion of hydrogen sulfide into sulfuric acid, leads to the degradation of the concrete structure. An analysis of corroded samples collected from a sewage collection system revealed a significant 20% reduction in the usual compressive strength of the concrete in regions where a substantial amount of gypsum was identified within the corrosion layer (Beddoe and Dorner, 2005.

Based on the findings of on-site examinations conducted in six sewer systems across Australia, Wells (2015), the initial phase of sewer pipe deterioration exhibited minimal progression, and there was hardly any loss of concrete mass observed until the surface pH of the concrete dropped to approximately 5, indicating the initiation of mass loss. Once this point was reached, the decline in concrete mass began to increase steadily over time, and it was anticipated that this rate of increase would remain consistent throughout the operational lifespan of the sewer pipe.

It was observed that the time taken to reach this pH level varied depending on specific local conditions, ranging from several months to justunder two years (Tahereh et al, 2017)

Corrosion therefore starts when the pH of the sewer chamber reaches 5 andbelow when the walls of the sewer pipe becomes more acidic. According to studies carried out in Australia, this happens from 15 months to 2 years fromtime of installation.

2.3.1 Air Temperature within the Sewage Chamber

Temperature fluctuations notably influence various biological processes, with higher temperatures leading to increased biochemical reactions. This, in turn, affects the growth rate of bacteria, thereby exerting a significant influence on the density of microbial populations within sewer systems (Kiliswa, 2016).

In 1934, Baumgartner noted that the production rate of H_2S significantly decreases at temperatures below 7°C, while the highest production rate occurs at approximately 30°C. Pomeroy and Bowlus (1946) reported that the H_2S generation rate increases by roughly 7% for every one-degree Celsius rise in temperature within the range of 15°C to 38°C. Mara and Horan (2003) further confirmed that temperature plays a role in the pace of biological processes within sewage systems by affecting the solubility of gases. They observed that elevated sewage temperatures lead to diminished oxygen solubility, resulting in heightened activity of SRB (Sulfate-Reducing Bacteria) due to limited dissolved oxygen availability, consequently leading to increased anaerobic activity and accelerated H_2S production rates.

Guangming (2014) was able to demonstrate that corrosion initiation time reduced with increased air temperature within experimental corrosion chambers as shown in figure 2.1. Corrosion initiation time reduced to less than 15 months when the temperature was 30°C

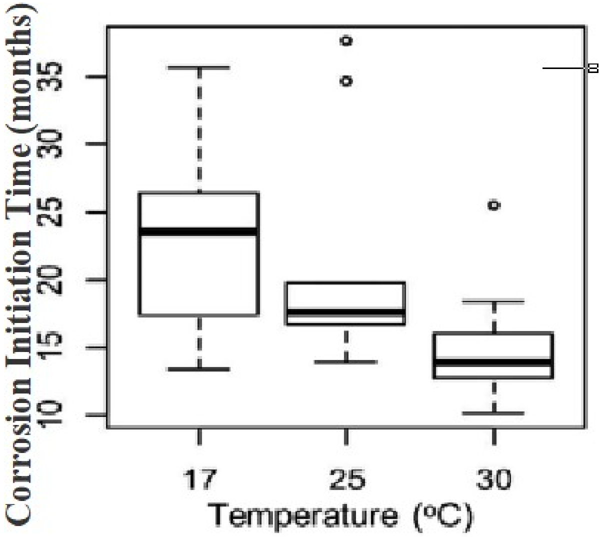

Figure 2. 1: Relationship between temperature and corrosion initiation time (Guangming, 2014)

2.3.2 pH of the Sewage

Typically, municipal wastewater has a pH level ranging from 6.0 to 8.0, impacting various factors that contribute to the corrosion-related deterioration of sewer pipes (Hvitved et al, in 2013). Previous research has indicated that the optimal conditions for sulfide production within wastewater occur when the pH falls within the range of 6.5 to 8, as discussed by Mara and Horan (2003). According to Barjenbruch (2008) Sulfate-reducing bacteria (SRB) thrive within a pH range of 5.5 to 9. Nielsen et al (2006) determined that a decrease in wastewater pH from 7.9 to 7.2 was linked to an increase in hydrogen sulfide gas production in the upper sectionof the sewer, as depicted in figure 2.2.

Okabe et al. (2006) determined that mass loss did not commence until pH level of 4 was reached. Wells (2011) while studying corrosion of concrete sewer pipes noted that the onset of corrosion of concrete coupons occurred when the surface pH declined to 6.

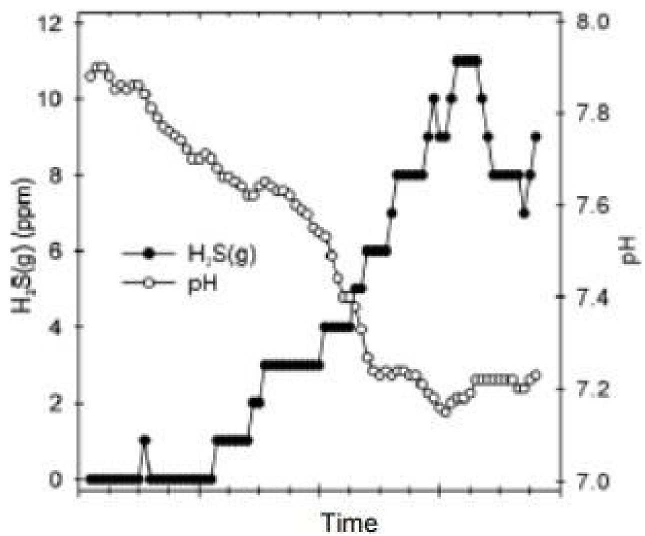

Figure 2. 2: Correlation linking sewage pH and the level of H2S (Nielsen, 2006).

Wells (2011) noted that once the pH of the sewer pipe's surface reaches a value of 6, a notable transformation of intact concrete into a corroded substance, predominantly gypsum, initiates. This signifies an elevation in H_2S concentration, subsequently undergoing oxidation to form H_2SO_4, which reacts with the concrete structure.

Guangming (2014) was able to demonstrate from an experiment using concrete coupons exposed in sewer chambers that the pH of the sewer chamber was inversely proportional to concrete corrosion initiation time.

2.3.3 Biochemical Oxygen Demand (BOD) of the Sewage

Biochemical Oxygen Demand (BOD) is a measurement that indicates the amount of oxygen consumed by microorganisms in wastewater. It is commonly expressed as the quantity of dissolved oxygen consumed byaerobic bacteria within a 5-day period at a wastewater temperature of 20°C, as defined originally by British Royal Commission on River Pollution, established in 1865. The organic nutrients conducive to hydrogen sulfide production correspond directly to the sewage's BOD. Consequently, agreater BOD results in an escalated pace of hydrogen sulfide generation and subsequent H_2SO_4 production within the sewage compartment, thereby shortening the onset period for concrete corrosion and intensifying the corrosionrate.

2.3.4 Flow Characteristics

The speed of flow and the level of turbulence play a crucial role in biogenic corrosion, affecting the aeration or release of air from sewage, as well as thesettling of materials on the sewer bed (Kiliswa, 2016). Under conditions of elevated flow velocities, sewage draws in air, with most particulates remaining suspended throughout the sewer. Conversely, lower velocities lead to diminished air incorporation and the sedimentation of solidson the sewer's base.

According to the United States Environmental Protection Agency the entrainment of air establishes the character of the effluent as either aerobic or anaerobic, consequently affecting the reduction of sulfates and nitrates to varying degrees. Furthermore, sluggish velocities encourage the accumulation of solids on the sewer's base, manifesting as sludge and silt, thereby providing an added habitat for the bacteria accountable for the reduction of nitrates and sulfates within the sewage. Subsequently, exceedingly low velocities correlate with an elevated rate of hydrogen sulfide generation within the sewage chambers (Kiliswa, 2016)

2.3.5 Sewer Pipe Materials

Concrete sewer pipes are produced from fundamental components: the binding system, aggregates, water, and various admixtures. These materials are carefully designed to withstand the harsh conditions of sewer environments. Formulating a concrete mixture using these constituents that can effectively resist corrosion would consequently extend the lifespan ofthe sewer structure. The following are individual elements of concrete and how they can significantly influence ability to resist corrosion in such settings.

2.3.5.1 Cement

The type of cement used in concrete can impact its corrosion resistance. Portland cement is commonly used, but certain types of cement, such as sulfate-resistant cement, can offer better resistance to chemical attacks and corrosion in aggressive sewer environments. The BS 5911 recommends the use of Sulphate Reducing Portland, Portland blast furnace or Portland pulverized fly ash cements for manufacturing precast concrete pipes used in sewer environments.

2.3.5.2. Aggregates

Aggregates are an important component of concrete. Reactive aggregates containing minerals can lead to a phenomenon called reactions, which can cause concrete expansion and cracking, creating pathways for corrosive agents. Using non-reactive or low-alkali aggregates can also help mitigate this issue. The BS 5911 recommends a maximum aggregate size of 20mm, a flakiness index of not more than 35 and a maximum aggregate impact value 30% for aggregates utilized in such concretes.

2.3.5.3. Water Cement Ratio

A lower water-cement ratio generally results in denser and more impermeable concrete, reducing the potential for aggressive chemicals and moisture to penetrate the concrete. The BS 5911 recommends a minimum cement contentof 360kg/m^3 and a water cement ratio of not more than 0.45.

2.3.5.4. Admixtures

Various chemical admixtures can be added to concrete to improve its properties. Corrosion-inhibiting admixtures can help slow down the corrosion process by creating a protective layer or improving the acidic inhibition properties of concrete. These properties have been discussed elaborately in section 2.6 of this report.

2.4 Rice Husk Ash as an Admixture

Rice husk (RH) is an agricultural byproduct, representing about 20% of the total weight of rice. Its composition includes roughly 50% cellulose, 25–30% lignin, and 15–20% silica. Typically, 20% of a rice paddy consists of husk, resulting in an annual production of 120 million tonnes worldwide. In manycountries that cultivate rice, a substantial amount of the husk generated during rice processing is either incinerated or disposed of as waste.

The process of burning rice husk results in the formation of rice husk ash (RHA). This combustion eliminates cellulose and lignin, leaving behind an ash predominantly composed of silica. The quality of RHA is determined by carefully controlled burning conditions, which dictate its particle size and specific surface area. Completely burnt rice husk ash appears gray to white, while partially burnt ash takes on a blackish coloration.

Rice husk ash (RHA) takes the form of an exceptionally fine pozzolanic material. The utilization of RHA as a pozzolanic component in cement and concrete offers several advantages, such as enhanced strength and durability properties, reduced material costs due to reduced cement usage, and environmental benefits related to waste management and reduced carbon dioxide emissions (Ali, 2014)

The presence of silica, along with its notably extensive surface area, is accountable for the high pozzolanic impact when blended with cement. Studies indicate that the heightened silica content plays a pivotal role in augmenting the concrete's durability when appropriately incorporated with cement proportions (Ayesha et al, 2017).

2.5 Influence Of Rha And W/C on Workability OfConcrete

Workability in concrete refers to the ease and ability with which freshly mixed concrete can be manipulated, placed, and compacted during construction without segregation or excessive effort. It is a fundamental property of concrete that affects its handling, transportation, and placement. The workability of concrete is influenced by its consistency, fluidity, and resistance to segregation.

Workability is an important factor because it directly impacts the construction process and the quality of the final hardened concrete structure or precast concrete products like concrete sewer pipes that require flexibility in shape.

Concrete that is too stiff or too fluid can lead to difficulties during placement, resulting in inadequate compaction, poor surface finish, or even structural defects. On the other hand, concrete with optimal workability can be placed efficiently, compacted thoroughly, and molded into desired shapes without compromising its integrity.

Previous studies have demonstrated that incorporating fine rice husk ash particles into concrete blends enhances the cohesiveness of the mixture thus resulting in reduction in workability.

In 1992, Ikpong and Okpala conducted a study to investigate the influence of incorporating rice husk ash (RHA) into concrete mixes designed for various strength levels on workability. They replaced a portion of cement with RHA at ratios of 0%, 20%, 25%, and 30%, corresponding to concrete strengths of 20N/mm², 25N/mm², 30N/mm², and 40N/mm² at 28 days. They observed that achieving the same level of workability required a higher water-cement ratio in mixes containing RHA compared to those with only ordinary Portland cement as the binding material. This difference was evident in the water-cement ratios of the mixes (0%, 30%, and 40% RHA) for each design strength. These ratios were calculated assuming a consistent cement content by weight (Ikpong and Okpala, 1992)

Furthermore, they concluded that the disparity in water content between mixes containing RHA and conventional mixes increased with the design strength of the concrete. For mixes containing 30% RHA, the percentage increases were 3.2%, 4.4%, 8.5%, and 5.6% for design strengths of 20N/mm², 25N/mm², 30N/mm², and 40N/mm², respectively. Similarly, for mixes with 40% RHA, the percentage increases were 6.3%, 8.7%, 10.2%, and 13.0% for the corresponding design strengths.

Bui et al (2005) investigated the impact of rice husk ash (RHA) on the consistency of concrete mixtures. He employed two different types of ordinary Portland cement, PC30 and PC40, each possessing specific surface areas of 2700 and 3759 g/cm2, respectively. Three distinct water-to-cement ratios (0.30, 0.32, and 0.34) were utilized. RHA was introduced as a replacement for 10%, 15%, and 20% of the mass of PC in all mixtures. Superplasticizer was added to enhance workability across all mixtures. In cases where the water-to-cement ratio was 0.34, the quantity of superplasticizer was held constant to examine the impact of RHA on workability. He concluded that, for an equivalent level of superplasticizer, slump decreased as RHA content increased. Maisarah et al (2015) carried out workability test on concrete incorporating 0% and 5% RHA in cement with 0.36 water cement ratio. The study determined that the slump was higher with 0% RHA. The presence of RHA therefore reduced the workability of the mix. The reduced workability was a result of the hygroscopic characteristic of RHA, which denotes its capacity to draw in and retain water molecules from its surroundings. Consequently, the inclusion ofRHA in the concrete led to increased permeability of concrete specimens.

Naraindas et al (2018) conducted an experiment to determine the effect of10% RHA in cement on the workability of class C20 concrete with three watercement ratios i.e 0.45, 0.5, 0.6. He determined that the workability of fresh concrete with 0% RHA was slightly higher than the workability of concrete with 10% RHA.

While studying effect of rice husk ash and water cement ratio on the strengthand durability characteristics of concrete, Hwang et al in 2011 determined that concrete with RHA required a higher quantity of superplasticizer requiredto obtain the desired workability. To obtain the required slump, concrete withRHA required higher water content than that with 0% RHA. Hence, the superplasticizer (SP) content within RHA concrete blends surpassed that of the standard mixture. The SP content increased in tandem with the proportion of RHA.

2.6 Effects Of RHA and W/C on Compressive Strength Of Concrete

The compressive strength of concrete is a crucial and valuable characteristic, with concrete commonly utilized in structural applications to primarily withstand compressive forces. Earlier research has documented a significant enhancement in the compressive strengths of mortars and concretes that include RHA, as reported by Ali in 2014. Previous studies have shown that RHA contains silica which gives the pozzolanic effect that improves strength and also reduces permeability of concrete. The following are some of the findings by previous researchers on the compressive strength of concrete incorporating RHA.

Zhang and Malhotra (1996) conducted a study to investigate the influence ofincorporating 10% rice husk ash (RHA) as a partial substitute for cement, while maintaining a water-to-cement ratio of 0.40, on the compressive strength of concrete. Their results indicated that, on the whole, the concrete containing RHA exhibited higher strength compared to the conventional concrete mixture. Specifically, after 28 days, the compressive strength of the RHA-infused concrete reached 38.6 N/mm², whereas the standard concrete had a strength of 36.4 N/mm². After 180 days, the RHA concrete demonstrated a compressive strength of 48.3 N/mm², while the standard concrete reached 44.2 N/mm².

In a study conducted by Ramezanianpour in 2009, he investigated the changes in the strength of concrete incorporating rice husk ash (RHA). They prepared a total of four concrete mixes: one serving as the control, and the other three with 7%, 10%, and 15% of RHA replacing cement by weight. Overall, the concrete containing RHA exhibited higher compressive strengths at different ages, particularly up to 90 days, when compared to the control concrete.

In 2010 Chandan and Malleswara carried out a study on the benefits of RHA on concrete. They carried out experiments on the effect of 0%, 5%, 7.5%, 10%. 12.5% and 15% RHA in cement on the 3, 7, 14, 28 and 56 days strength of class 20 concrete. The highest strength of 37.62N/mm^2 was obtained with 7.5% RHA after 56 days.

Rammasamy (2011) carried out an experimental study on the effect of 0, 5, 10, 15 and 20 percent RHA in cement on the compressive strength of classes 30 N/mm^2 and 60 N/mm^2 concrete. The highest compressive strengths for the two classes were achieved at 56 days with 10% RHA in cement. Mehta and Malhotra (1997) also obtained similar results on compressive strength with 10% RHA.

Naraindas et al (2018) conducted an experiment to determine the effect of 10% RHA in cement on the compressive strength of class C20 concrete with three water cement ratios i.e 0.45, 0.5, 0.6. The tests were carried for 7, 14, 28 and 56 days. He obtained the highest compressive strength with 10% RHAin cement after 56 days with 0.45 water cement ratio.

Hwang et al in 2011 studied the effect of RHA and W/C on the compressive strength of concrete. The study considered three water cement ratios namely 0.23, 0.35 and 0.47 to produce concrete samples incorporating RHA at 0, 10, 20 and 30 percentages. The compressive strengths were determined for 1, 3 , 7, 14, 28 , 56 and 91 days. The highest compressive strength was obtained with 10% RHA, 0.23 W/C at 91 days curing. Table 2.1 summarizes the optimum percentage RHA in cement for maximum compressive strengths as determined by previous researchers.

Table 2. 1: Summary of Optimum Percentage RHA in cement for Maximum Compressive Strength at 28 days (Previous Studies)

Year	Author	Concrete Class	% RHA	Explanation
1996	Zhang and Malhotra	C40	10%	**Pozzolanic effect in RHA**
1997	Mehta and Malhotra	C30	10%	**Pozzolanic effect in RHA**
2005	Gemma .	C30	10%	**Filler and pozzolaniceffect**
2010	Chandan and Malleswara	C30	7.5%	**Pozzolanic effect**
2010	Ghassan Abood et al	C35	10%	**Silica in RHA reacting with calcium silicate hydrate (C-S-H)**
2011	Ramasamy	C30	10%	**Pozzolanic effect**
2012	Godwin et al	C35	10%	**High pozzolanity effect**
2014	Thanh Le et al.	C30	10%	**PozzolaniC effect, large specific surface area and silica content.**
2019	Naraindas . et al.	C30	10%	**Pozzolanic effect**
2019	Kaarthik etal.	C35	10%	**Pozzolanic effect**
2019	Ankit et al. 2019	C30	7.5%	**Pozzolanic effect**

Average % RHA	**10.5%**

From these studies, the average %RHA for maximum compressive strength is 10%. Incorporation of RHA therefore increases compressive strength to an optimum level.

2.7 Effects Of Rha And W/C On Mass Loss, Porosity And Surface Roughness of Concrete in Aggressive Environment

A number of studies have been conducted to determine the performance of concrete incorporating RHA in simulated aggressive acidic environments. Evaluations have been carried out on a number of properties such as compressive strength, porosity, permeability, mass loss and surface roughness of concrete as the indicators of performance in such environments. Similarly, a number of studies have been carried out to determine the effects of varying W/C ratio on the properties of concrete. Some of these studies and the findings are discussed in this section.

In terms of durability, RHA has been determined to frequently enhance concrete's resilience against deterioration caused by sulphates, chlorides and acids, while also lowering the temperature of fresh concrete (Chatveera and Lertwattanaruk, 2010).

Ramasamy (2011) conducted a series of assessments on RHA within cement concrete, encompassing compressive strength evaluation, measurements of saturated water absorption, porosity, chloride permeability testing, as well as assessments involving exposure to acid and alkaline solutions. The study examined the decline in compressive strength within concrete cubes without RHA and the enhancement in acid resistance observed in concrete cubes incorporating RHA. The outcomes of the tests indicated that concrete with RHA showed greater inhibition against deterioration in acidic solution compared to the control samples. This improved acid resistance in the RHA concrete was partially attributed to the substantial decrease in permeability enabled by incorporation of RHA.

The research determined that concrete with RHA with a notable quantity of amorphous silica showed improved compressive strength alongside reduced permeability. This phenomenon was attributed to the substantial presence of silica in RHA, which led to a more rapid depletion of calcium hydroxide, particularly in the early stages, ultimately resulting in enhanced strength and decreased permeability. Furthermore, the study indicated that the porosity value decreased as the replacement percentage increased. The utilization of fine rice husk ash particles improved the packing density of the concrete mixture, leading to a reduction in the volume of larger pores. A similar trendwas reported by Saraswathy et al. in 2007.

In 2017, Ehsan et al. conducted investigations involving metakaolin (MK) and RHA as substitutes for cement in mortar. The aim was to assess their impact on mechanical and water absorption properties. The findings revealed an approximately 13% enhancement in compressive strength.

In 2018, Sandrex et al conducted an investigation into the implications of incorporating RHA into concrete. The study determined that increasing the proportion of RHA in concrete led to an improvement in its resistance to chloride penetration. The study's ultimate observation was that the inclusion of RHA within the concrete matrix resulted in a decrease in its permeability.

In 2011, Chatveera and Lertwattanaruk conducted an investigation on the resilience of mortar cements incorporating RHA against nitric and acetic acids. The research determined that introducing RHA as a partial replacementof cement produced a favorable outcome by reducing the expansion, weight loss, and loss of compressive strength in mortar when subjected to acid exposure. The study indicated that, within the range of RHA replacement from 0% to 50% by weight of cement, the mortars with a 10% RHA replacement exhibited the least decline in strength and weight due to acid attacks. Additionally, the study determined that increasing the W/C tended to have an adverse impact by increasing expansion and the loss of compressivestrength in mortars.

In 2017, Ahmed and Kamau conducted an analysis on the performance of RHA-infused concrete when subjected to sodium sulfate (Na2SO4) and magnesium sulfate (MgSO4) solutions. The research deduced that substituting 7.5% of cement with RHA proved more effective in bolstering the resistance of concrete's surface against deterioration when exposed to these solutions.

Yun-Yong Kim et al in 2013 conducted a test on the effect of W/C ratio on durability and porosity in Cement Mortar. The study determined that with increasing w/c ratio (additional water amount) from 0.45 to 0.60, porosity increased up to 150% and compressive strength reduced to 75.6%.

Mohammed (2021) determined the variation of properties of concrete with different water cement ratios. He determined that variations in porosity, permeability and absorption increased with increased water cement ratio. The variation in compressive strength increased but negatively, the higher the water cement ratio the lower the compressive strength. The study determined that permeability of the concrete mixes increased with increased water cement ratio.

In 1996, Hong Min carried out a study on the relationship between development of compressive strength and three water cement ratios, 0.31, 0.4 and 0.5, for concrete with 10% RHA. The study determined that the lowest water cement ratio of 0.31 developed the highest increase in compressive strength with time.

Shamsher et al in 2015 studied the role of water cement ratio on strength development of mortar. The study determined that the compressive strengths of various mortar mixes decreased with increasing water cement ratios

It's evident from previous studies that water cement ratio has a significant influence on the durability of concrete meant for aggressive sewer environments since it influences strength and permeability. A less permeable and more compact concrete in aggressive environment means reduced probability of having corrosive chemicals ingress into the concrete matrix. In summary, it can be established from previous studies that utilization of RHA as a pozzolanic material in cement at a certain W/C in concrete provides several advantages, such as improved strength and durability properties, improved permeability, reduced porosity and reduced mass loss when exposed to aggressive environments.

2.8 Previous Interventions to Mitigate ConcreteCorrosion in Sewer Works

A number of interventions have been used to minimize corrosion of concretein sewer works. These can be classified into two main categories, namely:

2.8.1 Managing the Underlying Environmental Conditions

One approach for tackling degradation challenges involves managing the factors responsible for initiating the creation of detrimental conditions. For instance, a proactive step to mitigate the rate of biogenic degradation within sewer systems is to lower the emission rates of sulfide and H_2S in the sewage. The introduction of various chemicals, including magnesium hydroxide, sodium hydroxide, iron salts, and nitrates, into the sewage has been extensively employed to curtail the release of H_2S in both liquid and gaseousphases [Zhang et al, 2008, Ochi et al, 1998, Park et al, 2014].

While these approaches can indeed lower the concentration of sulfides in theliquid phase, certain methods have encountered challenges in managing sulfide levels in the gas phase within the upper section of the sewer. Moreover, they mean high substantial operational and maintenance expenses throughout the system's lifespan and, on occasion, lead to the creation of undesired secondary products [Vaidya and Allouche, 2010].

2.8.2 Altering Material Properties of Concrete to Enhance Its Resilience against Corrosion

2.8.2.1. Coatings on Existing Structures

A technique employed for safeguarding concrete structures involves separating the concrete from exposure to hostile surroundings. Coating and lining stand out as the prevalent techniques for averting concrete corrosion in wastewater treatment facilities, such as concrete tanks. Typically, the inner surfaces of these structures are coated or lined, creating a robust, acid-resistant, and low-permeability barrier between the concrete and the corrosive setting (Piotr et al, 2022). As a result, defensive coatings and sealants like polyurethane, bitumen, polyvinyl chloride, acrylic, and epoxy resins have been administered either proactively for new constructions or toprolong the operational lifespan of structures that have experienced partial degradation [Almusallam et al, 2003].

Pore liners such as silane, siloxane, and fluorinated polymers have also been utilized to coat concrete surfaces (Scarfato et al, 2012). The efficacy of epoxy coating in safeguarding concrete against biological deterioration was investigated in laboratory experiments (Berndt, 2011). Concrete samples coated with epoxy demonstrated impressive protection, except when the coating thickness fell outside the recommended limits.

Following a 60-day exposure, no biofilm was detected on the surface of the coated samples. Epoxy resins generally exhibit strong adhesion to substrates and exceptional chemical resistance. Nevertheless, they are susceptible to brittleness and have relatively low fracture toughness (Wang et al, 2012). Additionally, they hinder the concrete's breathability, which could result in blistering and coating failure.

Coatings containing an incorporated antimicrobial substance have also been utilized to prevent the proliferation of microorganisms on the concrete's surface (Haile et al, 2008). The presence of heavy metal oxides like cuprous oxide and silver oxide was observed to notably diminish the production of sulfide by sulfate-reducing bacteria (SRB) when these oxides were combined with epoxy and applied as a spray onto the inner wall of concrete sewer pipes [Hewayde et al, 2007]. Nonetheless, inadequate adhesion between epoxy and the concrete base led to the release of metal oxides into the simulated sewer solution.

In spite of the extensive use of protective coatings, their functional properties like strength, flexibility, and adhesion could be influenced by microbial activities, encompassing the generation of corrosive metabolites, enzymatic degradation, as well as physical infiltration and disruption (Cappitelli and Sorlini, 2008). In the United States for example, numerous instances of coating failures have been documented in wastewater treatment plants over the past thirty years (Piotr et al, 2022). Nixon [2001] presented six cases where diverse coatings experienced in under two years of service in sewage facilities. Epoxy, coal tar, polyester, vinyl ester, and elastomeric polyurethane-based coatings all exhibited blistering. This underscores the significance of upholding the integrity of coating systems, as the presence of flaws can result in the separation of the coating.

2.8.2.2. Admixtures in New Concrete

Mitigating concrete corrosion can predominantly be accomplished during the design stage by altering the composition of the concrete mixture. As microorganisms can cause detrimental effects on concrete structures through the creation of corrosive byproducts like sulfuric acid, the concept of crafting acid-resistant concrete has been put forth. This can be achieved by enhancing the concrete's microstructure or introducing protective barriers against acidic substances [Khitab et al, 2013].

In addition to modifying mix design parameters, the reinforcement of concrete's resilience and acid resistance has been achieved by incorporating supplementary cementitious materials and mineral additives like silica fume, fly ash, limestone, and blast furnace slag (Goyal et al, 2009) The incorporation of silica fume (SF), metakaolin (MK), and low-calcium fly ash into mortar samples originally made with ordinary Portland cement (OPC) was observed to enhance their ability to withstand various aggressive environments at different concentrations. These environments included sulfuric acid (1% and 5%), hydrochloric acid (1%), nitric acid (1%), acetic acid (5%), phosphoric acid (5%), and a combination of sodium and magnesium sulfates (Roy et al, 2001).

Another avenue explored has been the incorporation of polymers into cement mortar or concrete, aiming to enhance their resilience against aggressive substances like lactic, acetic, and sulfuric acid [Janfeshan et al, 2015]. The primary objective of incorporating polymers into the concrete matrix is to lower its permeability, thereby slowing down the infiltration of hydrogensulfide, carbon dioxide, as well as the entry of microorganisms and their byproducts. This reduction in permeability in polymer-modified concrete is brought about by bridging micro-cracks, diminishing pore dimensions, and obstructing pores with polymer particles [Beeldens et al, 2001].

Despite the fact that polymer modification diminishes concrete's permeability, the harmony between the polymer and the constituents within the concrete mixture can have an adverse impact on the conduct of polymer-

modified concrete. Reduced cement hydration and a drop in compressive strength in the modified concrete have been documented, particularly at elevated polymer/cement ratios (Wang R and Wang P, 2010). Furthermore, substantial enhancement of concrete properties has predominantly been attained at polymer/cement (p/c) ratios falling within the 3-20% range. This significantly escalates the concrete's material expenses and, consequently, constrains its practical applicability (Kong X-M et al, 2013).

The inclusion of growth-inhibiting compounds, namely bactericidal and fungicidal additives, has been employed within concrete mixtures to mitigate the process of deterioration. Mortar specimens enriched with two distinct biocides, metallic nickel and calcium tungstate, were examined for their ability to deter bio deterioration after being exposed to a sewer environment containing various concentrations of H_2S over a two-year period (Negishi et al, 2005). Following exposure to 28 ppm of H_2S, the mortar specimens without biocides, those modified with 0.075% metallic nickel, and those with 0.075% calcium tungstate displayed weight losses of 10%, 6%, and 1%, respectively. Although notable enhancement in the resistance of concrete against microbial-induced corrosion has been witnessed upon introducing commercial additives, their efficacy is typically transient. Furthermore, at elevated dosages, they could potentially impact the structural attributes of concrete (Sun et al, 2015). Moreover, apart from the substantial expenses incurred, another obstacle to their application is the limited experimentation with only a handful of these agents.

In 2013, Motsieloa conducted a study with the aim of determining the rate of acid attack and resistance to corrosion in specific concrete blends. The study spanned 12 weeks during which various concrete samples were exposed to an acidic solution. The research encompassed concrete mixtures that included both Portland Cement (PC) and Calcium Aluminate Cements in their pure forms, as well as with varying proportions of admixtures. These admixtures consisted of ground granulated blast-furnace slag (GGBS), Fly Ash (FA), and Silica Fume (SF). The properties examined in the studied concrete mixtures encompassed compressive strength, tensile strength, density, permeability assessed using the Oxygen Permeability Index (OPI), water sorptivity, resistance to acid dissolution, and the consumption of hydrogen ions when exposed to a hydrochloric acid solution.

The research findings indicated increased compressive strength in Portland Cement (PC) based mixtures containing Silica Fume (SF) when compared to plain mixtures and those including Fly Ash (FA). This enhancement was attributed to the heightened pozzolanic activity of SF. Incorporation of SF into PC-based mixtures also induced a compaction of the concrete matrix, consequently resulting in reduced permeability and exhibiting low water sorptivity characteristics. This is primarily due to the fine filler effect of SF, which inferred the development of a more refined pore structure. The experimentation's conclusion highlighted that SF in PC mixtures contributedto the refinement of the matrices, resulting in diminished porosity, improved resistance to acids, and the lowest mass loss as opposed to the other two admixtures.

One of the admixtures that have not been explored extensively for use in such environments is the RHA that is readily available as an agricultural waste. In this regard, experiments need to be carried out to explore the use of such locally available material as admixtures in concrete exposed in simulated aggressive acidic sewer environments.

2.9 Desired Properties of Concrete for AggressiveSewer Environments

Sewer works are very significant infrastructure in the developmentand planning of urban establishments. For this reason, they are designed and built for a design life of 75 to 100 years. With standard maintenance, the concrete mix used should therefore have desired physiochemical properties that make it durable to withstand the aggressive sewer environment while inuse for this period of time.

The BS is not specific on the required characteristic concrete strength for sewer environments though the concrete class can be assumed for concrete in similar environments mentioned in the BS.

Besides the compressive strength, such concrete should also be able to inhibit ingress of aggressive acidic compounds into its matrices with very minimal or no reaction of the binder material with these compounds.

In environments where concrete is exposed to acidic conditions, such as sewersystems, the corrosive nature of the substances present can lead to gradual deterioration of the concrete's structural and chemical integrity. Acidic compounds, often originating from wastewater and industrial effluents, can react with the components of concrete, causing it to weaken, crack, and lose its protective properties. To combat this degradation, concrete mix designs foracidic sewer environments are tailored to enhance the concrete's resistance to acid attack and ensure its long-term durability. Several key properties are taken into consideration when designing concrete for such challenging settings.

The primary objective of designing concrete for acidic sewer environments isto bolster its resistance against chemical reactions triggered by acidic compounds. These reactions can lead to the dissolution of cementitious phasesand the deterioration of the concrete matrix. By selecting appropriate materials and proportions, the concrete's chemical stability is improved, minimizing its susceptibility to acid-induced degradation (Ng and Albert, 2015).

Secondly, given the prolonged exposure to corrosive agents, strength becomes paramount. Concrete structures in sewer systems need to maintain their strength and integrity over extended periods. An emphasis on strength ensuresthat the concrete remains structurally sound, avoiding premature failures and the need for frequent maintenance or replacement (Ng and Albert, 2015).

Thirdly, the ability of acidic substances to infiltrate concrete can accelerate its deterioration. To counteract this, concrete mix designs should also focus on achieving low permeability. A dense microstructure with limited interconnected pores hinders the movement of acids through the concrete, reducing the risk of chemical attacks and prolonging the material's lifespan. Acidic sewer environments often contain sulfate ions, which can triggersulfate attack on concrete. This phenomenon involves the expansion of the concrete due to the formation of expansive sulfate compounds. Concrete mix designs need to incorporate measures to resist sulfate attack and prevent the associated cracking and weakening of the structure Acidic conditions can also compromise the bond between the concrete and embedded steel reinforcement. Special attention need to be given to ensure strong adhesion between these components to maintain the overall structural stability of the sewer system. Additionally, strategies to protect the reinforcement from corrosion should be integrated into the mix design (Alexandra et al, 2013).

Shrinkage can lead to cracks and fissures that provide pathways for acid penetration. Concrete mixes for such environments should therefore be designed to minimize shrinkage, reduce the risk of crack formation andsafeguard the concrete's integrity.

Microbial activity in sewer environments can contribute to acid generation and corrosion. Concrete mix designs should consider incorporating antimicrobial additives or use materials that resist microbial growth, to further enhance the concrete's resistance to deterioration (Czajkowska et al, 2021)

Proper curing practices are also essential for achieving the desired properties in concrete, including its strength, durability, and chemical resistance. Adequate curing enhances the formation of hydrated cementitious phases, which contribute to the concrete's overall resistance to acids. Aggregates play a crucial role in determining the concrete's properties (Czajkowska et al, 2021).

By addressing these key properties in the concrete mix design process, engineers and designers can develop concrete that is tailored to withstand the aggressive conditions of acidic sewer environments.

2.10 Focus of the Current Study

It has been determined from literature that corrosion rate is closely linked to the microstructural features of the concrete mixtures employed in sewer pipe production. These features are primarily influenced by the composition of the binders (including cement and admixtures), aggregates, and the water-to- cement ratio. This combination leads to concrete mixtures with two specific physiochemical characteristics that contribute to resistance to deterioration, namely; permeability, and compressive strength. These properties combine to determine the inhibitory properties of a particular mixture to corrosion.

The two parameters RHA and water cement ratio considered in the literature above addressed their influence exclusively on the properties of concrete that contribute to its durability. This study considered the combination of the twovariables in developing a mix that would be ideal for an aggressive acidic sewer environment.

2.11 Conceptual Framework

In this experimental study the independent variables are the RHA and the W/C which have an effect on the dependent variable, corrosion resistant mix design that the study aims to achieve. There are mediator variables namely; compressive strength, porosity, mass loss and surface texture which are influenced by the two independent variables and impact on the corrosion resistant mix design. In this framework, the moderator variable is the acidic solution that influences the impact RHA and W/C will have on the mix.

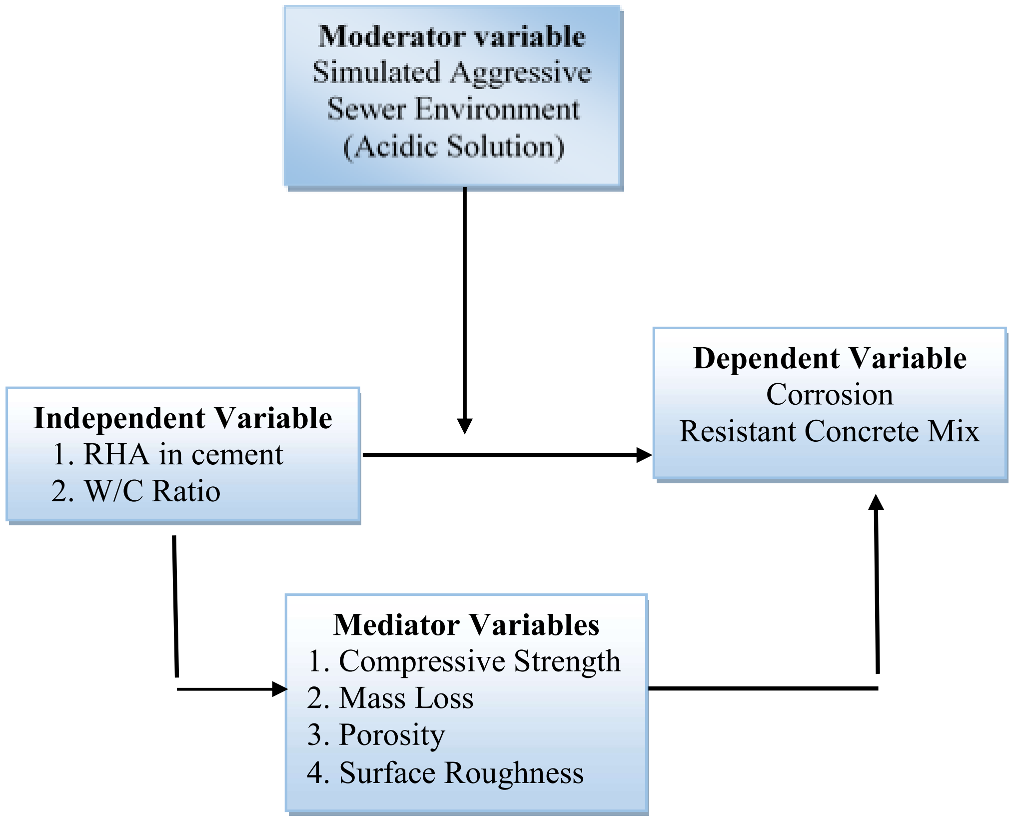

Figure 2. 3: Conceptual Framework

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter provides comprehensive information on the materials used, the experimental setup, tests conducted and calculations carried out as part of this research. The primary objective was to assess the performance of concrete specimens with different proportions of Rice Husk Ash (RHA).They were then subjected to a simulated aggressive acidic sewer environment in the form of a H2SO4 solution. The ultimate goal was to develop a concrete mixture capable of enduring corrosion when exposed to such environments, all while maintaining its structural integrity. Figure 3.1 shows the general concept of the study indicating the framework of steps taken in the study.

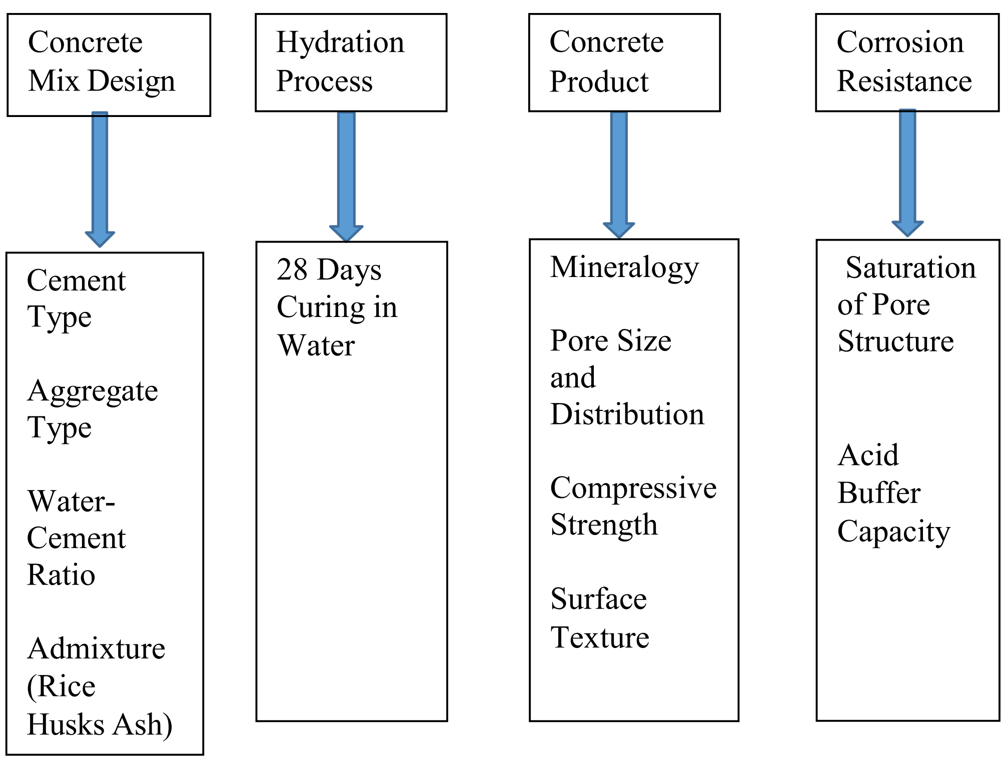

Figure 3. 1: The General Concept of the Study

3.2 Materials and Sample Preparation

3.2.1 Materials

The course aggregates used in this study were angular crushed aggregates sourced from Kisumu Concrete Ltd. Gradation was carried out to have a maximum size of 20mm as per clause 5.3 of BS 5911 and were determined to have a flakiness index of 30 and aggregate impact value of 24%. The grading curve is shown in figure 3.2 while the sieve analysis results are shown in appendix I.

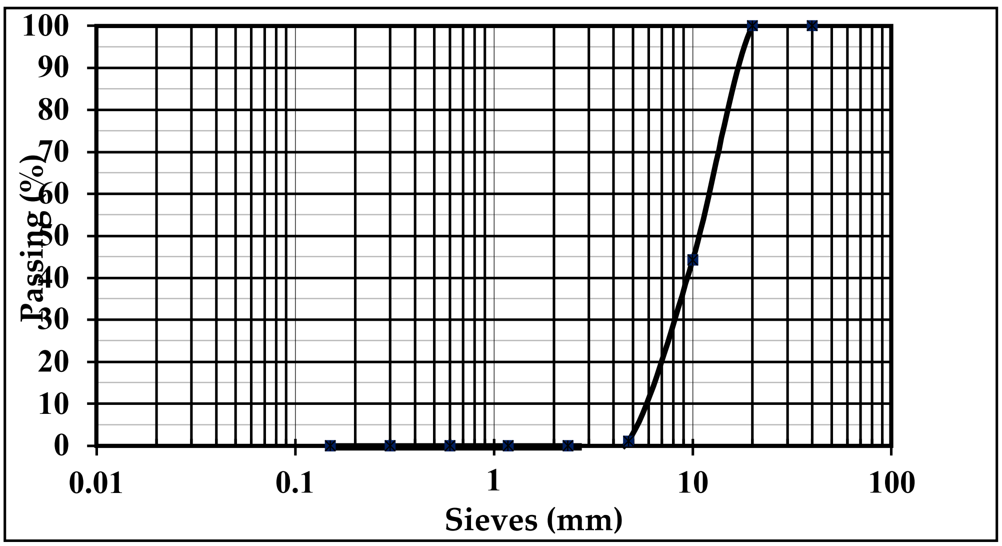

Figure 3. 2: Grading Curve for coarse Aggregates

Locally available naturally occurring building sand, obtained from Nyodorerain Siaya and conforming to table 4 of BS 882 for heavy duty concrete was used in the experiment. The grading curve is shown in figure 3.3. The aggregates were determined to have a fineness index of 2.93 as shown in appendix I.

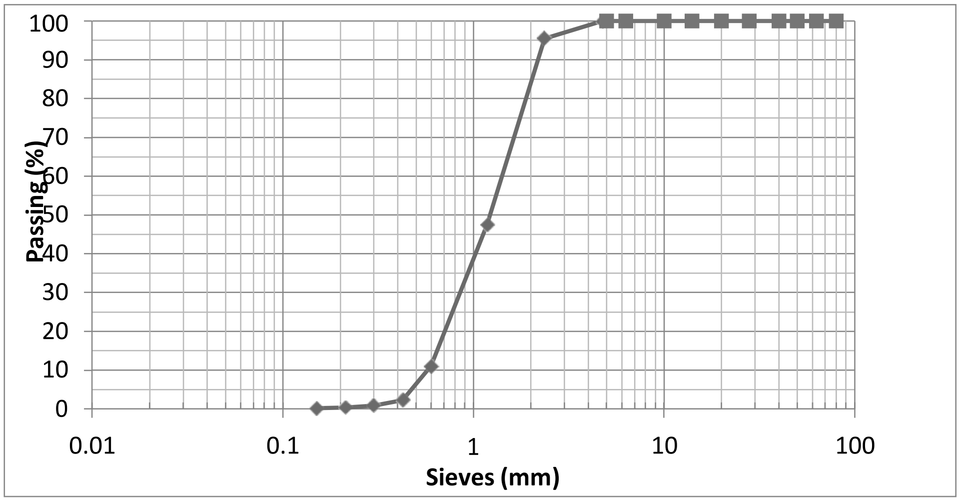

Figure 3. 3: Grading Curve for fine Aggregates

Duracem Cement, a sulphate resisting cement from Bamburi Cement was used in the study as a requirement of tables A15 and A17 of BS 8500 Part I. The Rice Husk used in this experiment was sourced from Lake Basin Development Company. The ash was prepared in the laboratory by burning the husk in an enclosed container at a controlled temperature. This was ground then collected through BS sieve size 75µm. The sieving was done to remove large unburnt particles.

Blended cements were produced in the laboratory by thoroughly mixing cement and RHA. Available clean potable tap water was used in concrete mixing.

3.2.2 Concrete Mix Design

Concrete mix design was done in two phases; specification using BS 8500 part 1 to obtain the appropriate designated concrete and mix design according to Building Research Establishment (BRE) to obtain the target strength and weight of constituent materials. The detailed calculations are shown in appendix II.

3.2.3 Designated Concrete to BS 8500

The objective is to ensure that specified concrete conforms to BS 8500 Part I,that is, for an appropriate concrete designation for particular application From tables A2, A3, A4, A7, A8, A15 and A18 of BS 8500 Part I, the aggregate type and maximum size is specified and that the right consistence class is maintained.

The information is obtained from tables in the following steps:

Step 1: Determination of Aggressive Chemical Environment forConcrete (ACEC) Class

Tables A1 of BS 8500 part 1 is not specific on the type of exposure class thatdescribes a sewer environment. Therefore, Table A2 was used to determine the Aggressive Chemical Environment for Concrete (ACEC) class. Concrete in sewer environment are exposed to SO_4 before formation of sulphuric acid. Therefore, a potential sulphate > 2.4 and a design sulphate class DS – 5m is assumed. Sewer lines also contain chemicals that are similar to those that areindustrial in nature. The wastes are therefore categorized as 'Brownfield' for mobile water (in this case sewage). For all pH values ACEC class AC-5m is selected.

Table A2 BS 8500 Part I: Classification of Ground Conditions

Sulfate and magnesium					Design sulfate class	Brownfield[a]		ACEC-class (design sulfate class)
2:1 water/soil extract		Groundwater		Total potential sulfate b		Static water	Mobile water	
SO_4 g/l	Mg[c] g/l	SO_4 g/l	Mg[c] g/l	SO_4 %		pH[d]	pH[d]	
<1.2	—	<0.4	—	<0.24	DS-1	All pH values	—	AC-1s
						—	>6.5	AC-1
						—	5.6 to 6.5	AC-2z
						—	4.5 to 5.5	AC-3z
						—	<4.5	AC-4z
1.2 to 2.3	—	0.4 to 1.4	—	0.24 to 0.6	DS-2	>5.5	—	AC-1s (DS-2)
						—	>6.5	AC-2
						«5.5	—	AC-2s
						—	5.6 to 6.5	AC-3z (DS-2)
						—	4.5 to 5.5	AC-4z (DS-2)
						—	<4.5	AC-5z
2.4 to 3.7	—	1.5 to 3.0	—	0.7 to 1.2	DS-3	>5.5	—	AC-2s
						—	>6.5	AC-3
						«5.5	—	AC-3s
						—	5.6 to 6.5	AC-4
						—	<5.5	AC-5
3.8 to 6.7	«1.2	3.1 to 6.0	«1.0	1.3 to 2.4	DS-4	>5.5	—	AC-3s
						—	>6.5	AC-4
						«5.5	—	AC-4s
						—	«6.5	AC-5
3.8 to 6.7	>1.2c	3.1 to 6.0	>1.0c	1.3 to 2.4	DS-4m	>5.5	—	AC-3s
						—	>6.5	AC-4m
						«5.5	—	AC-4ms
						—	«6.5	AC-5m
>6.7	«1.2	>6.0	«1.0	>2.4	DS-5	>5.5	—	AC-4s
						«5.5	All pH values	AC-5
>6.7	>1.2c	>6.0	>1.0c	>2.4	DS-5m	>5.5	—	AC-4ms
						«5.5	All pH values	AC-5m

Step 2: Determination of Structural Performance Level

Table A3 of BS 8500 part 1 is used to determine the structural performance level. The structural performance is categorized as high since concrete sewerpipes retain and convey hazardous content.

Table A3 BS 8500 Part I: Guidance on selection of the structural performance level

Structural Performance level	Typical attributes
Low	Short service life structures (less than 30 years) Unreinforced concrete Non-critical structural details Temporary structures Long service life structures, but with associated low stress levels, e.g. house foundations (unreinforced)
Normal	Intermediate service life structures (30 years to 100 years) Not falling in either high or low category
High	Long service life structures (more than 100 years), e.g. transport structure foundations Vulnerable critical details such as slender structural elements, hinges, joints etc. Structures retaining hazardous materials

Step 3: Determination of Design Chemical (DC) Class

Table A4 of BS 8500 Part I is used to determine the design chemical class (DC class). For high structural performance, ACEC class AC-5m and assuming concrete class section between 150 to 450mm in thickness, a designchemical class of DC-4mm is selected.

Tabel A4 of BS 8500 Part I: Design Chemical Class (DC – Class)

ASEC Class	Normal structural performance level			High structural performance level	
	Section width “140[e] mm	**Section width 150 mm to 450 mm**	**Section width >450[d] mm**	**Section width 150 mm to 450[f] mm**	**Section width >450[d] mm**
AC-1s	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0	**DC-1/ 0**
AC-1	DC-2/ 0	DC-1/ 0	DC-1/ 0	DC-1/ 0	**DC-1/ 0**
AC-1s (DS-2)	DC-2/ 0[g]	DC-1/ 0	DC-1/ 0	DC-1/ 0	**DC-1/ 0**
AC-2s	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-2/ 0	**DC-1/ 0**
AC-2z	DC-3z/ 0	DC-2z/ 0	DC-1/ 0	DC-2z/ 0	**DC-1/ 0**
AC-2	DC-3/ 0	DC-2/ 0	DC-1/ 0	DC-2/ 0	**DC-1/ 0**
AC-3s	DC-4/ 0	DC-3/ 0	DC-2/ 0	DC-3/ 0	**DC-2/ 0**
AC-3z	DC-4z/ 0	DC-3z/ 0	DC-2z/ 0	DC-3z/ 0	**DC-2z/ 0**
AC-3z (DS-2)	DC-4z/ 0[g]	DC-3z/ 0[g]	DC-2z/ 0[g]	DC-3z/ 0[g]	**DC-2z/ 0[g]**
AC-3	DC-3/ 3	DC-3/ 2	DC-2/ 2	DC-3/ 3	**DC-2/ 3**
AC-4s	DC-4/ 0	DC-4/ 0	DC-3/ 0	DC-4/ 0	**DC-3/ 0**
AC-4z	DC-4z/ 1[i]	DC-4z/ 0	DC-3z/ 0	DC-4z/ 0	**DC-3z/ 0**
AC-4z (DS-2)	DC-4z/ 1[g, i]	DC-4z/ 0[g]	DC-3z/ 0[g]	DC-4z/ 0[g]	**DC-3z/ 0[g]**
AC-4	DC-4/ 3	DC-4/ 2	DC-3/ 2	DC-4/ 3	**DC-3/ 3**
AC-4ms	DC-4m/ 0	DC-4m/ 0	DC-3/ 0	DC-4m/ 0	**DC-3/ 0**
AC-4m	DC-4m/ 3	DC-4m/ 2	DC-4m/ 1	DC-4m/ 3	**DC-4m/ 2**
AC-5z	DC-4z/ 1[g, i]	DC-4z/ 1[g, i]	DC-3z/ 1[g, i]	DC-4z/ 1[g, i]	**DC-4z/ 1[g, i]**
AC-5	DC-4/ 3[j]	DC-4/ 2[j]	DC-3/ 2[j]	DC- 4**/ 1[i]	**DC-3**/ 1[i]**
AC-5m	**DC-4m/ 3[j]**	**DC-4m/ 2[j]**	**DC-4m/ 1[i]**	**DC-4m**/ 1[i]**	**DC-4m**/ 1[i]**

Step 4: Determination of Designated Concrete and Consistence Class

Table A7 of BS 8500 Part 1 is used to select the designated concrete and recommended consistence class. For a design chemical concrete class of DC-4m, previously determined, a designated concrete of FND4M and a consistence class of S3 is selected.

Table A7 of BS 8500 Part I: Guidance on Selection of Designated Concrete

Application[a]	Designated concrete	Recommended consistence class[b]
Plain and reinforced foundations requiring DC-2 to DC-4[c] concrete		
DC-2	FND2	**S3[d]**
DC-2z	FND2Z	**S3[d]**
DC-3	FND3	**S3[d]**
DC-3*	FND3*	**S3[d]**
DC-3**	FND3**	**S3[d]**
DC-3z	FND3Z	**S3[d]**
DC-4	FND4	**S3[d]**
DC-4*	FND4*	**S3[d]**
DC-4**	FND4**	**S3[d]**
DC-4z	FND4Z	**S3[d]**
DC-4m	FND4M	**S3[d]**
DC-4m*	FND4M*	**S3[d]**
DC-4m**	FND4M**	**S3[d]**
		S3[d]
General applications		
Kerb bedding and backing	GEN0	**S1**
Drainage works to give immediate support[e]	GEN1	**S1**
Other drainage works[e]	GEN1	**S3**
Oversite below suspended slabs[e]	GEN1	**S3**
Floors		
House floors with no embedded metal (see NOTE 2 to 4.2.2)		
— Permanent finish to be added, e.g. a screed or floating floor	GEN1	**S2**
— No permanent finish to be added, e.g. carpeted	GEN2	**S2**
Garage floors with no embedded metal	GEN3	**S2**
Wearing surface: light foot and trolley traffic	RC30	**S2**
Wearing surface:	RC40	**S2**
	RC50	**S2**

general industrial		
Wearing surface: heavy industrial[f]		
Paving		
House drives, domestic parking and external parking Heavy-duty external paving with rubber tyre vehicles[f]	**PAV1PAV2**	**S2** **S2[g]**

Step 5: Determination of Characteristic Concrete Strength

Table A8 is used to determine the designated concrete strength. For all FNDdesignations, the required strength class is C28/35. The required cube strength at 28 days is therefore 35N/mm2.

Table A8 of BS 8500 Part I: Strength Class for Designated Concrete

Designated concrete	Required strength class
GEN0	C6/8
GEN1	C8/10
GEN2	C12/15
GEN3	C16/20
FND (all designations)	C28/35
PAV1	C25/30
PAV2	C28/35
RC25	C20/25
RC30	C25/30
RC35	C28/35
RC40	C32/40
RC45	C35/45
RC50	C40/50
RC50XF	C40/50

Step 6: Determination of Limiting Concrete Constituents

Table A15 of BS 8500 part 1 is used to determine the limiting values of composition of concrete where a design chemical class (DC) is specified. For a DC-4mm class, the composition is determined as; aggregate carbonate range – C, cement combination group - 3, minimum cement combination – 400kg/m^3 and a maximum water cement ratio 0.4. The cement combination group 3 is Sulphate Resisting Portland Cement (SRPC). In this research Duracem Cement, a sulphate resisting cement from Bamburi Cement Company was used.

Table A15 of BS 8500 Part I: Limiting Values of Composition and Properties of Concrete

DC-class	Aggregate carbonate range	Cement or combination group[a]	Dense fully compacted concrete	
			Minimum cement or combination content	Maximum w/c ratio
			kg/m3	
DC-1	A, B, C	1, 2, 3	—	—
DC-2	A[b], B, C	1[c]	340	**0.50**
	A[b], B, C	2, 3	300	**0.55**
DC-2z	A, B, C	1[c], 2, 3	300	**0.55**
	A	2a	400	**0.40**
DC-3	A	2b, 3	380	**0.45**
	B, C	2, 3	340	**0.50**
DC-3*[d]	B	2, 3	380	**0.45**
DC-3**	C	2, 3	380	**0.45**
DC-3z	A, B, C	1[c], 2, 3	340	**0.50**
	A	2a	400	**0.35**
DC-4	A	2b, 3	400	**0.40**
	B, C	2, 3	380	**0.45**
DC-4*[d]	B	2, 3	400	**0.40**
DC-4**	C	2, 3	400	**0.40**
DC-4z	A, B, C	1[c], 2, 3	380	**0.45**
DC-4m	A	2b, 3	400	**0.40**
	B, C	3	380	**0.45**
DC-4m*[d]	B	3	400	**0.40**
DC-4m**	**C**	**3**	**400**	**0.40**

Step 7: Determination of Limiting Cement Content and Aggregate Size

Table A18 is used to determine minimum cement and aggregate size. For a water cement ratio of 0.4 and a maximum aggregate size of 20mm, a minimum cement content of 360kg/m^3 is selected. This is minimum and therefore a previously assumed cement content of 400kg/m^3 from table A15 is still applicable.

Table A18 of BS 8500 Part I: Minimum Cement of Combination Content

Specified maximum w/c ratio	**Minimum cement or combination content (kg/m^3)**			
	Maximum aggregate size =40 mm	**Maximum aggregate size = 20 mm**	**Maximum aggregate size= 14 mm**	**Maximum aggregate size= 10 mm**
0.70	240	240	260	**280**
0.65	240	260	280	**300**
0.60	260	280	300	**320**
0.55	280	300	320	**340**
0.50	300	320	340	**360**
0.45	320	340	360	**360**
0.40	340	360	360	**360**
0.35	**360**	**360**	**360**	**360**

Table 3.1 below shows a summary of constituent materials to achieve the characteristic strength as obtained from the above BS 8500 Part I process in section 3.2.3. The BRE Mix Design Procedure was then used to calculate the quantities of cement, fine and coarse aggregates.

Table 3. 1: Requirements for Characteristic Strength

Parameter	Requirement
Characteristic compressive strength f_c	35N/mm
Target Mean Strength	43N/mm^2
Crushed aggregates, maximum size	20mm
Cement Type	Sulphate Reducing Portland Cement, SRPC 42.5
Minimum cement content	400kg/m^3
Maximum water cement ratio, W/C	0.4
Slump	60 to 180mm

3.2.4 Quantities of constituent materials

Appendix II shows the calculation of quantities of constituent materials to produce 1m^3 of concrete for each of the two water cement ratios. To achievethe given range of workability given a maximum coarse aggregate size of 20mm, a water content of 225kg/m^3 (obtained from table 3 of BRE) was used. The quantities of cement, course aggregates and fine aggregates werethen determined (See Appendix I for calculations). 6 cubes (0.02m^3) were prepared for each category of % RHA in cement. The cube strengths were determined before and after exposure in aggressive solution. Batching was carried out by weight, as shown in figure 3.4 and the quantities for preparation of 6 cubes, 0.02m^3 for each category of % RHA in cement determined as shown in table 3.2.

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Figure 3. 4: Batching By Weight

The cubes were then cured in water for 28 days, dried for 7 days then immersed in the simulated aggressive acidic solution. Figure 3.5 showsprepared cubes and the process of curing.

Table 3. 2: Calculated quantities for every % RHA category

% RHA in Cement	W/C	Cement(kg)	RHA (kg)	Water(Kg)	Fine Aggregate(kg)	Coarse Aggregate(kg)	Total Noof Cubes
0%	0.4	11.3	0	4.5	11.9	20.3	**6**
	0.35	12.9	0	4.5	11.3	19.3	**6**
5%	0.4	10.7	0.6	4.5	11.9	20.3	**6**
	0.35	12.3	0.6	4.5	11.3	19.3	**6**
10%	0.4	10.2	1.1	4.5	11.9	20.3	**6**
	0.35	11.6	1.3	4.5	11.3	19.3	**6**
15%	0.4	9.6	1.7	4.5	11.9	20.3	**6**
	0.35	11	1.9	4.5	11.3	19.3	**6**
20%	0.4	9	2.3	4.5	11.9	20.3	**6**
	0.35	10.3	2.6	4.5	11.3	19.3	**6**
Total No. of Cubes							**60**

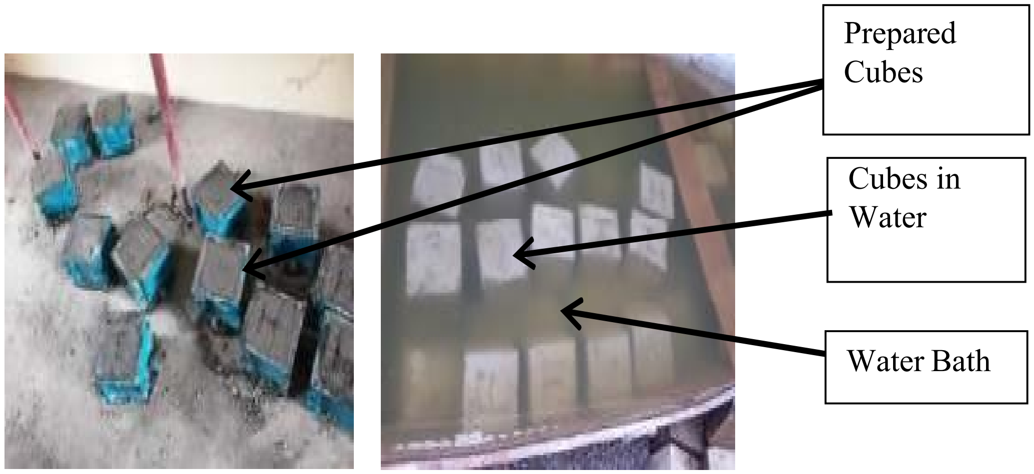

Figure 3. 5: Concrete Cubes Cast and Cured in Water

3.3 Simulation of Aggressive Acidic Environment

In this experimental study, concentrated sulphuric acid solution was prepared and used to simulate an aggressive acidic sewer environment. Having established from literature that corrosion commences when the pH of the sewer headspace falls to below 5 with increased generation of H_2SO_4, sulphuric acid solution with a pH of 2.5 and a concentration of 5% was prepared to simulate the aggressive environment. This was used to accelerate degradation of the samples. The cubes were fully immersed in the solution for 12 weeks, with the solution being replaced and stirred to maintain the concentration and uniformity after every 2 weeks. The 12-week period of exposure was adopted from the trend on previous studies as discussed in chapter 2.

3.3.1 Preparation of Acid Solution

Commercially available sulphuric acid with a 35% concentration was used in the experiment. The acidic solution was prepared to a concentration of 5% to represent the aggressive sewer environment. The cubes were supported on a steel frame as shown in in figure 3.6 to ensure their surfaces are fully in contact with the solution.

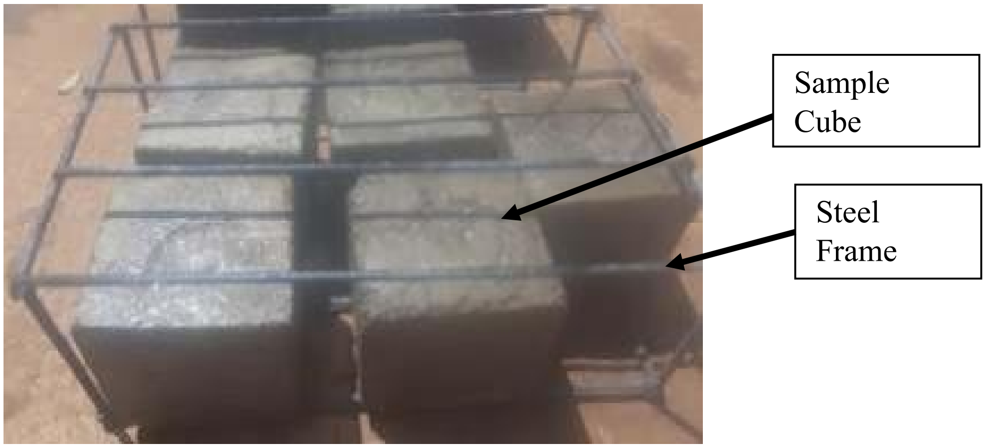

Figure 3. 6: Samples suspended on a steel frame, ready for immersion in solution

The acid baths were contained in six 100-litre containers able to fully submerge 5 cubes in 50 liters of the solution. The volume of commercial H_2SO_4 required was calculated using equation i.

C_1 x V_1 = C_2 x V_2 .... Equation i

Where

C_1 = concentration of commercially available H_2SO_4 in this case 35%

V_1 = Volume of commercially available acid (of 35% concentration) requiredC_2 =

Concentration of the solution to be prepared = 5%

V_2 = volume of the 5% solution required (in this case 50 liters to fullysubmerge 5 cubes)

Thus, 35 x V_1 = 5% x 50Therefore

V_1 = (5 x 50) / 35 = 7.15 liters

7.15 liters of commercially available acid used to prepare 50 liters of acid bath to submerge 5 cubes. 42.85 liters of water therefore mixed with 7.15 liters of commercially available acid to obtain 50 liters of acid solution with5% concentration. Samples were then submerged in solution as shown in figure 3.7.

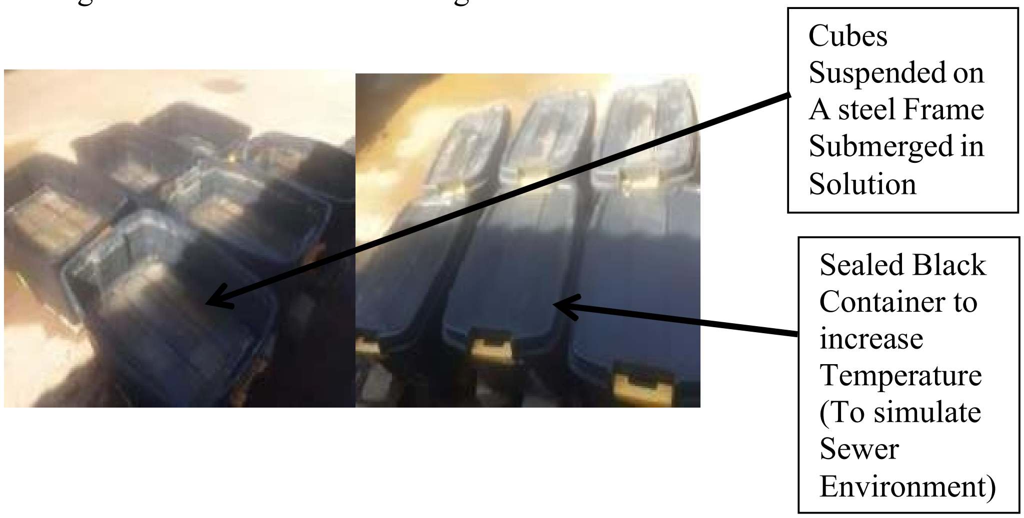

Figure 3. 7: Samples in acidic solution

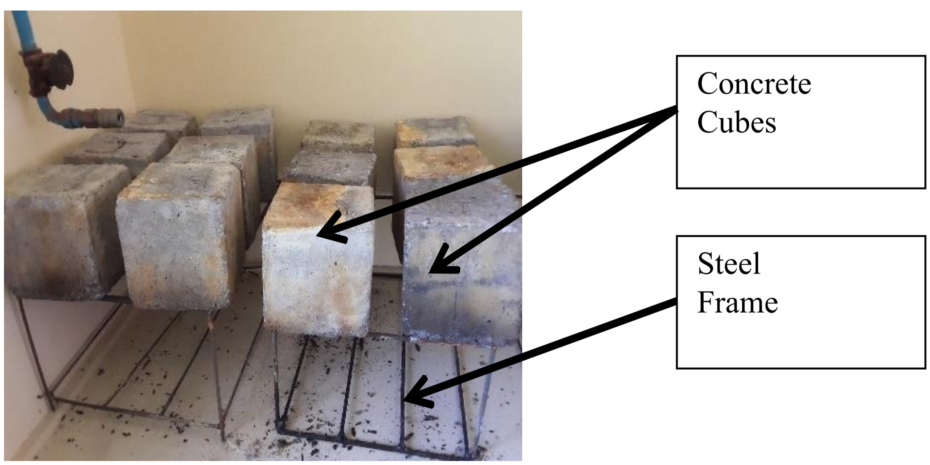

Figure 3. 8: Samples air dried after exposure in acidic solution.

3.4 Measurement of Workability

Slump test was carried out in all fresh concrete incorporating different percentages of RHA for the two W/C ratios. This was done following the BS12350-6:2009 procedures on testing fresh concrete.

3.5 Determination of Compressive Strength

Compressive strengths were determined using an ASTM Automatic Concrete Compression Testing Machine in accordance with the ASTM C39 standard procedure. Three concrete cubes were produced and subjected to testing before and after being exposed to acidic solution, for each of the two water-to-cement ratios (W/C) and different percentages of RHA in the cement. Figure 3.9 shows the machine loaded with a cube sample and the display screen showing the loading process.

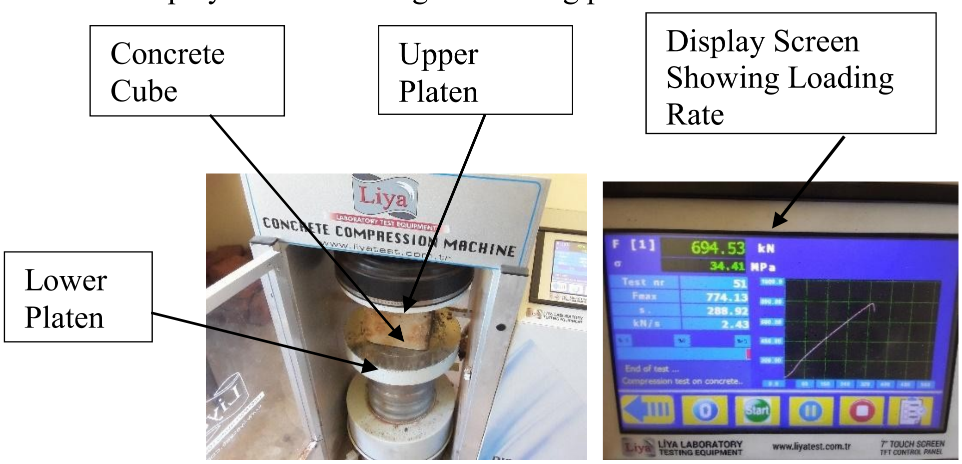

Figure 3. 9: Compression Test on Samples

3.6 Determination of Mass Loss

Concrete cubes with different percentages of RHA in cement, after curing for 28 days, were weighed before immersion in aggressive solution. Upon retrieval from the aggressive solution, they were then air dried for a period of 24 hours letting off loose material on the surfaces to drop off. The weights were again determined and changes in mass recorded. It was also observed that some material disintegrated and fell off while still in the aggressive solution. The trends in percentage mass loss for the different percentages of RHA in cement and the two water-cement ratios were recorded. The percentage mass loss was determined using equation ii.

Percentage Mass Loss = $(M1 - M2)/M1 * 100$ ....Equation ii

Where M_1 is the mass of the cube before immersion in acidic solution and M_2 is the mass of the cube after immersion in acidic solution.

3.7 Determination of Porosity

In this experimental study porosity measurements of samples of approximately 50mm x 50mm x 50mm were carried out using Archimedes principle as per the following procedure:

Pore volume, $V_p = (W_{sat} - W_{dry})/\rho_w$ ....Equation iii

Bulk volume, $V_b = (W_{sat} - W_{sub})/\rho_w$..Equation iv

Porosity $\phi = (V_p / V_b) \times 100$ .... Equation v

Where, W_{dry} is the dry weight of the sample,

W_{sat} is the saturated weight of the sample,

W_{sub} is the submerged weight of the sample and ρ_w is the density of water.

The trend on porosity with varying RHA and W/C was then determined.

3.8 Surface Texture

This is the observable surface appearance of the cubes after they were removed from the aggressive solution. The surfaces of the samples with various percentage RHA in cement appeared differently after degradation asshown in table 4.1

3.9 Determination of Optimum % RHA for Aggressive Acidic Environment Using Analytical Hierarchy Process (AHP)

Given the concrete samples with the five categories of % RHA performed differently in terms of workability, compressive strength, mass loss, surface texture and porosity, there was need for a tool to develop weights and hence score the performance of these categories.

The Analytic Hierarchy Process (AHP) is a comprehensive measurement theory employed to establish ratio or weight scales based on real measurements obtained from both discrete and continuous paired comparisons. In this research, the comparisons were derived from actual laboratory measurements of various parameters.

AHP was used to develop criteria weights for each parameter depending on its importance and how it influences durability of concrete in aggressive environment. The main steps of AHP involved creating a pairwise comparison matrix using the scale of relative importance of each property compared to another, creating a normalized comparison matrix, calculating criteria weights for each parameter and calculation of consistency ratio to check on the consistency of the pairing before accepting the weights. The AHP relative scale of importance used is shown in table 3.3.

Table 3.3: Scale of Relative Importance

Scale	Relative Importance
1	Equal Importance
2	Equal to Moderate Importance
3	Moderate Importance
4	Moderate to Strong Importance
5	Strong Importance
6	Strong to Very Strong Importance
7	Very Strong Importance
8	Very Strong to extreme importance
9	Extreme Importance

Using the scale in table 3.3, a pairwise comparison matrix was developed to compare the relative importance of the four parameters namely workability, strength, mass loss and porosity to each other. The pairwise matrix was then used to develop a normalized comparison matrix, determination of criteria weights for every parameter and a consistency ratio calculated to determine the consistency of the adopted pairwise matrix.

The accepted criteria weights were used to create a mathematical model or scoring system that takes into account the values of each property (compressive strength, % mass loss, workability, % porosity) for different % RHA levels using equation vi.

Total Score = (Weight_strength x % Score_strength) +(Weight_massLoss X % Score_massLoss) + (Weight_workability x % Score_workability) + (Weight_porosity x % Score_porosity) ....Equation vi

The percentage score for compressive strength, for every category of RHA was determined in relation to the standard characteristic required determined in from the BS 8500 Part I in section 3.2.3 of this report. Percentage scores for mass loss and porosity were determined in relation to the worst and the best performing categories with the best performing category given the highest score while the least performingcategory given the least score. Percentage score for slump was determined inrelation to the average slump of 120mm (average of 60 to 180mm) which is the characteristic requirement determined from the BS 8500 Part I.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results and analysis of the experimental data conducted in order to achieve the objectives of the study. The effects of the presence of RHA in cement and the varied water cement ratios on workability of fresh concrete, compressive strength, surface texture, mass loss and porosity of concrete exposed to a simulated aggressive acidic environment are discussed based on the determined results. The discussion is done in comparison with the findings of previous studies in a attempt to arrive at a conclusion on the optimum percentage RHA in cement and W/C for concrete in a simulated aggressive acidic environment. Given the performance of different percentages of RHA in terms of workability, strength, surface texture, mass and porosity, Analytical Hierarchy Process (AHP) is used to award weights and scores to the properties evaluated and a decision made on the optimum percentage RHA in cement for concrete in such environments.

4.2 Effect Of RHA and W/C on Workability of Concrete

Workability is the ease with which fresh concrete can be mixed, placed, compacted, and finished without experiencing segregation or excessive bleeding. It is a measure of how easily concrete can be manipulated and worked with during construction. The workability of concrete is a crucial property because it directly influences the ease of construction and the quality of the final hardened concrete structure. In this context, workability would be very key since manufacture of concrete sewer pipes requires a good measure of flexibility when making the circular sections.

In this study, workability on fresh concrete for all the categories wasmeasured by the slump test.

Figure 4.1 shows the trend on the slump tests of fresh concrete for the twoW/C ratios for the various percentages of RHA in cement.

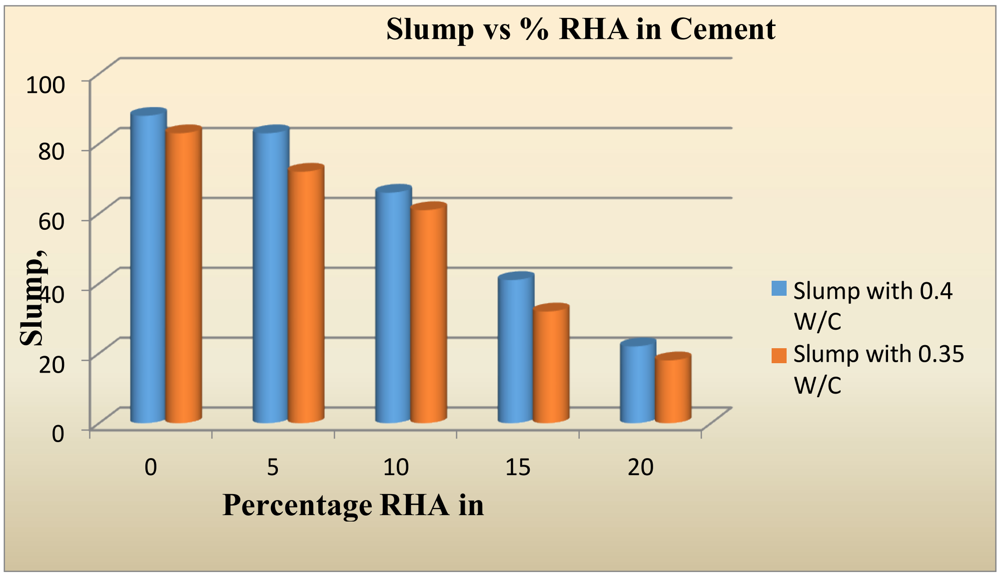

Figure 4. 1: Slump Test Results for Fresh Concrete

Workability of fresh concrete reduced with increased presence of RHA in cement for both water cement ratios. As previously determined, RHA particles are finely divided and have a large surface area leading to absorption of more water from the mix, during hydration process, leading to a reduction of water available for proper lubrication of the mix. This experimental study maintained the maximum water content set by the two W/C ratios in the design.

4.3 Effect of RHA and Water-Cement Ratio on Compressive Strength

Compressive strength is a measure of the capacity of concrete to withstand loads applied on it before failure. It is the main indicating factor that a concrete mix design has met its ultimate purpose of achieving a design strength that is required during a structure's design life. Besides other physiochemical properties that enable concrete to resist corrosion in aggressive sewer environments, compressive strength is an indicator of the overall quality of the mix to meet desired durability of the structure.

In this study, the minimum concrete class that was determined from BS 8500 that is required for an equivalent aggressive environment was C28/35 N/mm^2; the 28- day characteristic cube strength was therefore set at 35N/mm^2. The mix design was carried out as per the British Standard Mix Design Method. Figures 4.2 and 4.3 show the trends in compressive strength of cubes before and after immersion in aggressive acidic solution, for the two W/C ratios.

4.3.1 Compressive Strengths with 0.4 W/C

Figure 4.2 shows the trend in compressive strength of samples before and after exposure for concrete with restricted 0.4 W/C and cement incorporated with different quantities of RHA. The highest strength was achieved with 5% RHA incorporation in cement. The strength then reduces with incorporation of more RHA as shown in figure 4.2. The cube strengths were slightly lower after the cubes were exposed in acidic solution an indication that there was deterioration of concrete integrity.

Figure 4.2 shows the trend in compressive strength of samples before and after exposure for concrete with restricted 0.35 W/C and cement incorporatedwith different quantities of RHA. The results showed a similar trend with thehighest strength achieved with 5% RHA then the strengths reduced with incorporation of more RHA as shown in figure 4.3.

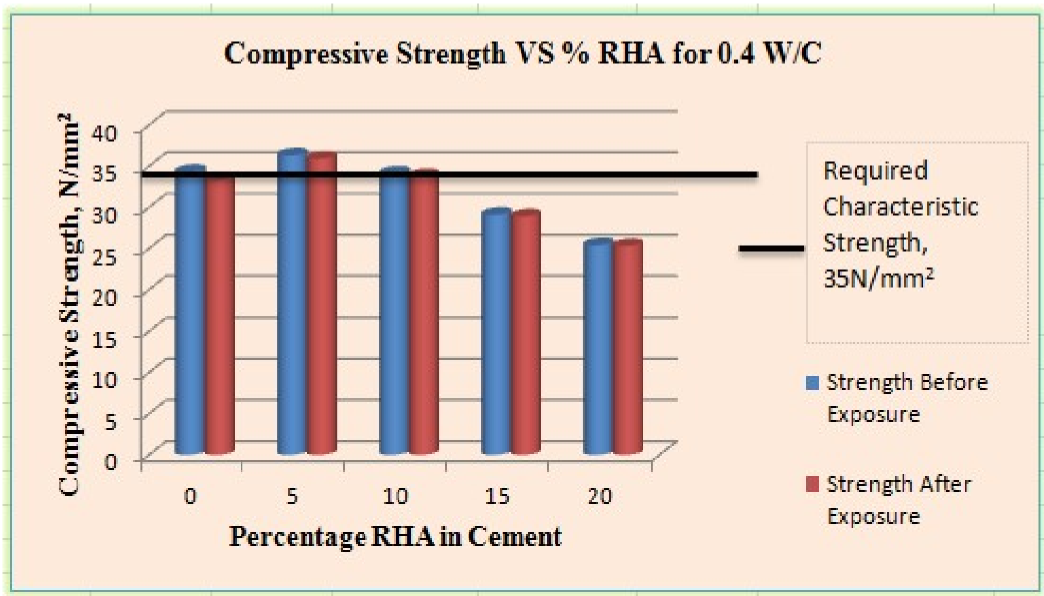

Figure 4. 2: Compressive Strength vs % RHA in cement for 0.4 W/C

4.3.2 Compressive Strengths with 0.35 W/C

The cube strengths were also slightly lower after the cubes were exposed inacidic solution an indication that there was deterioration of concrete integrity.

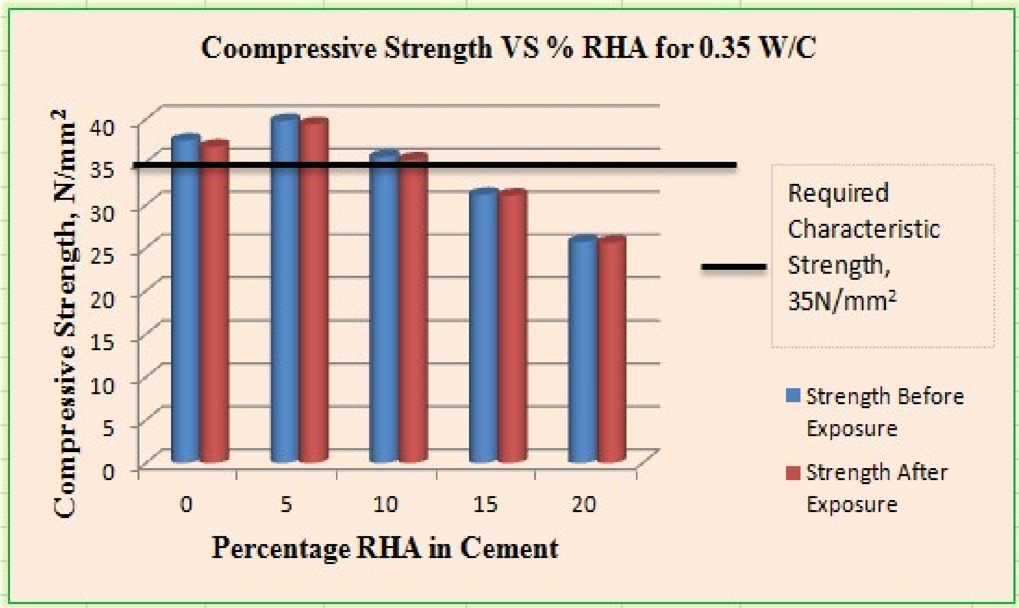

Figure 4. 3: Compressive Strength vs % RHA in cement 0.35 W/C

From the experiments, the compressive strengths before and after exposure were slightly higher with 0.35 W/C ratio than 0.4 W/C ratio for all the samples.It was established from previous studies that water-cement ratio has an important influence on the development and microstructure of concrete. It was determined that generally a low water to cement ratio concrete is recommended from durability perspective as samples with lower W/C ratios developed higher compressive strengths than those with higher W/C. The twowater cement ratios experienced the best strengths with 5% RHA in cement. The highest compressive strength after exposure to aggressive solution was obtained with 5% RHA in cement and a 0.35 water cement ratio. The trend then showed a decrease in strengths with increased RHA in cement. The common explanations for improved compressive strength were the physical filler effect due to the high specific surface area and the pozzolanic reaction of the available silica from RHA which reacts with C-H released from hydration process. With increased RHA in cement to 10%, 15% and 20%, the strengths decreased with the produced C-H not sufficient enough to react with all available silica in

RHA. The silica in RHA therefore remains inert and doesn't contribute to strength development of concrete (Maisarah et al, 2015). With 10% RHA in cement and 0.35 W/C, a compressive strength of 35.29 N/mm^2 that is higher than the characteristic strength as determined from the BS was obtained.

In addition, the study determined that there was a similar trend in loss of strength with the two W/C ratios as the quantity of RHA was increased in cement as shown in figure 4.4. The highest percentage loss was observed with 0% RHA with 0.4W/C while the lowest was observed with 20% RHA with

0.35 W/C.

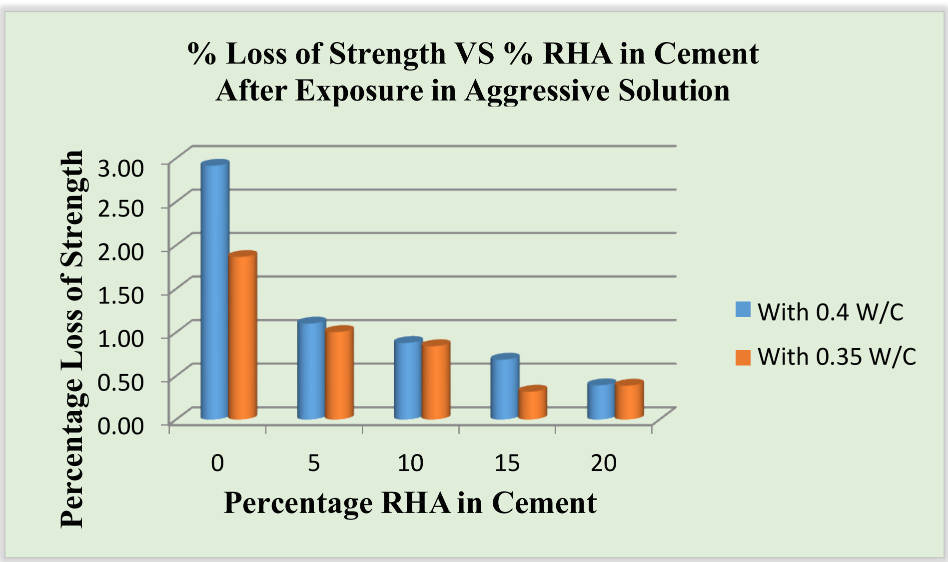

Figure 4. 4: Percentage Loss of Strength vs % RHA in Cement

Despite having lower compressive strengths, samples with higher quantities of RHA exhibited lower percentage loss in strength an indication that RHA contributed to acid buffer capacity of the samples.

This is evidence that RHA contributed to permeability and of the concrete microstructure and therefore inhibitory nature of the concrete to ingress by aggressive substances.

4.4 Effect of RHA and Water Cement Ratio On Surface Texture

Surface texture in this context refers to the smoothness, roughness or waviness of a specimen surface that resulted from the concrete interaction with the aggressive solution. The first observable sign of degradation of a sample was the surface appearance after interaction with the acidic solution. The most affected samples had their surfaces easily peeling off upon removal from the acid bath leaving a very rough surface. The least affected samples however had very firm, smooth and compact surfaces that indicated their surfaces inhibited ingress of aggressive media into their matrices. Table 4.1 shows the appearance of surfaces of specimen with different quantities of RHA in cement and water cement ratios after exposure in acidic solution.

The study determined that control samples which had 0% RHA in cement were the most affected when exposed to aggressive solution while surfaces ofsamples with 10%, 15% and 20% RHA in cement were least affected in that order.

Table 4. 1: Surface Appearance of Cubes after Exposure in Acid Bath

% R H A in Cement	**0.4 W/C**	**0.35 W/C**	**Remarks**
0			Samples with0% RHA in cement most affected, surfaces easily peeling off.
5			An improvement on surface appearance, surfaces affected but notso much
10			Significant improvement on surface, surfaces indicate very minimal degradation.
15			Surfaces showed verylittle indication of mass loss.
20			Surfaces are firm, smooth and compact, leastaffected by aggressive media.

Figures 4.5 and 4.6 show the difference in surface texture of samples with 0% and 20% RHA in cement after exposure in acidic solution.

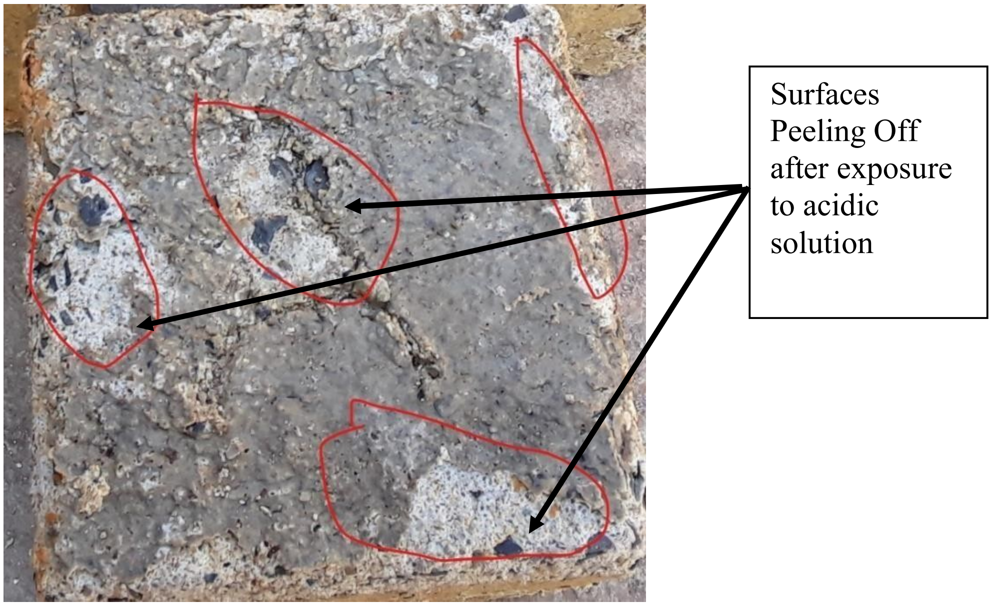

Figure 4. 5: Sample with 0% RHA showing surface degradation after exposure to acidic solution

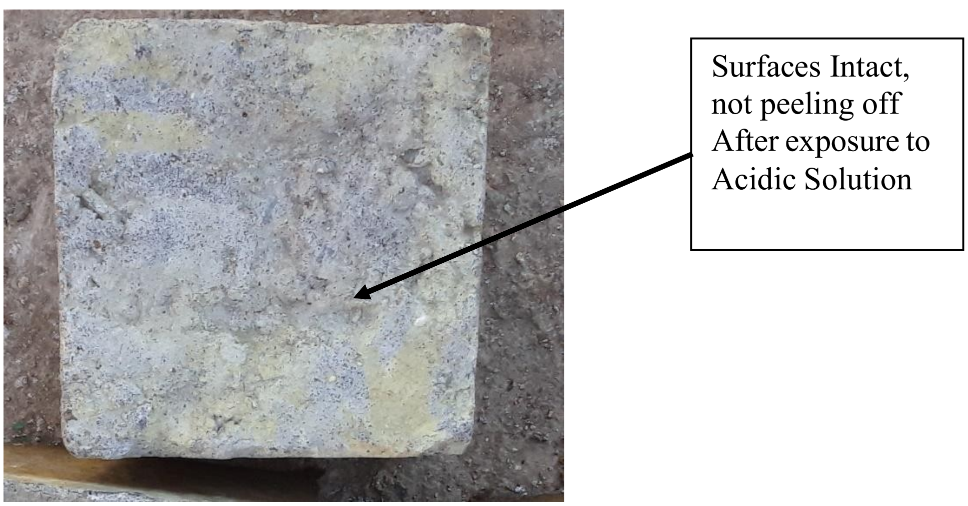

Figure 4. 6: Sample with 20% RHA and 0.35 W/C ratio,

From these observations, concrete specimen with 0% RHA in cement replacement experienced the worst surface deterioration and peeling off. Thisphenomenon was common for 0.4 and 0.35 W/C ratios. Cubes with 10%, 15%

and 20% experienced the least surface degradation and peeling off. This supports previous findings that suggested RHA to having a filler effect thus reducing the probability of ingress of aggressive solution into concrete matrices.

4.5 Effect of RHA and Water Cement Ratio on MassLoss

Mass loss in this context is the process by which part of concrete exposed to aggressive environment disintegrates and pills off from the main body as a result of corrosion. In this case the concrete surface in contact with the aggressive medium normally disintegrates first.

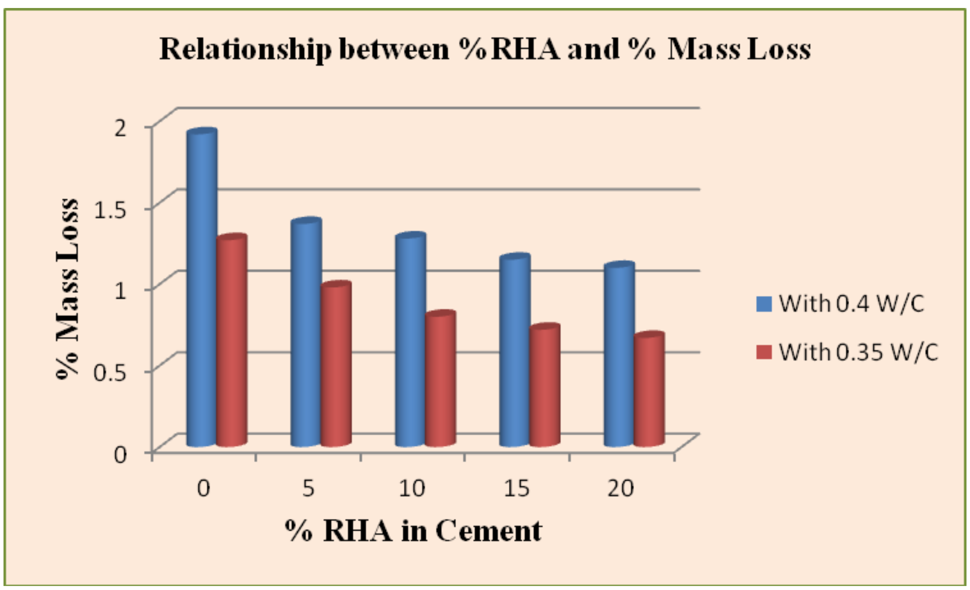

Figure 4. 7: Comparison of % Mass Loss for the two W/C Ratios

The mass loss was more severe in specimen with 0% RHA in cement for both water cement ratios. These disintegrated faster in acidic solutioncompared to those with RHA. The percentage mass loss reduced with increasing quantities of RHA in concrete and the lowest mass loss was obtained at 20% RHA with 0.35 W/C. This would imply the presence of RHA produced a more impermeable concrete mix. The % mass loss is however slightly higher for specimen with 0.4 w/c ratio than those with 0.35w/c ratio as shown in figure 4.7.

Samples with the highest quantity of RHA in cement experienced the least mass loss, an indication that the presence of RHA in cement produced a morecompact and dense concrete that resisted disintegration. The micro filler effect of RHA contributed to development of a more permeable concrete matrix compared to ordinary concrete. It was also previously determined from literature that a lower W/C ratio produced a more permeable concrete (Mohammed 2021). Thus a slightly lower mass loss with 0.35 W/C. Incorporation of RHA in cement improved the concrete microstructure hence the durability of concrete exposed to aggressive solution.

A study by Gemma (2010) showed that the mass loss of sampleswith RHA after immersion in acid varied depending on percentage RHA where samples with 15% RHA experienced the least mass loss whilesamples with 0% RHA experienced the highest mass loss. This confirms the trend as determined by this study that the presence of RHA in cement reduces mass loss in concrete thus improving on durability especially for concrete in aggressive environments.

4.6 Effect of RHA and Water-Cement Ratio on Porosity

Porosity is the ratio of the volume of voids to the total volume of a solid specimen. It is therefore a measure of the voids in concrete that are created during the manufacturing process. Concrete being a relatively porous materialhas air and water permeable properties which has a lot of effect on its durability characteristics, especially while in contact with aggressive environment. Corrosive chemical compounds before reacting with the concrete matrix, flow into concrete mass through pores. Hence, as porosity increases, so does the susceptibility to the penetration of corrosive substancesinto the concrete structure, leading to a potential reduction in overall durability. Samples with a 0.35 w/c ratio showed slightly lower porosities ascompared to those of with 0.4 w/c ratio as shown in figure 4.8. For both w/c ratios, porosity reduced with percentage increase of RHA in concrete. This is mainly due to the filler effect of the RHA on the cement matrix. This confirmsa previous study by Mohammed in 2021 that showed w/c ratios influenced significantly variation of physical parameters including porosity, permeability, strength, density and absorption.

This experimental study thus confirmed that incorporation of RHA incementand reduction in W/C improved the pore structure of concrete. Jie
W. et al in 2022 while studying the use of RHA as an alternative cementitious material, determined that porosity decreased with increased presence of RHA in cement.

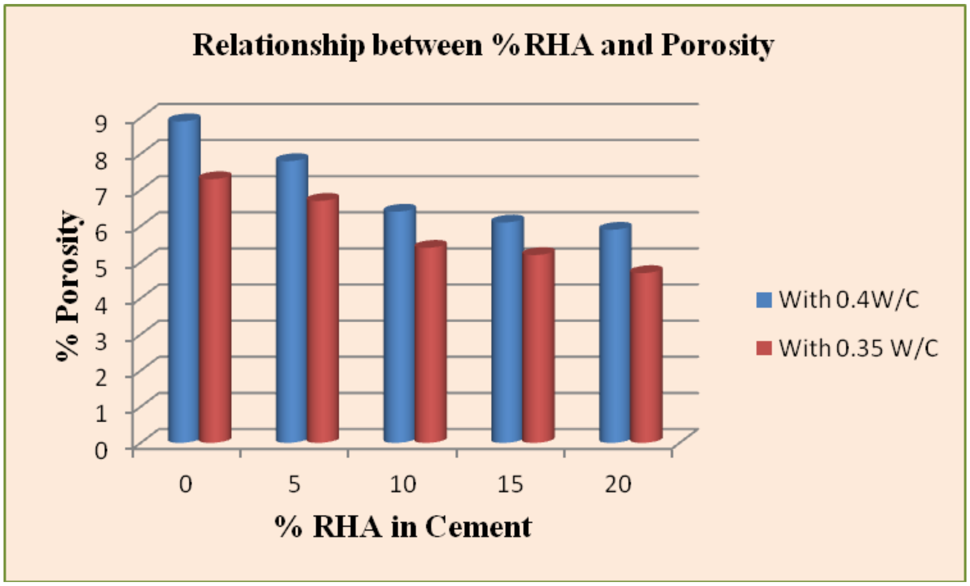

Figure 4. 8: Comparison of % Porosities of degraded samples

4.7 Measurement of Corrosion

Corrosion prediction models have traditionally assessed corrosion by estimating the reduction in thickness of concrete pipes, typically measured in millimeters. One of the widely adopted deterministic models for describing the corrosion process in sewer systems is the Life Factor Method (LFM), as discussed by Vollertsen and colleagues in 2011. This model is grounded in the relationship between sulphide generation within sewage and the release of hydrogen sulphide (H2S) from sewage. It connects these factors to the corrosion rate of concrete through two functions: (i) the rate at which H2S is consumed on the damp concrete surface, and (ii) the alkalinity of the concrete materials, as elaborated by Kiliswa in 2016. The model expresses corrosion on the concrete surface in mm/year. Corrosion is therefore measured in millimeters over a period of time (mm/year).

In this experimental study degraded samples with various percentages ofRHA in cement were evaluated to determine the extent of surface degradation or formation of the ettringite due to reaction with the acidic solution. Figures 4.9 and 4.10 show the depths of corrosion and formation of expansive ettringite for samples with different percentages of RHA in cement.

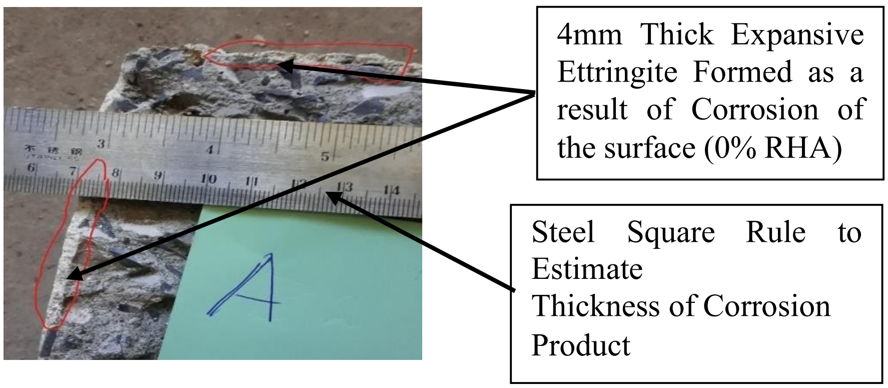

Figure 4. 9: Corrosion Depth for Sample with 0% RHA and 0.4 W/C

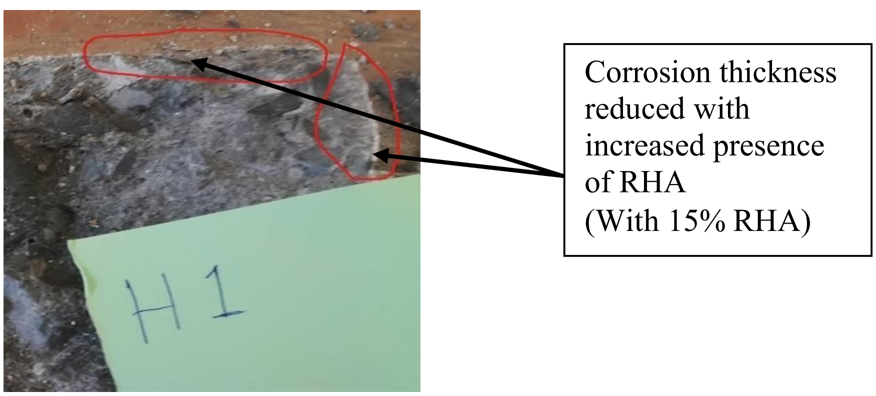

Figure 4. 10: Corrosion Depth for Sample with 15% RHA and 0.35 W/C

4.8 Optimization of Percentage RHA using Analytical Hierarchy Process (AHP)

Based on the trends observed, for compressive strength, the highest values are achieved at 5% RHA. However, for mitigating the percentage loss in strength, higher RHA percentages (10-20%) show better performance.

Percentage Mass loss and percentage porosity both decreased as RHA content increased. Workability significantly diminished as the content of RHA increased, even though this can be mitigated using a superplasticizer meaning additional cost. Considering these trends, there is a trade-off among the properties. If we prioritize higher initial compressive strength, then 5%

RHA might be considered optimal. However, if we are to also consider minimizing reductionin strength, reduction in percentage mass loss and a lower percentage porosity, over time, a higher RHA content (10 to 20%) could be preferred. Based on these observed trends, Analytical Hierarchy Process (AHP) was used to optimize the percentage RHA in cement required for concrete in aggressive acidic environments.

4.9 Determination of Criteria Weights By AnalyticalHierarchy Process (AHP)

4.9.1 Pairwise Comparison Matrix

The pairwise comparison matrix developed is developed from the scale of relative importance as shown in table 4.2.

Table 4. 2: Pairwise Comparison Matrix

	Workability	**Strength**	**Mass Loss**	**Porosity**
Workability	1	0.2	0.33	**0.33**
Strength	5	1	3	**4**
Mass Loss	3	0.33	1	**3**
Porosity	3	0.25	0.33	**1**
Total	**12**	**1.78**	**4.67**	**8.33**

4.9.2 Normalized Pairwise Comparison Matrix

The values for this matrix are calculated from totals obtained in the pairwise comparison matrix. They are determined by dividing individual values in the pairwise matrix by the totals. The criteria weights are then determined by averaging the values in the rows, for example for workability the criteria weight = (0.08+0.11+0.07+0.04)/4 = 0.08. The values are shown in table 4.3.

Table 4. 3: Normalized Pairwise Comparison Matrix

	Workability	Strength	Mass Loss	Porosity	Criteria weight
Workability	0.08	0.11	0.07	0.04	**0.08**
Strength	0.42	0.56	0.64	0.48	**0.53**
Mass Loss	0.25	0.19	0.21	0.36	**0.25**
Porosity	**0.25**	**0.14**	**0.07**	**0.12**	**0.15**

4.9.3 Determination of Consistency

The values in every column were determined by multiplying the values in thepairwise matrix with the criteria weights. The results are as shown in table 4.4

Table 4. 4: Determination of Consistency Ratio (C.R.)

Criteria Weight	**0.08**	**0.53**	**0.25**	**0.15**			
	Workability	**Strength**	**Mass**	**Porosity**	**weighted sum value, x**	**criteria weights, y**	**x/y**
Workability	0.08	0.11	0.08	0.05	0.31	0.08	4.10
Strength	0.38	0.53	0.76	0.58	2.25	0.53	4.28
Mass	0.23	0.18	0.25	0.44	1.09	0.25	4.33
Porosity	0.23	0.13	0.08	0.15	0.59	0.15	4.07

The weighted sum x, is determined by summation of the terms in the rows. The ratios of weighted sum values to criteria weights are then calculated. This is calculated for each row. The average of all these ratios, λ_{max}, is then determined by averaging the four (Equation vii)

λ_{max}, = (4.1 + 4.28 + 4.33 + 4.07)/4 = 4.2 ....Equation vii

λ_{max} was used to calculate the consistency index CI (Equation viii).

$CI = \frac{\lambda_{max} - n}{n-1}$ .... Equation viii

Where n is the number of criteria, in this case 4. Therefore C.I. = (4.2 − 4)/(4 − 1) = 0.07. The Consistency Ratio (C.R.) is then determined usingthe C.I. and the random index (RI), equation ix.

C.R. = $(C.I.)/(R.I.)$... Equation ix

The random index for n= 4 is 0.90. Therefore C. R. = 0.07/0.90 = 0.08 < 0.1, we therefore assume our matrix is reasonably consistent so we continuewith the process making using the weights generated by our AHP. The adopted criteria weights are as shown in table 4.5.

Table 4. 5: Criteria Weights

Property	**Criteria**
Compressive	**0.53**
Mass Loss	**0.25**
Porosity	**0.14**
Workability	**0.08**
Total	**1.00**

The adopted criteria weights were used to determine the weighted scores for category of % RHA using equation vi discussed in section 3.9 of this report. These calculated scores for all the categories of % RHA using the two water cement ratios are shown in appendix III. Figure 4.11 shows the weighted percentage scores for the different categories of percentage RHA in cement with the two water cement ratios.

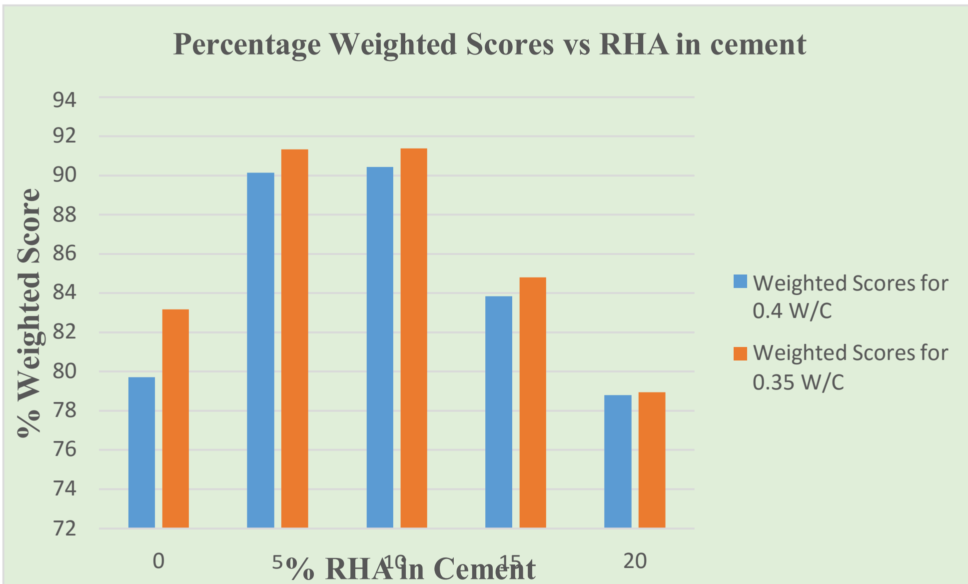

Figure 4. 11: Weighted Scores for Different % RHA in Cement

The highest score of 91.39% depicting the best trade-offs between the four parameters was achieved at 10% RHA with 0.35 W/C.

4.10 Optimum mix design

With determination of 10% RHA in cement and 0.35 W/C as the optimum, a mix design for a simulated aggressive acidic sewer environment was developed and the quantities determined as shown as shown in tables 4.6 and 4.7. The initial design and quantities for a $1m^3$ was done using the BRE procedure before incorporation ofRHA as an admixture as shown in appendix II.

With the quantities for $1m^3$ determined from the BRE using a 0.35 W/C ratio, the quantity of cement is replaced by 10% of RHA to obtain the quantities ratios shown in tables 4.6 and 4.7.

Table 4. 6: Quantities for Optimum Mix Design for 1m3 concrete

Description	Quantity
Characteristic strength	$35N/mm^2$
Target strength	$43N/mm^2$
Water cement ratio	0.35
Aggregate type	crushed
Maximum aggregate size	20mm
Cement type	Sulphate Resisting 42.5
Slump	60 - 80
Water quantity	225kg
Cement quantity	578kg
RHA quantity	65kg
Fine Aggregate quantity	567kg`
Coarse Aggregate quantity	965kg

Table 4. 7: Mix Design Ratios

	Cement	Fine Aggregates	Coarse Aggregates	RHA	Water
Kgs	578	567	965	65	225
Ratios	1	0.98	1.67		

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1. Introduction

This chapter summarizes the findings of this experimental study and proposesway forward in areas that require further study in a bid to developingsustainable concrete for aggressive sewer environments. The main motivation of this study was to develop a concrete mix design for a better corrosion inhibition particularly in aggressive acidic sewer applications. The study focused on two main independent variables that is percentage RHA in cementin varied quantities and two water cement ratios; 0.4 and 0.35. This producedconcrete that performed differently when exposed to an acidic solution that simulated a closed sewer environment. The performance was measured in terms of compressive strength, surface roughness or appearance, mass loss and porosity. Corrosion was determined in form of thickness loss of degradedsamples.

5.2 Conclusions

Based on the findings of the study it can therefore be concluded that:

1. The presence of RHA significantly reduces the workability of concrete and increases the need for a higher water content or the use of a plasticizer in orderto produce workable concrete.

2. The highest compressive strength of samples exposed in acidic solution was obtained with 5% RHA in cement with 0.35 W/C. The strengths then reduced as the quantity of RHA was increased in cement.

3. The presence of RHA in concrete improves the surface texture of concrete exposed to simulated aggressive sewer environment as higher percentages of RHA leads to smoother surfaces of samples even after exposure in acidic environment.

Incorporation of RHA in cement and a lower W/C reduces mass loss of concrete exposed to a simulated aggressive sewer environment. Thus the presence of RHA in concrete reduces ingress of simulated aggressive solution, reduces the rate of deterioration and improves on the durability of concrete.

Incorporating RHA into cement leads to a reduction in the porosity of concrete, enhances its permeability, and augments the durability of concrete when it is exposed to a simulated aggressive sewer environment.

4. A design mix of cement, fine aggregates and coarse aggregates in the ratio of 1:0.98: 1.67 incorporating 10% RHA was determined as the optimum mix for concrete in a simulated aggressive acidic environment.

5.3 Recommendations

This research was inspired by the necessity to create a concrete mixture suitable for use in harsh environments, particularly within concrete sewer pipes that transport sewage prone to becoming corrosive as a result of the oxidation process generating sulfuric acid.

In light of the objectives outlined to address the scope of this study, the following recommendations can be proposed:

1. In this study, sulphate resisting cement 42.5 was used in preparation of samples, as recommended in the BS 8500 for such environments. However, it has been observed that construction of current manholes still utilizes the ordinary Portland cement 32.5. The study therefore recommends further study that would utilize cement 32.5 with RHA in acidic environment.

2. The study recommends real time study of concrete coupons with RHA presence and varied W/C in real sewers for a longer period of time, between 15 to 36 months, to observe their performance in a real sewerage environment. There have been similar studies in South Africa and Australia but with concrete coupons not incorporating RHA in the binder system.

3. The study recommends further research on the microstructural characteristics of concrete with RHA presence to further explain the interaction between this kind of binder system and the aggressive acidic environment.

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APPENDICES

APPENDIX I: GRADATION OF FINE AND COARSE AGGREGATES

Sieve Analysis for Coarse Aggregates

S. No.	IS Sieves Size (mm)	Weight Retained (grams)	Cumulative Weight Retained (grams)	Cumulative % Weight Retained	% Passing
1	40	0	0	0	100
2	20	0	0	0	100
3	10	2820	2820	55.73	44.27
4	4.75	2184	5004	98.89	41.09
5	2.36	56	5060	100	0.99
6	1.18	0	0	100	0
7	0.6	0	0	100	0
8	0.3	0	0	100	0
9	0.15	0	0	100	0
10	Total	5060	5060	658.11	

A. Sieve Analysis for Fine Aggregates

S. No.	IS Sieves Size	Weight Retained(g)	Cumulative Weight Retained (g)	Cumulative % Weight Retained	% Passing
1	4.75	21	21	2	98
2	2.36	144	165	16	84
3	1.18	213	378	37	63
4	0.6	213	591	58	42
6	0.3	247	838	83	17
8	0.15	143	981	97	3
9	Pan	31	1012		0

10	Total	1012		**293.3**	

Fineness Modulus of Fine Aggregate = (293.3/100) = 2.93

APPENDIX II: MIX DESIGN FOR 1M^3 CONCRETE

Mix Design

With a characteristic strength of 35N/mm^2 obtained from the BSThe target Mean Strength
$f_m = f_c + ks$
Assuming a standard deviation s of 4 and 5% defectives, k = 1.64
$f_m = 35 + (1.64 \times 5) = 43N/mm^2$

Mix design for a maximum water cement ratio of 0.4

Stage	Item	Reference	Values
1	1.1 Characteristic strength	Specified	35 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3 (BRE)	4
	1.3 Margin	Eqn C1 (BRE)	M = fs = 1.64 x 5 = 8N/mm^2
	1.4 Target Mean Strength	Eqn C2 (BRE)	35 + 8 = 43 N/mm^2
	1.5 Cement Strength Class	BS 8500 Part 1	42.5
	1.6 AggregateType: Course		Crushed
	Aggregate Type : Fine		Uncrushed
	1.7 Maximum free water/cement ratio	Specified	0.4
2	2.1 Slump	Specified	60 - 180
	2.2 Maximum aggregate size	BS 8500 Part 1	20mm
	2.3 Free Water Content	Table 3 (BRE)	225Kg/m^2
3	3.1 Cement content	Eqn C3 (BRE)	225/0.4 = 563kg
4	4.1 Relative Density of Aggregate		2.5
	4.2 ConcreteDensity	Assumed	2400
	4.3 Total Aggregate Content	Eqn C4 (BRE)	2400 – 563 – 225 = 1612kg/mm^2

5	5.1 Proportion offine aggregate		For 2.9 fineness modulus 37%
	5.3 Fine Aggregate Content		1612 x 0.37 = 596kg

	5.4 Coarse AggregateContent			1612 – 596 = 1016kg
Quantities	**Cement (Kg)**	**Water (Kg)**	**Fine Aggregate (Kg)**	**Course Aggregates (Kg)**
Per m^3	563	225	596	1016
Per $0.02m^3$	11.3	4.5	11.9	20.3

A. Mix design for a maximum water cement ratio of 0.35

Stage	Item	Reference	Values
1	1.1 Characteristic strength	Specified	35 N/mm^2 at 28days
	1.2 Standard deviation	Fig 3 (BRE)	4
	1.3 Margin	Eqn C1 (BRE)	M = fs = 1.64 x 5 = $8N/mm^2$
	1.4 Target Mean Strength	Eqn C2 (BRE)	35 + 8 = 43 N/mm^2
	1.5 Cement Strength Class	BS 8500 Part 1	42.5
	1.6 AggregateType: Course		Crushed
	Aggregate Type : Fine		Uncrushed
	1.7 Maximum free water/cement ratio	Specified	0.35
2	2.1 Slump	Specified	60 - 180
	2.2 Maximum aggregate size	BS 8500 Part 1	20mm
	2.3 Free Water Content	Table 3 (BRE)	$225Kg/m^2$
3	3.1 Cement content	Eqn C3 (BRE)	225/0.35 = 643kg
4	4.1 Relative Density ofAggregate		2.5
	4.2 ConcreteDensity	Assumed	2400

	4.3 Total Aggregate Content	Eqn C4 (BRE)	2400 – 643 – 225 = 1532kg/mm^2	
5	5.1 Proportionoffine aggregate		For 2.9 fineness modulus 37%	
	5.3 Fine Aggregate Content		1532 x 0.37 = 567kg	
	5.4 Coarse Aggregate Content		1532 – 567= 965kg	
Quantities	**Cement (Kg)**	**Water (Kg)**	**Fine Aggregate (Kg)**	**Course Aggregate (Kg)**
Per m^3	643	225	567	965
Per 0.02m^3	12.9	4.5	11.3	19.3

APPENDIX III: WEIGHTED SCORES USING AHP

A. Calculated Scores with 0.4 W/C

	Compressive Strength		Mass Loss		Porosity		Workability		
% RHA	Strength	% Score	Mass Loss	% Scores	Porosity	% Scores	Slump	% Scores	Weighted Score
0	33.30	95.14	1.92	57.29	8.9	66.29	88	73.33	**79.71**
5	35.90	102.57	1.37	80.29	7.8	75.64	78	65.00	**90.14**
10	33.80	96.57	1.28	85.94	6.4	92.19	72	60.00	**90.44**
15	28.90	82.57	1.15	95.65	6.1	96.72	35	29.17	**83.84**
20	25.30	72.29	1.1	100.00	5.9	100.00	16	13.33	**78.80**

Calculated Scores with 0.35 W/C

	Compressive Strength		Mass Loss		Porosity		Workability		
% RHA	Strength	% Score	Mass Loss	% Score	Porosity	% Score	Slump	% Score	Weighted Score
0	36.80	105.14	1.27	52.76	7.3	64.38	82	68.33	**83.15**
5	39.40	112.57	0.98	68.37	6.7	70.15	74	61.67	**91.32**
10	35.30	100.86	0.8	83.75	5.4	87.04	72	60.00	**91.39**
15	31.10	88.86	0.72	93.06	5.2	90.38	23	19.17	**84.79**
20	25.60	73.14	0.67	100.00	4.7	100.00	11	9.17	**78.93**