CHARACTERISATION OF CONCRETE WITH EXPANDED POLYSTYRENE, EGGSHELL POWDER AND NON-POTABLE WATER – A CASE STUDY

By

Bonke Mncwango

Submitted in fulfilment of the academic requirements for the Degree of
Doctor of Engineering in the
Department of Civil Engineering and Geomatics
Faculty of Engineering and the Built Environment
At the Durban University of Technology
October 2022

DECLARATION

I, Bonke Mncwango, hereby declare that this thesis is my own work. Where I have used other people's work, I have referenced it accordingly. This thesis has not been published in any other University, apart from prior publication in the form of journal articles and conference papers which are listed in Annexure A.

Bonke Mncwango

APPROVED FOR FINAL SUBMISSION

Prof. Dhiren Allopi

DTech (Civil Eng.) (MLST); MDT (Civil Eng.) (TN);
Postgrad Dip Eng. (Natal); Dip Datametrics (cum laude) (UNISA)
PrTech Eng: FSAICE; MIPET; MSAT; MCILT

DEDICATION

This thesis is dedicated to my late mother, Biziwe Rosemary Mncwango, thank you for the gift of the gospel as well as that of education.

ACKNOWLEDGEMENTS

My biggest thanks goes to the almighty God who always trains my hands for war and my fingers for battle. Even at the conclusion of this work I still find myself asking what shall I render unto the Lord for all his benefits toward me. It is indeed true that he gives grace to the humble, and I shall forever be indebted to the almighty God. Even with the sum total of this work, I concur with the words of John when he says may the Lord continue to become greater and may I become less.

I would like to express my deepest gratitude to Durban University of Technology for the financial assistance and infrastructural support in making this work a success. I am also indebted to the many professionals and organisations such as the Council for Scientific and Industrial Research (CSIR) who assisted me in the realisation of this work. These are too numerous to list individually since it includes generous skilled men and women who possess mastery in various areas within the engineering profession.

I would also like to acknowledge all of my siblings and my wonderful wife for their continued support and encouragement.

Lastly, I would like to extend my sincere thanks to Prof. Dhiren Allopi who has been an excellent mentor on this journey.

ABSTRACT

Urbanisation has brought many benefits but it has also highlighted the global lack of housing alongside global natural resource scarcity. Lack of housing on the surface appears to be a singular problem, however in reality it represents a number of society's biggest challenges such as crime, pollution (as a result of inadequate waste disposal strategies), unhygienic living conditions, as well as numerous health problems. Governments across the world have made various attempts at addressing the issue of lack of housing, including embarking on large scale social and public housing initiatives, building smaller homes for the homeless, as well as removing certain regulatory barriers to allow more houses to be built at a reduced timeframe. These advances have assisted many individuals and families globally, however, there are still many individuals and families that government housing-aid or housing initiatives have not yet reached. These individuals and families are faced with solving their housing crisis on their own, with their own resources.

Globally, concrete remains a supreme building material in the construction industry and therefore is a primary factor of consideration for solving the housing crisis, especially for those who have no financial assistance or aid from government. Concrete's composition is simple: cement, fine aggregate, coarse aggregate and water. The intricate interaction between all four components is meant to stand the test of time. Unfortunately, it is not only the earth's diminishing natural resource reserves which are causing a decline in the popularity of conventionally produced concrete, but it is also the irreparable harm that it is causing to the environment. The process of concrete production requires large volumes of cement, and cement remains one of the biggest producers of carbon dioxide. Carbon dioxide is a greenhouse gas which in excessive amounts creates a cover that traps the sun's heat energy in the atmosphere. Another major criticism of conventional concrete is the requirement that it be produced with clean water which is of a drinkable standard. This criticism is justified when considering the extreme water shortages that are experienced by many low to middle income countries around the world. The amount of financial and human resources that local authorities invest in cleansing water to bring it to a drinkable standard is often overlooked. It is obvious that it is less expensive to use water directly from a river in its natural state than using it after it has undergone numerous cleansing processes by local authorities.

There have been a notable number of advances in making concrete more resource-efficient and environmentally friendly. These include the advent of lightweight concretes such as expanded polystyrene concrete. Expanded polystyrene concrete not only saves the amount of aggregate that would normally be required in conventional concrete, it also has excellent acoustic and thermal properties, thereby reducing energy consumption which in turn saves money. However, even with such excellent properties, expanded polystyrene concrete still fails to address two of concrete's major criticisms which are related to the amount of cement used as well as the amount of clean potable water required for mixing.

Therefore, by building on the qualities of expanded polystyrene concrete, this research investigates the potential of lowering the amount of cement required in a concrete mix through the use of eggshell powder. Eggshells are a waste product found everywhere in the world and are readily available in almost limitless quantities. The use of eggshells in concrete to lower the amount of cement required will not only achieve a reduction in the amount of carbon dioxide that is produced in the process of producing concrete, it will also assist in contributing toward solving the escalating waste disposal crisis that currently exists for many waste types such as eggshells.

It is common for communities to reside close to a river or a natural flowing watercourse, so this research included river water as a variable. Four different concrete mix scenarios were tested to ascertain through experimentation whether the strength properties of concrete that contains expanded polystyrene, eggshell powder and natural river water in various proportions could in any way compare to a conventionally produced concrete mix.

In order to comprehensively study material behaviour in this case, sieve analysis, bulk density, fineness modulus, moisture content as well as specific gravity tests were performed on all aggregates used. Furthermore, in order to achieve the required analytical depth for the materials being studied, x-ray diffraction and energy dispersive spectroscopy tests were conducted. As a means of conducting further trend analysis on the different experimental mixes, logarithmic regression models were developed.

Through analysis of the output attained from the aforementioned strategies, this research study found that when cement was substituted by eggshell powder at a percentage of 5 % and simultaneously when coarse aggregate was also substituted by expanded polystyrene at a percentage of 5 %, all mixed with non-potable water, the compressive and flexural strength outcomes marginally differed from the strength outcomes of conventionally produced concrete. Furthermore, the substitution of stone by EPS at a percentage of 10 % when mixed with river water was comparable to the substitution of stone by EPS at a percentage of 10 % when mixed with potable water. The results showed that there was a difference of not more than 1.4 MPa and 0.3 MPa in compressive and flexural strength respectively amongst the averages obtained at each age tested.

Study results show that the substitution of potable water by non-potable water reduced both the compressive and flexural strength of the concrete when the mix did not contain eggshell powder. However, when eggshell powder was included in the mix, the strength outcomes of the compressive and flexural strength of the concrete mix was comparable to that of conventionally produced concrete.

There may be many reasons why it is important to not deviate from convention in the production of numerous products such as concrete; nevertheless, the value of experimentation as demonstrated in this research is that experimentation can give rise to a variety of innovations accompanied by a wealth of solutions to the environmental and socio-economic issues that the world is currently faced with.

Key words: Eggshell powder, expanded polystyrene, concrete, compressive strength, flexural strength

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KEY TERMS

Aggregate- aggregates are used in the building and construction industry as material that is mixed with cement and water to form concrete.

Characterisation- in materials science, characterisation refers to the broad and general process by which a material's structure and properties are probed and measured**.**

Compressive strength- compressive strength can be described as the resistance of a material to breaking under compression.

Concrete- concrete is a structural material that consists of a hard, chemically inert particulate substance known as aggregate that is bonded together by cement and water.

Eggshell- eggshells are the hard thin outer layer of an egg.

Environment- the environment is the complex of physical, chemical, and biotic factors that act upon an organism or an ecological community and ultimately determine its form and survival.

Expanded polystyrene- expanded polystyrene is a rigid, closed cell, thermoplastic foam material. It is produced from solid beads of polystyrene.

Flexural strength- flexural strength is the ability of the material to withstand bending forces applied perpendicular to its longitudinal axis and is tested as an indication of concretes tensile strength.

Modification- modification is the act of changing something in pursuit of improving its functionality.

Non-potable water- non-potable water (also known as non-fresh water) is water that is not of drinking quality, but may still be used for many other purposes, depending on its quality.

Polymer- a polymer is a substance which has a molecular structure built up chiefly or completely from a large number of similar units bonded together.

Potable water- Treated water that is regarded as safe to drink.

River water- river water is a type of non-potable water.

Substitution- substitution is the act, process, or result of substituting one thing for another.

Urbanisation- urbanisation is the process by which large numbers of people become permanently concentrated in relatively small areas, forming cities and can also be large scale migration towards existing cities.

LIST OF ABBREVIATIONS

APHA	American Public Health Association
ASTM	American Society for Testing and Materials
BOD	Biological Oxygen Demand
BS	British Standard Institution
CBD	Central Business District
COD	Chemical Oxygen Demand
EDS	Energy Dispersive Spectroscopy
EN	European Standard
EPASA	Expanded Polystyrene Association of Southern Africa
EPS	Expanded Polystyrene
MDL	Method Detection Limit
NTU	Nephelometric Turbidity Units
SANS	South African National Standards
SEM	Scanning Electron Microscopy
TDS	Total Dissolved Solids
UN	United Nations
WHO	World Health Organization
XRD	X-ray Diffraction
W/C	Water-to-cement ratio

CHAPTER 1: INTRODUCTION

1.1 Background of the study

Concrete is a building material that is widely used in infrastructure development. One of the key factors that drives countries around the world to relentlessly build more buildings is the process of urbanisation (Glaeser, 2014). Urbanisation is the upsurge in the amount of people residing in cities and towns and arises as a result of the movement of people from rural areas to urban settings (Glaeser, 2014). Scholars propose that urbanisation started in early Mesopotamia during the Uruk Period that spanned 4300 BCE to 3100 BCE, although there is no agreement as to what exactly sparked this phenomenon (Walton, 1995). One theory suggests that a predominantly efficient and prosperous village appealed to the attention of other less efficient and prosperous tribes who then willingly attached themselves to that village (World History, 2014). This shows that the factors of 'efficiency' and 'effectiveness' have long been upheld in history and in the development of the world to be the main driving factors of a prosperous city or town. These factors relate mostly to the efficiency of how commodities are moved around as well as to the effectiveness of the mobility strategies for citizens within the town (Walton, 1995).

It is understood that the earliest known 'urban' cities, namely, Uruk and Ur, were situated in close proximity to the banks of the Euphrates River. This points to an undisputable fact that the achievement of a town's 'efficiency' and 'effectiveness' was also heavily dependent on its proximity to raw materials. The spread of urbanisation can be traced from Mesopotamia to Egypt (Mortazavi, 2011) and from there to Greece (Davis, 1955). When analysing the urban centres of Mesopotamia, Egypt and Greece, it is clear that their pattern of development was very similar to that of Uruk and Ur.

One of the biggest known advantages of cities is their efficiency in the supply of everyday necessities such as water and electricity (McDonald et al., 2014). The people that move from rural areas to the cities move mainly because they are in pursuit of these amenities in the cities. Cities have also adopted ingenious ways of housing multitudes of people in one space while ensuring that they do not feel cramped. City planners in urban areas have achieved this through urban planning and through the construction of flats (apartment blocks). Flats are able to accommodate thousands of people on a single surface area at ground level because they are built vertically.

Another attraction of cities is that they have numerous health and education facilities (Kumar and Kober, 2012). Cities also have social structures meant for cultural activities and for serving food. These facilities are vital for the holistic development and health of a growing population (Gangola, 2020).

According to the United Nations (2018), 55 % of the world population resides in urban settings. This percentage is anticipated to rise by 13 % by the year 2050, which is an extra 2.5 billion people (United

Nations, 2018). The United Nations (2018) further states that 90 % of this expected increase will take place in Asia and Africa.

One of the biggest challenges that urbanisation has brought about is the lack of housing (World Bank, 2016). This deficiency in both developed and developing cities has created an enormous appetite for the use of concrete.

Urbanisation also leads to what is termed as 'urban poverty' as shown in Figure 1.1 (Okeke and Ahaotu, 2021). Urban poverty can be defined in two ways, according to McDonald and McMillen (2008): firstly, that it is an "absolute standard based on a minimum amount of income needed to sustain a healthy and minimally comfortable life", and secondly, that it is a "relative standard that is set based on the average standard of living in a nation".

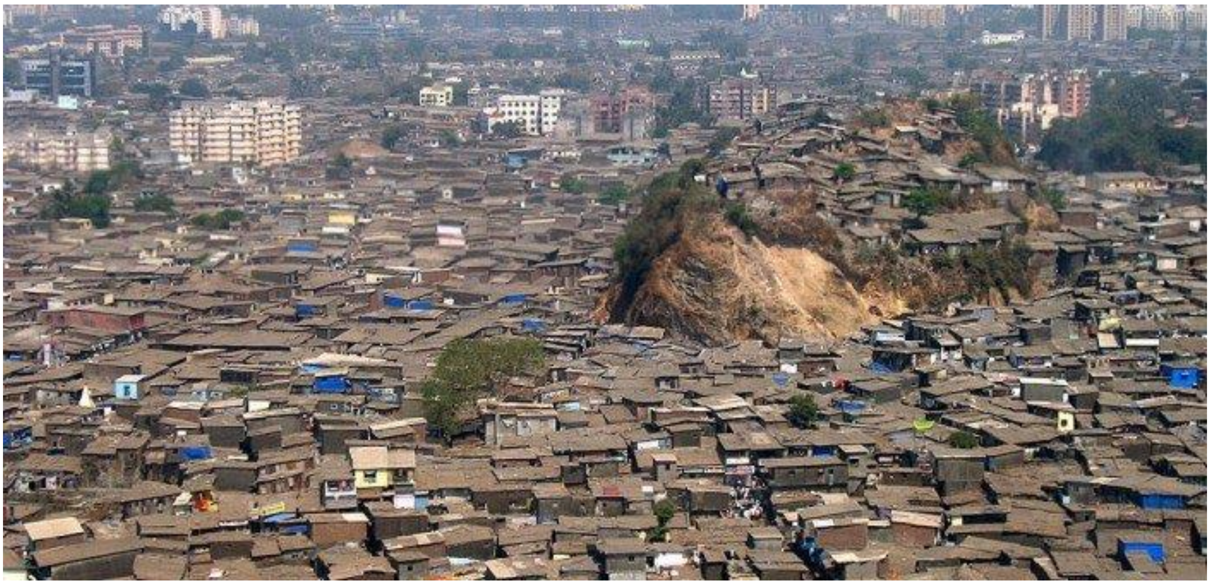


Figure 1.1: Infamous of urban poverty is slums that border the town and form infill pieces within it.

Concrete is an age-old material (International Association of Certified Home Inspectors, 2021). According to Giatec (2017), the roots of concrete can be traced to as early as 6500 BC, to the Nabataea traders in Syria and Jordan. The first products that they created out of concrete were housing structures with concrete floors (Giatec, 2017). Later in the period of 3000 BC, Egypt used mud mixed with straw to bind dried bricks in order to build houses (Radic et al., 2008). Egyptians also used lime mortar as well as gypsum mortar to build the famous pyramids at Giza. Around 3000 BC China used a form of cement to build the Great Wall of China (Radic et al., 2008). During the period of 600 BC the Romans started to use concrete for numerous applications in building their empire (Wang, 2013). The Romans' concrete mix contained lime, volcanic ash, and sea water. The biggest technological milestone in history for concrete was in 1824 when Joseph Aspdin invented Portland cement (Mir and Sagu, 2019). In order to make Portland cement, Aspdin burned finely ground chalk and clay until the carbon dioxide was removed (Mir and Sagu, 2019). Portland cement in concrete is responsible for the durability of the concrete.

As much as concrete has superb structural properties, it is expensive and inaccessible to many low-income families (Envirocrete, 2021). The structures that families from low-income households often resort to are shown in Figure 1.2.

(a) (b)

Figure 1.2: Corrugated sheet (a) and traffic signs (b) used as materials for low-income household houses.

A common aspect of urbanised cities nowadays is that sustainability inclusive of environmental elements are growing problems. Concrete, being the most popularly used material in the modern age, is one of the biggest environmental offenders. There are a number of issues that fuel the crisis of sustainability. For a very long time humanity has viewed the environment as something that is an external factor instead of co-existing proportionally with humanity. A Promethean view holds that technology and the knowledge of humanity is capable of overcoming any environmental or naturally occurring strain. This has proven to be false particularly when viewing the many environmental pressures that currently exist. These include global warming, inappropriate waste disposal, loss of biodiversity, ozone depletion as well as pollution. Singh and Singh (2016) state that most of the environmental problems which currently exist can be attributed to the unsustainable use of natural materials. Lack of sustainability in how resources are used has led to unsafe drinking water, poor hygiene and sanitation conditions, as well as air pollution (Remoundou and Koundouri, 2009). The best way to understand sustainability is through the three overlapping circles model as shown in Figure 1.3 (Morandin-Ahuerma et al., 2019). Sustainability is driven by a careful balancing act between the economy, society and the environment. If one of these contributors grow beyond the set limits, it ultimately affects the sustainability of all three. This is illustrated in Figure 1.3.

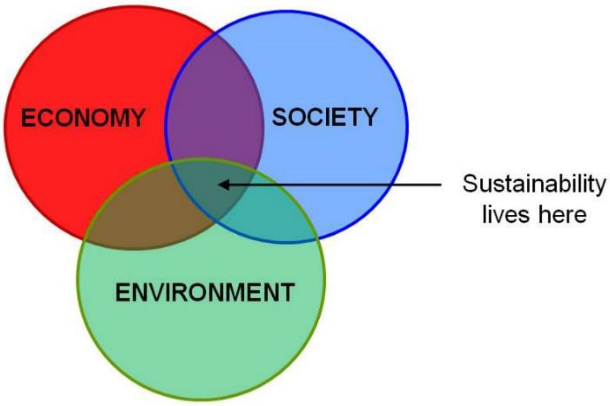


Figure 1.3: The three overlapping circles model of sustainability.
Source: Morandin-Ahuerma et al. (2019)

Figure 1.4. shows the type of dependency pattern that exists between the environment, society and the economy (Morandin-Ahuerma et al., 2019) The environment is the most important circle since it carries both society and the economy.

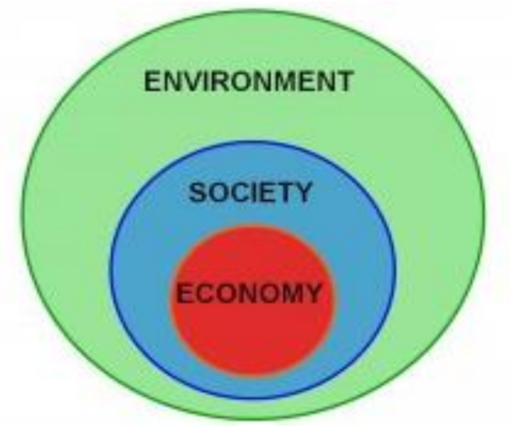


Figure 1.4: The interdependency of the environment, society and the economy.
Source: Morandin-Ahuerma et al. (2019)

The qualities of concrete are superb when compared to other modern-day construction materials, and can scarcely be matched by any other construction material. However, the earth's resources are fast being depleted in an effort to make concrete. This includes water as well as fine and coarse aggregate.

1.2 Research framework

The conceptual framework for this research involved the study of theories of concrete production together with the properties of eggshell powder and expanded polystyrene (EPS) in its various configurations. An experimental approach was used to determine the strength of optimal material mixes for the production of sustainable expanded polystyrene-eggshell concrete with varying densities. The research framework is presented as a flow chart in Figure 1.5.

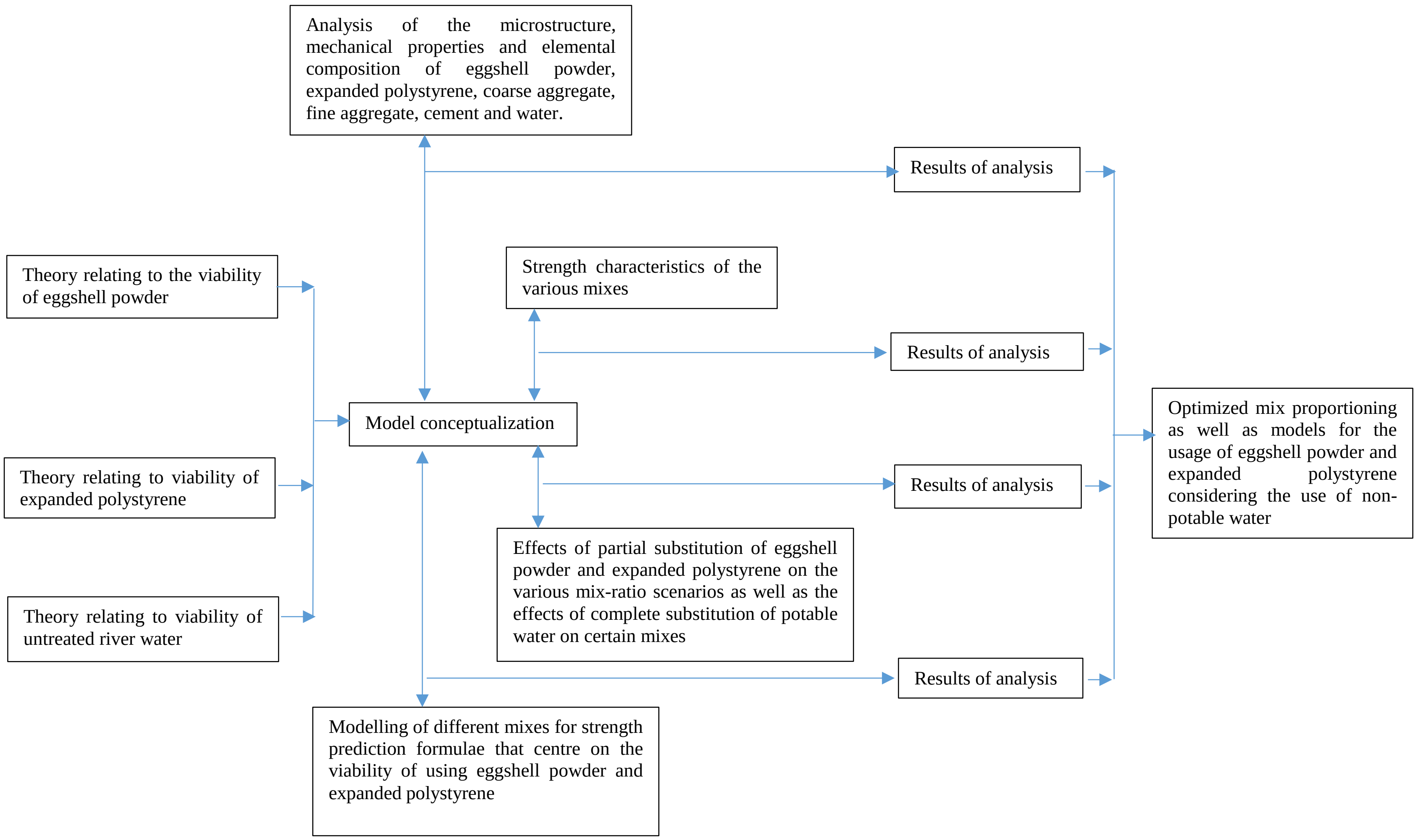


Figure 1.5: Research framework.

1.3 Statement of the problem

The current focus in concrete research is on the type of materials that can be used as substitutes in concrete, as can be found in industrial usage from other spheres of engineering applications such as tyres or glass shavings. This research investigated the usage of agricultural waste in the form of eggshell powder coupled with EPS in an effort to find a durable and lightweight concrete. Furthermore, this study investigated how concrete samples consisting of varying material compositions mixed with a type of non-potable water such as natural river water compared with conventional concrete mixed with non-potable water.

In a world of resource scarcity as is the case today, material re-use is emerging as a major theme in the arena of construction. Material re-use in construction mainly refers to the re-use of fundamental resources such as coarse aggregate. In the context of EPS concrete, previous researchers have neglected the re-use of less commonly considered materials such as eggshell waste. This research investigated how the qualities of EPS concrete differ when some of the constituent materials are not of virgin material quality as would be the case for conventionally produced concrete, but are rather re-used materials such as agricultural eggshell waste.

According to Onwubu et al. (2017), global egg production is 65.5 million metric tons per year. South Africa alone produces 133.9 million eggs per week for its nine provinces with a combined population of approximately 57.78 million (Onwubu et al., 2017). This not only shows that eggshells are in abundant supply, but also the size of the current domestic and commercial kitchen waste burden that is experienced by landfills across the world. The current volumes of eggshell waste also further shows that if we are able to mix concrete with eggshells as a replacement material, we will also in effect be reducing a waste source.

1.4 Aim and objectives of the study

The aim of this research was to investigate through the analysis of experimental results whether:

- Eggshell powder, EPS and river water have qualities that are suitable for use in concrete in order to reduce the amount of conventional cement, fine aggregate as well as potable water that would normally be required; and
- If, when eggshell powder and EPS are used in a concrete mix which has been mixed with river water in place of potable water, they are most suited to produce a higher strength mix when used in combination simultaneously or when used separately.

The three existing constituents that the researcher sought to alter or to substitute in concrete were cement, fine aggregate, and potable water. Compressive and flexural strength tests as well as the slump tests of each substituted mix were conducted in order to study the effects of partial material substitution for both cement and fine aggregate as well as of complete substitution for potable water.

The specific objectives of this research were to:

a) Determine the morphology of cement compared to eggshell powder.
b) Determine the elemental composition of cement, eggshell powder, potable water, river water, fine aggregate and coarse aggregate.
c) Determine the mechanical properties of eggshell powder/expanded polystyrene/river water concrete when used as substitute materials in concrete production.
d) Determine which mix out of the four experimental mixes investigated displayed an optimal mix in terms of strength output for the concrete produced through substitutionary trials of cement and fine aggregate with the use of river water in place of potable water.
e) Develop regression models for estimating the compressive and flexural strength of eggshell powder/expanded polystyrene/river water concrete within various scenarios of substitution.

1.5 Justification for the study

While many may argue that the use of natural river water in its raw form is not ideal for a number of reasons, it is undeniable that many people across the world rely on the use of natural river water or water from local streams for a number of uses. The controlled use of available river water for concrete production would act as an enabler for numerous communities across the world who remain at a disadvantage due to their juxtaposed state of water scarcity alongside the growing need of adequate housing. Furthermore, by omitting a portion of the usual required quantities of both cement and fine aggregate and substituting them with eggshell powder and expanded polystyrene, this would contribute immensely to alleviating the burden that concrete production places on the environment. What may be considered to be extreme materials to consider in the incorporation of concrete mixes may well be the gateway to a healthier co-existence of the environment alongside concrete production. An example of what may be considered an extreme material to use in concrete production is sea water; however, according to Brandon et al. (2014), the Roman Empire used sea water in concrete mixes which have survived for centuries. This is evidence that innovation in concrete is not new to the world, and different countries have made, and are continuing to make, attempts at conserving the earth's natural resources. The positive environmental impact potential is extremely high if eggshell powder/expanded polystyrene/river water concrete in its various configurations is able to reduce the amount of cement, fine aggregate and potable water used in the production of concrete.

Along with the abundance of eggshell waste, EPS as a material of interest in this research has a number of distinct benefits. According to the Expanded Polystyrene Association of Southern Africa (2018), these include:

- Light weight- Air is amongst the most naturally abundant foundational elements in the world. EPS is composed of 98 % air and this illustrates just how resource-efficient it is.

- Moisture resistance- Due to the structure of EPS being a closed cell, it does not readily absorb water. When immersed in water for long periods, EPS still maintains its composure, size and structure.
- Durability- The cellular composition of EPS in terms of its dimensions is balanced and therefore does not weaken with age. When placed in the ground, EPS is capable of surviving up to 100 years without deterioration.
- Thermal efficiency- When compared to bricks, EPS has superior thermal properties. This can be seen when comparing the "R-value" of the two materials, i.e., the thermal resistance of the materials. Thermal resistance is an approximate measurement of how much a material will prevent the transfer of heat.

The combination of fine aggregate, coarse aggregate and cement has proven over the centuries that it can produce a long lasting and stable concrete structure with benefits such as thermal comfort and durability. However, some of the most widely known disadvantages of concrete are as follows (Civil Engineering, 2021a):

- The properties of concrete differ widely as a result of the variations in its proportioning and mixing.
- The placing and curing of concrete is not as precisely controlled as is the production of other construction materials such as structural steel.
- Shrinkage in concrete causes cracks to develop and hence results in strength loss.
- Concrete has a very low tensile strength which requires the use of reinforcing bars.
- Concrete in its current composition is not only expensive, but is also detrimental to the environment due to the high cement content that it requires.

This research is mainly focused on addressing the last disadvantage by focusing on the viability of replacing a portion of the cement and fine aggregate used in concrete production to see if this reduces concrete's overall environmental impact.

The main concern with using cement for infrastructure development is the energy that it consumes during manufacture and the subsequent environmental impact that it has on the environment. Cement production is one of the most energy intensive industrial manufacturing processes in the world (Schneider et al., 2011). According to Babor et al. (2009), air pollutant emissions include nitrous oxides (NO_X) and sulfur dioxide (SO_2). "SO_2 emissions (and to a lesser extent SO_3, sulfuric acid, and hydrogen sulfide) result from sulfur content of both the raw materials and the fuel" (Babor et al., 2009). In addition to air-pollution, another environmental impact of cement and concrete production is water usage. Ragheb (2011) states that on a global scale "they [cement and concrete production] account for one-sixth of the world's freshwater withdrawals." There are also health concerns related to handling and working with concrete and cement. Wet concrete requires that the skin be protected from the high alkalinity of concrete (Babor et al., 2009). However, there are also some health concerns regarding the usage of river water since it may contain varying levels of contamination due to the differing bacteriological constituents in rivers. If the contamination levels of river water are high this can lead to diseases such as diarrhoea, cholera, hepatitis A, polio and typhoid if mistakenly ingested (World Health Organization, 2022).

As the demand for cement grows, the impact on the environment will also continue to grow therefore it is important that alternatives such as eggshell powder in concrete production are investigated.

1.6 Limitations

- This study only looked at one type of eggshell which are chicken eggshells whereas there are a number of other types of eggshells from different animals across the world.
- This study only considered the use of EPS in its virgin form in order to achieve the best possible strength outcomes, however, EPS is also readily available in different forms such as recycled material or as waste material.
- The study only considered one source of river water which is the Msunduzi River. The microbiological variables that existed for the river water used for the control samples were E. coli at 200.5 CFU/100ml and Total coliform at 2005 CFU/100ml. For mix 2 to 5 the microbiological variables that existed were E. coli at 2000 CFU/100ml and Total coliform at 9000 CFU/100ml, however, the extent of contamination in different rivers may differ substantially.
- The river water used to make the control sample specimens was taken from the same source as the river water used for mix 2 to mix 5, but was taken at a different time.
- The study only considered the use of CEM III cement. The main reason for the use of CEM III is that clinker is mainly the backbone of cement production and CEM III contains a much lower percentage of clinker than does CEM I & II. The process of making clinker emits the largest amount of CO_2 during cement production and as a means of this study contributing meaningfully to environmental sustainability, it was therefore important to consider the use of a cement type with a generally lower clinker content than CEM I & II have.

1.7 Study area

The study area was Durban, South Africa. Durban is located 29.85.87 S and 31.02.18 E, and is one of the major tourism hubs in South Africa. Durban, formally called eThekwini, is the largest city of the KwaZulu-Natal province and is the supreme seaport of South Africa, positioned on Natal Bay of the Indian Ocean. After World War I, Durban transitioned from a prim Victorian town to a modern metropolitan area with office towers and multi-storeyed buildings. This therefore shows that the demand for concrete even within the study area has grown exponentially over time and continues to grow especially since Durban is also home to the command centre of South Africa's sugar industry and a centre for numerous manufacturing enterprises.

The growth of Durban can be associated with the expansion of the food and sugar processing industry and its link in the transportation system to the expanding economy of the Witwatersrand. In later years this has been enhanced by petro-chemical industries dependent on close proximity to the port facilities for exporting and importing various products.

1.8 Outline of thesis

This research work is presented in five chapters.

- Chapter 1 presents the background of the research, the problem, the extent of scope and the main objectives of the study.
- Chapter 2 presents an evaluation of literature that is related to the contents of the research on the partial replacement of cement, fine aggregate and potable water.
- Chapter 3 presents the procedures as well as materials used for achieving the objectives of the study.
- Chapter 4 presents the results and analyses of the various scenarios of different configurations of cement, fine aggregate and potable water when partially substituted with eggshell powder, EPS and river water.
- Chapter 5 discusses the overall outcome and gives an overall conclusion of the research along with relevant recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Properties of concrete

Concrete is an age-old material that is durable and traditionally behaves well during a fire (Jahren and Sui, 2017). It is a material that consists of very basic components, namely, fine and coarse aggregate, water and cement. The cement in concrete plays the role of a binder (Liu et al., 2014), forming the glue between all three constituents. Freshly mixed concrete in its fluid state has the ability to adopt a hardened shape of whatever mould that it is placed in. Upon hardening, the density of the concrete is generally 2 400 kg/m^3 (Rahman et al., 2015).

Concrete has multiple applications and can be manufactured in a number of different settings. These range from informal to formal settings. A single individual can mix concrete for domestic purposes such as for the construction of a concrete apron around the house; or a number of individuals working at a batch plant can mix large tonnages of concrete for large construction corporates. It is possible to attain consistent quality levels when the mixing is done in a controlled environment such as at a batch plant, however the risk of inconsistent mixes is higher when mixing is being done manually (The Constructor, 2020).

The plastic state of concrete has a limited duration before it begins to harden (Jahren and Sui, 2017). The window of time from completion of mixing to the point of it being placed influences the properties of the hardened concrete. This is the main reason (amongst other reasons) why large scale projects such as the Mall of Africa in the economic hub of South Africa, built on-site batch plants in order to mitigate adverse effects on the concrete resulting from transport over a long distance.

Although concrete has numerous advantages, it also has a high potential for surface cracking (Xi and Yang, 2017). When concrete cracks this allows the penetration of chemicals into the structure. These chemicals may begin to further degrade the concrete by deepening newly formed cracks. The formation of cracks in concrete directly translates to reduced durability (Safiuddin et al., 2018). Cracks do not only form in the hardened state, but can also form while concrete is in its plastic state. There are a number of causes for cracking of concrete during its plastic phase. These include rapid loss of water, plastic settlement, as well as formwork movement (Xi and Yang, 2017). Once concrete has hardened, the causes of concrete cracking include thermal stress, weathering, poor design, and insufficient detailing (Safiuddin et al., 2018). Cracking of concrete in its hardened state may also result from continued overloading (Seifan et al., 2016).

Once concrete hardens, it becomes extremely hard and dense. However, in its plastic state it is very sensitive to alterations. This is why, if the procedure of transportation and placing is not monitored carefully, certain vital properties of concrete will inevitably be affected.

The largest constituent in concrete is coarse aggregate. Coarse aggregate varies in width and shape depending on the specific quarry it is sourced from. The most popular size of stone is 19 mm (Midmar Group, 2020).

Due to the nature of developing countries such as South Africa, there is often a lot of construction and demolition. Demolition of concrete is problematic for multiple reasons. Not only does it create environmental difficulties, but it also causes landfills to fill up quicker than envisioned (Yeheyis et al., 2013). As such, it has become increasingly important in the construction industry to recycle concrete. The recycling of concrete has advantages such as being a cheaper source of aggregate than newly mined aggregate, and also contributes to prolonging the life of landfill spaces (Islam et al., 2019).

In some cases the demands of clients and corporates leave contractors and consultants with very little time to have a well-spaced out programme of activities for their construction programme. In such instances, modified or enhanced concrete is often used, instead of conventional concrete (Punurai et al., 2007). Enhancements such as latex emulsion were used in the USA as early as 1969 on highway bridges (Federal Highway Administration, 2016). Traffic loading was permitted within 24 hours instead of four to seven days.

There are immediate properties of concrete that are directly affected when it is still in either plastic form or hardened state. These are workability, segregation, bleeding, strength, permeability, and durability. These are discussed in detail below.

2.1.1 Workability

The workability of concrete is a property of fresh concrete which is commonly measured in millimetres by conducting a slump test (Yang et al., 2021). Historically the workability of concrete was assessed visually through experience, but in modern day batches, the mixes are technically assessed through designated instruments such as a slump kit shown in Figure 2.1 (Civil Engineering, 2021b). The slump kit includes a mould, base plate, tamping rod and a tape measure (Civil Engineering, 2021b).

Figure 2.1: Slump test equipment.
Source: Civil Engineering (2021b)

The workability of concrete in its plastic state is dependent on the mix proportions, the materials used, as well as the environmental conditions (Hussein, 2015). In order to enhance the workability of concrete, pozzolans such as fly ash may be used (Yang et al., 2021). Ghais et al. (2014) found that the workability of concrete improved when the water-to-binder ratio was reduced by 10 % through the use of fly ash. Khaleel et al. (2018) found that when cement is replaced with meta-kaolin with a water cement ratio of 0.45, the workability of the concrete decreases. This contrasting result in workability is important since it highlights the delicacy with which any substitution in concrete should be approached.

Figure 2.2 shows how the workability of concrete increases as the percentage of fly ash in concrete increases. In contrast, the typical decrease in workability with increased cement replacement with meta-kaolin is shown in Figure 2.3.

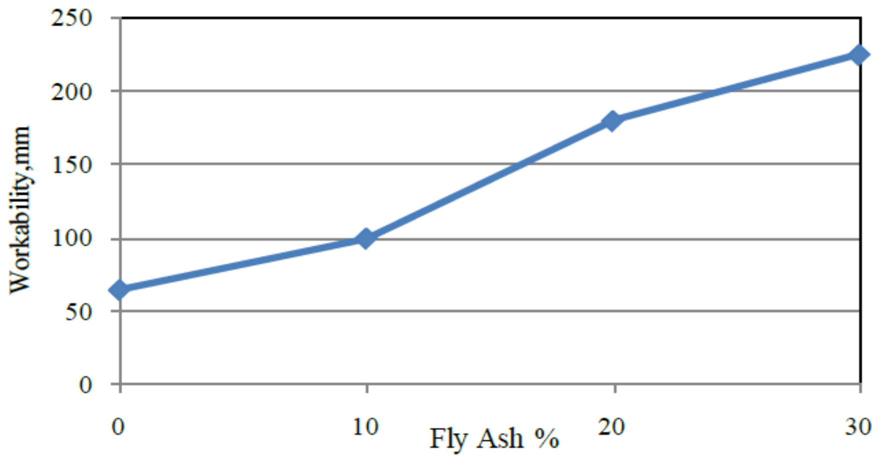


Figure 2.2: The workability of concrete with fly ash.
Source: Ghais et al. (2014)

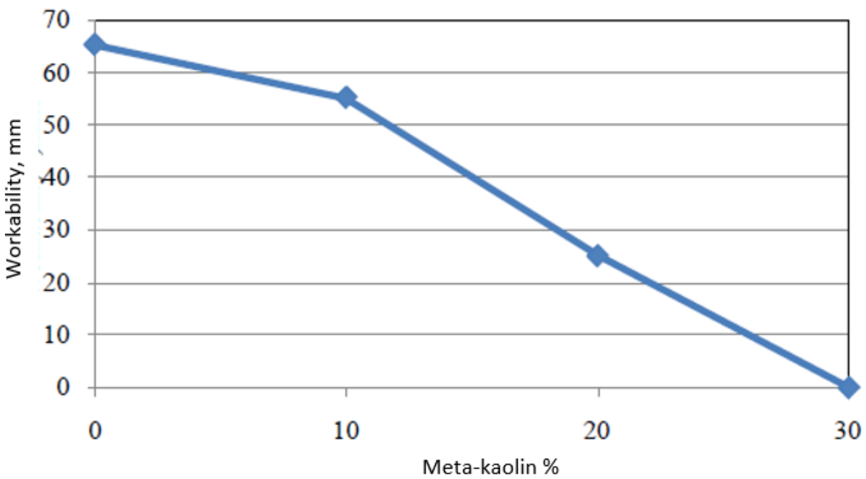


Figure 2.3: The workability of concrete with Meta-Kaolin.
Source: Ghais et al. (2014)

2.1.2 Strength

The strength of concrete can be defined as its ability to resist force. The strength quality of concrete is an important indication of other properties of practical importance in concrete. It is common in research pertaining to concrete strength to find the strength of concrete samples being measured at 7 days, 14 days, 28 days, and 90 days.

Due to the excellent strength qualities of conventional concrete having been established centuries ago, a lot of investment in terms of research has been made in the area of establishing the strength qualities of unconventional concrete types. An example of this is concrete containing recycled aggregates. Silva et al. (2015) tested the tensile strength of concrete containing recycled aggregates. Generally, recyclable aggregates can be found from three main sources of construction and demolition waste, namely, mixed demolition debris, crushed masonry, and crushed concrete. They found that with an increased content of recycled aggregate, the strength of concrete decreases. However, during the investigation, it was also noted that it is possible to reduce the severity of this effect through carefully selecting the recycled aggregate by quality, type and size. This enhances the gradation of the aggregate and ensures that the strength of the concrete is not compromised.

Although the tensile strength of concrete that contains recycled aggregates is initially low, Silva et al. (2015) found positive results of tensile strength improvement over time. Concrete that contains an increased quantity of recycled aggregates may achieve higher tensile strength one year after being placed when compared to conventional concrete that contains newly mined aggregates.

2.1.3 Durability

The durability of concrete is defined as the ability of concrete to repel any form of chemical attack, weathering, abrasion, or any manner of weakening from its original serviceability, quality and form (Tang et al., 2015).

The biggest durability threats in concrete include freeze-thaw, alkali-aggregate reaction, steel corrosion and sulfate attack (Cheng et al., 2016). Alkali-aggregate reaction in concrete is the interaction between active chemicals of fine and coarse aggregates and alkalis (Cheng et al., 2016). A sulfate attack occurs because of the interaction of sulfate ions with water in concrete and results in expansion deterioration (Venkatraman and Ramasamy, 2017). Corrosion of reinforcement steel in concrete is a frequent problem in practice. Factors that need careful control in the corrosion of steel are the specification of the concrete as well as the specified concrete cover to the reinforcement steel (Zhang et al., 2017); controlling these factors ensures that the rate of chloride ingress and carbonation are kept to a minimum (Zhang et al., 2017). Other strategies of protecting reinforcing steel include coating the rebar or increasing the concrete cover (Goffin et al., 2020). Concrete degradation as a result of thawing or freezing is the result of the presence of water in concrete. To determine the severity of such degradation, Cheng et al. (2016) discovered that any decrease in the dynamic modulus or reduction in mass can be said to be a direct indication of degradation.

2.2 Properties of ordinary Portland cement

Cement is a human-made powder that, when mixed with water and aggregates, forms concrete. According to the Association of Cementitious Material Producers (2016), naturally occurring calcareous deposits such as limestone, marl or chalk provide calcium carbonate and are extracted from quarries. Small amounts of additional materials such as bauxite, iron ore, clay, shale or sand are needed to provide extra silica (SiO_2), iron oxide (Fe_2O_3) and alumina (Al_2O_3) to adapt the chemical composition of the raw mix to the process and product requirements. Civil Engineering (2022) further presents the following main ingredients for cement along with their functions:

- Lime ($Ca(OH)_2$ or CaO) - calcium hydroxide or calcium oxide is required in order to form silicates and aluminates of calcium.
- Silica (SiO_2) - imparts strength to cement and is usually responsible for approximately 30 % of the volume of cement.
- Alumina (Al_2O_3) - imparts quick strength gain to cement.
- Magnesia (MgO) - imparts hardness and colour to cement.
- Iron oxide (Fe_2O_3) - acts as a flux in addition to being responsible for imparting colour to cement.
- Calcium sulfate ($CaSO_4$) - slows down or retards the setting action of cement.
- Sulfur trioxide (SO_3) - enhances the expansive performance of cement materials and prolongs the setting time of cement.

According to the European Committee for Standardization, there are five main types of cement, namely, CEM I to CEM V (Durastanti and Moretti, 2020). Many studies have been conducted on the environmental impacts of cement production. An example of one such study is that of Durastanti and Moretti (2020) who found that although the composition of the different types of cements differ by proportion of mass of the main constituents, all the types of cement contain clinker. According to the European Committee for Standardization, CEM I to CEM V is distinguished as follows:

- CEM I (i.e., Portland cement) has the most environmental impact because it contains at least 95 % by mass of clinker and gypsum as a minor additional constituent to control the “setting of cement”.
- CEM II (i.e., Portland composite cement) is composed of clinker with different proportions by mass (65 % to 94 %). Its main constituents are, for example, blast furnace slag, silica fume, pozzolana, fly ash, burnt shale or limestone, and gypsum.
- CEM III (i.e., blast furnace cement) is composed of 35 % to 64 % clinker, 36 % to 65 % blast furnace slag and 0 % to 5 % gypsum by mass.

- CEM IV (i.e., pozzolanic cement) is composed of clinker and pozzolanic constituents (i.e., blast furnace slag, silica fume, pozzolana, and fly ash).
- CEM V (i.e., composite cements) is composed of mixtures of Portland cement, slag and Pozzolana.

2.3 Examples of advances made by various researchers in using waste products as potential partial replacements within ordinary Portland cement

Cement has been an unmatched concrete binder for centuries, and it is only recently due to environmental pressures that researchers have looked into alternatives for cement.

Ahmad et al. (2013) studied waste paper sludge ash as a partial replacement of cement. Waste paper sludge ash is a by-product of the de-inking and re-pulping of paper. Its material qualities are that it is a sticky, hard to dry, viscous and lumpy material. There are many differences in chemical composition between ordinary Portland cement and waste paper sludge ash, but the main ones are that waste paper sludge ash contains significantly higher proportions of silicon and much lower percentages of calcium when compared to ordinary Portland cement. Ahmad et al. (2013) found that although the workability of the concrete mix decreased with an increase in waste paper sludge ash, the compressive strength at 7 days and 28 days increased by 10 % and 15 % respectively when a 5 % replacement of cement by waste paper sludge ash was used.

Utsev and Taku (2012) investigated the use of coconut shell ash as a partial replacement of ordinary Portland cement in concrete production. The chemical composition of the specific ordinary Portland cement and coconut shell ash used in the research is presented in Table 2.1.

Table 2.1: Chemical composition of ordinary Portland cement and coconut shell ash.

Chemical Composition	Ordinary Portland Cement (%)	Coconut Shell Ash (%)
SiO_2	20.70	37.97
Al_2O_3	5.75	24.12
Fe_2O_3	2.50	15.48
CaO	64	4.98
MgO	1	1.89
SO_3	2.75	0.71

Utsev and Taku (2012) found that the compressive strength decreased with increasing percentage of coconut shell ash. The optimal 28 day strength was found to be when coconut shell ash was used at 10 % replacement of cement.

Huang et al. (2013) conducted an experimental study aimed at assessing the proportions of fly ash needed to meet the required strength and workability criteria of concrete. Fly ash of grade ‘class F’ was used during the assessment. The assessment consisted of two groups of concrete mixtures that contain this type of low-calcium fly ash. The design parameters were such that the fly ash replacement for cement was between 20 % and 80 %, and the compressive strength was 24 MPa to 35 MPa. At the conclusion of the study, Huang et al. (2013) found that concrete that contained up to 80 % of fly ash as a replacement for cement may be proportioned in such a manner that it produces adequate workability, if the superplasticiser used is carefully chosen.

Naceri and Hamina (2009) investigated the use of waste brick as a partial replacement of cement. They found that the incorporation of waste brick in cement at varying percentages of 0 %, 5 %, 10 %, 15 % and 20 % increased the oxides SiO_2, Al_2O_3 and Fe_2O_3, but decreased the oxide CaO. This led to a decrease in the compressive and flexural strength of the cement at 7 day and 28 day testing.

The effects of partial replacement of cement by waste marble slurry have been investigated by Singh et al. (2017). Marble slurry is obtained in large amounts from marble processing mines and released into the environment as waste. By percentage, the chemical composition of marble slurry differs substantially from the main chemical composition of ordinary Portland cement. The main chemical differences are shown in Table 2.2.

Table 2.2: Chemical composition of ordinary Portland cement and marble slurry used in research.

Chemical Composition	**Ordinary Portland Cement (%)**	**Marble slurry (%)**
SiO_2	20.27	3.86
Al_2O_3	5.32	4.62
Fe_2O_3	3.56	0.78
CaO	60.41	28.63
MgO	2.46	16.9
SO_3	3.17	-

Singh et al. (2017) found that although the initial setting time increases as the marble slurry content increases from 0 % to 25 %, and the air content reduces with a continued increase in percentage of marble slurry, from 10 % marble slurry substitution of cement onwards the compressive strength of the mortar decreases.

In an effort to find a replacement for cement, Kaya and Kar (2016) investigated Tragacanth. Tragacanth is a glue substance that drips from the open wounds of Astragalus plants. Astragalus plants form molecules that consist of numerous sugar molecules that are bonded together. The plant consists of two portions: one that can be dissolved in water (trigakantin) and the other portion that does not dissolve in water (bassorin) (Bicer, 2019). The common uses of Astragalus plants by pharmaceutical companies are for preparing emulsions and for tablet production (Kaya and Kar, 2016). In order to produce Tragacanth resin, the astragalus plant is cut and stored in order to dry sufficiently (Bicer, 2019). This drying period normally takes 48 hours. Upon drying, the substance is kneaded and filtered to make a solution (Kaya and Kar, 2016). The dry components are shown in Figure 2.7 (a) and the solution made is shown in Figure 2.7 (b).

Figure 2.4: (a) Dry Astragalus.
Source: Kaya and Kar (2016)

(b) Filtered Tragacanth solution.
Source: Kaya and Kar (2016)

Kaya and Kar (2016) concluded that when EPS beads are used in conjunction with tragacanth resin, it is possible to reduce the quantity of cementitious material needed to make concrete. This shows that certain advances which have been made in trying to reduce the amount of cement required in a concrete mix have succeeded through substitutionary experimentation.

Various types of fibres such as steel, asbestos, polypropylene, carbon, polyethylene, aramid and glass have been used to strengthen cement products. Basalt fibre which is made through the process of extrusion of basalt rock, is a newly introduced inorganic fibre. Yan et al. (2021) investigated the use of fibres in concrete and examples of the basalt fibre and glass that they used are shown in Figure 2.8 (a) and (b).

Figure 2.5: (a) Basalt fibre.
Source: Yan et al. (2021)

(b) Glass fibre.
Source: Yan et al. (2021)

Yan et al. (2021) found that the inclusion of basalt fibre as well as glass fibre in a concrete mix lowered the workability of concrete. However, a lower slump was attained for glass fibre reinforced concrete when compared to basalt fibre reinforced concrete. It is common knowledge that one of the main drawbacks of fibre reinforced concrete is its poor workability (Saidani et al., 2016). The use of fibres results in a decrease in slump. There are numerous factors which affect the workability of fibre-reinforced concrete. These include the fibre content, the aspect ratio of the fibres, the percentage of the paste, and the water content within the mix (Saidani et al., 2016). If these factors are carefully managed, it is possible to slightly improve the workability of fibre reinforced concrete.

Aliabo et al. (2016) used glass powder as a substitute for cement in concrete. The most basic property of glass is that it is inert. Glass is also a material which may be recycled more than once without its chemical properties changing (Vijayakumar et al., 2013). Vijayakumar et al. (2013) conducted an experiment where cement was partially substituted with glass powder in increments of 10 % up to 40 %. The researchers utilised ordinary Portland cement throughout the experiment. The type of fine aggregate used was river sand that had a maximum size of 4.75 mm. The coarse aggregate used was blue granite that was mechanically crushed into angular shapes. There were two sizes of coarse aggregates that were used. The first size was 12.5 mm and the second size was 20 mm. Glass was procured from local waste skips and ground into fine powder before use. The resultant particle size after the process of grinding was 75 μm. As a benchmark, Vijayakumar et al. (2013) used 28 day properties of 31.1 N/mm^2 for compressive strength, 2.27 N/mm^2 for splitting tensile strength, and 3.25 N/mm^2 for flexural strength for conventionally produced concrete.

They concluded that:

1. When glass powder is used to replace cement by a percentage of 20 % to 40 %, the compressive strength increases by 19.6 % to 33.7 %.
2. If glass powder replaces cement in the concrete mixture by 40 %, the splitting tensile strength increases by 4.4 %.
3. When glass powder replaces cement by 20 % to 40 %, the flexural strength increases by 83.07 % to 100 %.

Vijayakumar et al. (2013) therefore concluded that when glass powder is used as a partial substitute for cement, it not only reduces the amount of cement needed, but also increases the flexural, tensile and compressive strength of the concrete.

Lollini et al. (2014) studied how limestone affects the characteristics of concrete when it is used as a binder to partially substitute cement. Limestone replaced cement in quantities ranging from 15 % to 30 % in mass. The following conclusions were drawn by Lollini et al. (2014):

- The strength and resistivity were notably affected, although the effect was observed on chloride diffusion and carbonation.
- The substitution of Portland cement with limestone by up to 15 % resulted in a reduced 28-day compressive strength. When Portland cement was substituted with limestone by up to 30 %, it drastically weakened all the properties of concrete simultaneously.

- The carbonation coefficient and the compressive strength correlated well with the water-to-cement ratio that was used.
- Due to the presence of limestone in the concrete mix, the diffusion coefficient of chloride increased.
- Regardless of the amount of Portland cement substituted with limestone, the researchers found that all concretes with equivalent compressive strengths had the same levels of resistance to carbonation.

2.4 Eggshell and seashell usage in concrete production

Yerramala (2014) investigated the effects of what is termed as 'poultry waste' in concrete. The poultry waste that was used in concrete was eggshell powder. Yerramala (2014) mixed different types of concretes by substituting ordinary Portland cement with eggshell powder at varying percentages of between 5 % and 15 %. Eggshell waste is rich in calcium, and its chemical composition is such that it is similar to that of limestone. Yerramala (2014) envisioned that the use of eggshell waste in construction could have numerous benefits such as lowering concrete's dependency on cement, utilising waste material and thereby contributing to increasing the useful life of landfills. The current yearly generation of eggshell waste in countries such as India, United States and the United Kingdom are 190 000, 150 000 and 11 000 tons respectively. The current uses of eggshell waste include being used as a fertiliser as well as being used as part of animal feed. However even with these uses, large quantities still end up in landfills around the world.

There is a paucity of studies on the use of eggshells in civil engineering. Amu et al. (2005) investigated the use of eggshell powder as a stabiliser in soil materials. Olarewaju et al. (2011) investigated the use of eggshell powder when used as a stabiliser for subgrade materials in the construction of roads. Yerramala (2014) confirmed that at the time of publishing, these were the only two studies that had been conducted on the use of eggshells in the sphere of civil engineering applications. Table 2.3 shows the various values for the mixed samples for the various characteristics of concrete such as compressive strength, splitting tensile strength and absorption found by Yerramala (2014).

Table 2.3: Strength qualities of conventionally produced concrete versus eggshell powder concrete.

Concrete name	Compressive strength, MPa			Splitting tensile strength, MPa			Density, kg/m^3	Absorption %		Permeable voids	Sorption, $mm/s^{0.5}$
	1 day	7 day	28 day	1 day	7 day	28 day		30 min	72 hr		
M1 (does not include any eggshell powder)	6.8	11.1	22.3	0.4	0.8	2.4	2 364	1.38	4.39	7.7	0.12
M2 (includes $15kg/m^3$ of eggshell powder)	4.9	14.4	24	0	1.3	2.4	2 347	1.02	2.94	7.7	0.106

M3 (includes 30kg/m^3 of eggshell powder)	7.7	10.7	18.9	0.2	1	2.3	2 323	1.39	3.41	8.89	0.11
M4 (includes 45kg/m^3 of eggshell powder)	6.9	9.8	16.1	0	1.4	1.6	2 305	1.67	4.38	8.3	0.16

Source: Yerramala (2014)

The results of the investigation showed that it is possible for eggshell powder to replace a portion of the cement used in the production of concrete. The major findings of the study were as follows:

- The compressive strength that was achieved at 7 days and 28 days for concrete that had 5 % of eggshell powder was higher than the control specimen concrete that was tested. The finding was that when Portland cement was replaced with 10 % or higher of eggshell powder, it adversely affected the compressive strength of the concrete.
- When up to 10 % of cement was replaced with eggshell powder, the splitting tensile strength remained comparable to that of conventional concrete. However, if this quantity of eggshell powder was increased to 15 %, the finding was that this lowered the splitting tensile strength significantly.
- When up to 10 % of eggshell powder was used to replace Portland cement, the sorptivity remained comparable to that of conventional concrete.

Yerramala (2014) did not explore the performance of concrete made with eggshell powder beyond a testing period of 28 days. Yerramala (2014) and other researchers also did not explore how the performance of concrete would change if eggshell powder was used in an already existing concrete mix-type such as EPS concrete (lightweight concrete). Had researchers gone to this extent, it would have answered the question of whether or not an even lighter weight concrete that is lighter than EPS concrete may be produced without compromising the strength qualities of the concrete. The current research explored these areas in an effort to reach a more comprehensive conclusion regarding the use of eggshell powder in concrete.

While there is a paucity of studies that have been conducted regarding the use eggshells from land animals in civil engineering, there are a number of studies on the use of aquatic shells in the production of concrete. Richardson and Fuller (2013) examined the use of seashells when mixed to produce concrete. Seashells were utilised as an aggregate replacement. The benefits of using seashells is that it minimises the storage needed for shell waste and also decreases the burden on quarrying fresh aggregates for concrete mixing.

Richardson and Fuller (2013) are not the first researchers to look into the use of sea shells for concrete. Historically sea shells were used in the production of “tabby”. Tabby was a material similar in nature to concrete that was used in the 1800s mainly around coastal areas because of its availability. The composition of tabby consisted of sand, ash, lime, water, ash and oyster shells. Tabby, if properly prepared, may have similar uses to standard concrete and can be used for floors, foundations and walls. The biggest drawback of tabby is its poor resistance to water penetration (Lauren, 1999). Upon careful study of tabby, Fischetti (2009) found that the porosity of tabby had never been satisfactorily documented due to insufficient testing.

Yoon et al. (2003) defined the properties of seashells as being predominantly composed of calcium carbonate. When looking at an oyster shell under a microscope, it can be seen that it is composed of two distinct layers. There is a solid sheet layer as well as a porous layer. The purpose of the sheet layer is to allow the seashell to grow in a specific shape. Although these two layers in seashells are distinct, they both have similar chemical compositions. Both layers are predominantly composed of 96 % mineral $CaCO_3$.

Richardson and Fuller (2013) found that when seashells are used in concrete production to partially substitute quarried aggregates, they lowered the porosity of the concrete. When seashells were added to concrete at a low percentage, this did not in any way negatively alter the compressive strength of the concrete. However, when a large percentage of conventional aggregate was substituted with seashells, the compressive strength dropped significantly.

According to Murakami et al. (2007), eggshells constitute 11 % of the total weight of the egg. Adogla et al. (2016) collected eggshells from local fast-food eateries. The eggshells that were collected are shown in Figure 2.9. These shells were all boiled in water in order to rid the shells of any remaining egg residue. The eggshells were then sun-dried. Using a laboratory grinder, the dried eggshells were ground into fine particles.

Figure 2.6: Eggshells collected and processed into fine particles.
Source: Adogla et al. (2016)

The eggshell quantities were varied in different proportions when mixed with the laterite samples. The eggshell quantities were added in increments of 10 % up to 40 %. The materials were mixed with potable water in a clean tray. Mixing of the samples was done in such a way that a homogenous mixture was obtained. All mixed specimens were placed in 200 mm × 100 mm × 75 mm metal boxes. The specimens were then manually compressed using plastic sheets. Care was taken to ensure that rapid evaporation did not occur since that could have resulted in undesirable defects such as cracks and dry shrinkage. The compressed bricks were cured for 28 days before the properties of the bricks were examined. Findings were that the eggshell powder notably improved the durability of laterite bricks in terms of their water absorption and abrasion resistance. Furthermore, findings were that the eggshell powder also improved the compressive strength of laterite bricks when compared to traditionally produced laterite bricks.

Ujin et al. (2017) examined the performance of concrete that had been mixed with eggshells in order to decrease the quantity of cement used in the mix. Eggshell powder was added to the concrete mix at a replacement factor of between 1 % to 2.5 % (Figure 2.10). The study found that concrete that contained a substitution of cement by 2.5 % had a significantly higher compressive strength than conventionally produced concrete in some instances.

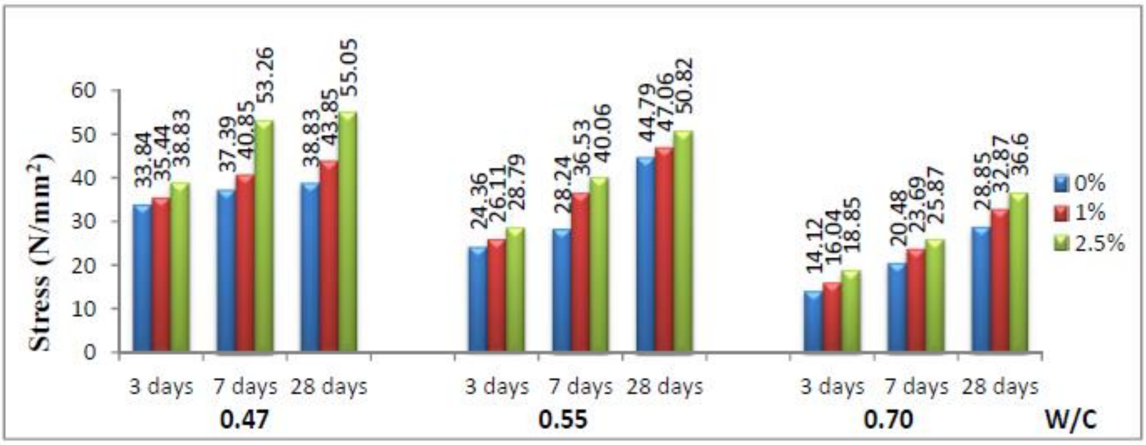


Figure 2.7: Mean compressive strength of concrete at 3, 7 and 28 days.
Source: Ujin et al. (2017)

Although the results obtained by Ujin et al. (2017) are impressive, it is fair to state that concrete users and designers across the world would be more motivated toward incorporating eggshell powder in their mix designs if the potential replacement factor of cement is at least 5 % instead of 2.5 %. This is because the assumption is that the monetary and environmental benefits of substituting only up to 2.5 % of cement with eggshell powder might be near to unnoticeable, whereas if it was 5 % and beyond then it would be noticeable enough to consider such substitution. Thus, this study examined the effect of substituting cement content by at least 5 %.

2.5 The usage of potable water in concrete production

Water quality plays an integral part in the production of concrete. Dauda et al. (2018) state that contaminants in water tend to slow the rate of hydration of cement. When the rate of hydration of cement is reduced, the strength and durability of the concrete is also adversely affected. The reason why the quality of water used in concrete also affects the strength and durability of concrete is because the chemicals present in water continue to participate actively in the strength development of the concrete until the concrete has fully moved from its plastic state to a hardened state (Dauda et al., 2018).

Although there is a strong scientific case for why concrete should be produced using potable water, there is also a very strong case for reducing the amount of potable water required to produce concrete, not only because of competition for access to potable water, but also because of the amount of financial resources that it takes to bring water that may be from diverse sources to that of a potable standard.

The amount of potable water needed in the construction industry to produce concrete is a growing challenge; for example, in 2010, 825 billion litres of water were used in concrete production (Kanitha et al., 2014). Usage of such large quantities of clean water which is of a drinkable standard are not sustainable, raising the importance of further investigating the impact of treated and untreated wastewater in concrete.

2.6 The usage of non-potable water in concrete production

Treated water (water treated to a level where it's suitable for irrigation purposes but not for drinking purposes) and untreated wastewater are types of non-potable water. Wastewater originates from a number of discharges from municipal, industrial and domestic channels (Water & Water Digest, 2020), and includes compounds such as copper, phosphorus, nickel, zinc, barium, manganese and sodium (Gardner et al., 2012). Although these chemicals might be numerous within wastewater, individually they are in very small concentrations. By the time that wastewater treatment plants have processed the wastewater, the chemical concentrations within the water are significantly reduced. The chemical properties of treated and untreated wastewater are detailed in Table 2.4. The comparison of the values of the treated and untreated wastewater are for a specific case study therefore values for 'before treatment' can be expected to vary considerably depending on the water source.

Table 2.4: Properties of untreated and treated wastewater.

SI no.	Parameters	Unit	Concentration (before treatment)	Concentration (after treatment)	Tolerable limits (Bangladesh standard)	ASTM limit for concrete use
1.	Ph	Overall	7.26	7.10	6.5-8.5	-
2.	Turbidity	NTU	35.5	6.70	25	-
3.	Colour	APHA Pt-Co	100	35	No guideline	-
4.	EC (Electrical conductivity)	mS	6.65	4.42	No guideline	-
5.	Chloride ion	mg/l		150	500	500
6.	Iron	mg/l	0.6	0.4	0.3-1.0	-
7.	Alkalinity	mg/l	75	480	1000	600
8.	CO_2	mg/l	10	5	No guideline	-
9.	Hardness	mg/l		500	200-500	-
10.	TDS	mg/l	4353	2953	1000	50 000

11.	COD	mg/l	110	70	≤150	-
12.	BOD	mg/l	30	20	100	-
13.	Lead	mg/l		0.004	500	-
14.	Cadmium (Cd)	mg/l		0.003	500	-
15.	Nickel	mg/l		≤ MDL	500	-

Source: Sultana and Sadiqul Islam (2018)

Sultana and Sadiqul Islam (2018) found that conventional concrete produced with potable water takes 130 minutes to initially set and 170 minutes to reach final setting time, whereas concrete produced with non-potable water takes five minutes longer for the initial setting time and nine minutes longer to reach final setting time. Notably, the target slump of 75 mm to 100 mm can still be met when using non-potable water (Sultana and Sadiqul Islam, 2018).

Researchers such as Shahidan et al. (2017) investigated the chemical characteristics of wastewater from a variety of sources such as car washes and compared this to clean tap water. The results are shown in Table 2.5. These researchers found that of the three properties tested, the chloride parameter compared most favourably between the two types of water.

Table 2.5: Car-wash wastewater characteristics.

Parameters/Source	**Parameters**		
	pH	**Chloride Cl^-, ppm**	**Sulfate SO_4^{2-}, ppm**
Car wash wastewater			
Mahaju Car Wash Station	8.8-9.5	19.4-33.0	12.6-115.5
Bandar U Car Wash Station	9.5-10.6	18.2-25.4	16.1-100.4
Tap water			
Tap water	7.6-8.1	19.4-19.7	13.3-13.4

Source: Shahidan et al. (2017)

In order to minimise the wastage of wastewater, researchers such as Duarte et al. (2019) investigated the effects of the mixed use of treated wastewater and potable water when mixing concrete. The researchers mixed treated wastewater with potable water in various quantities as shown in Table 2.6. The treated wastewater that they made use of during their investigation was from a community in Campinas, Brazil.

Table 2.6: Proportions of potable water and treated wastewater used in concrete production.

Group	Percentage of potable water (%)	Percentage of treated wastewater (%)
1	100	0
2	50	50
3	25	75
4	0	100

Source: Duarte et al. (2019)

Table 2.7 represents the chemical analysis of the treated wastewater and the potable water. The results from the chemical analysis show that the treated wastewater met the Brazilian standards.

Table 2.7: Chemical analysis of treated wastewater (TW) and potable water (PW).

Parameters	**TW**	**PW**	**Requirements for making water for concrete (ABNT 2009)**
pH	6.8-79	7.2	≥ 5
Total alkalinity (mg $CaCO_3$ L^{-1})	313.6	21.7	≤ 2,422
Conductivity (uS cm^{-1})	1,193	54.9	-
Dissolved oxygen (mg O_2 L^{-1})	4.4	8.1	-
Turbidity (uT)	10	0.19	-
Total solids (mg L^{-1})	519	55.2	≤ 50,000
Chemical oxygen demand (mg L^{-1})	85	-	-
Total N (mg L^{-1})	188	1.10	-
Nitrite (mg NO_2^-N L^{-1})	4.9	‹ 0.005	-
Nitrate (mg NO_3^-N L^{-1})	42.5	0.63	≤ 500
Total P (mg P L^{-1})	2,74	0.12	≤ 44
Sulfate (mg $SO_4^{2}N$ L^{-1})	50	3.99	≤ 2,000
Chloride (mg CI^- L^{-1})	113	0.36	≤ 500
Total coliforms (NMP/100mL)	1.0	0	-
Escherichia coli (NMP/100mL)	‹ 1.0	0	-
Lead (mg Pb^{2+} L^{-1})	‹ 0.1	‹ 0.1	≤ 100
Zinc (mg Zn^{2+} L^{-1})	‹ 0.1	‹ 0.1	≤ 100

Source: Duarte et al. (2019)

The results from the mixed concrete specimens showed that all the specimens that had 75 % and 100 % of treated wastewater showed no significant difference in compressive strength. The compressive strength of concrete containing treated wastewater was 32.94 MPa plus/minus 3.34 MPa and of that of concrete with potable water was 28.72 MPa plus/minus 2.57 MPa. The results obtained reflect the potential that reused water could have in concrete production.

Mahasneh (2014) found that the splitting tensile and compressive strength of concrete decreases when potable water is replaced with wastewater or treated water in the mixing process as shown in Figures 2.11 and 2.12.

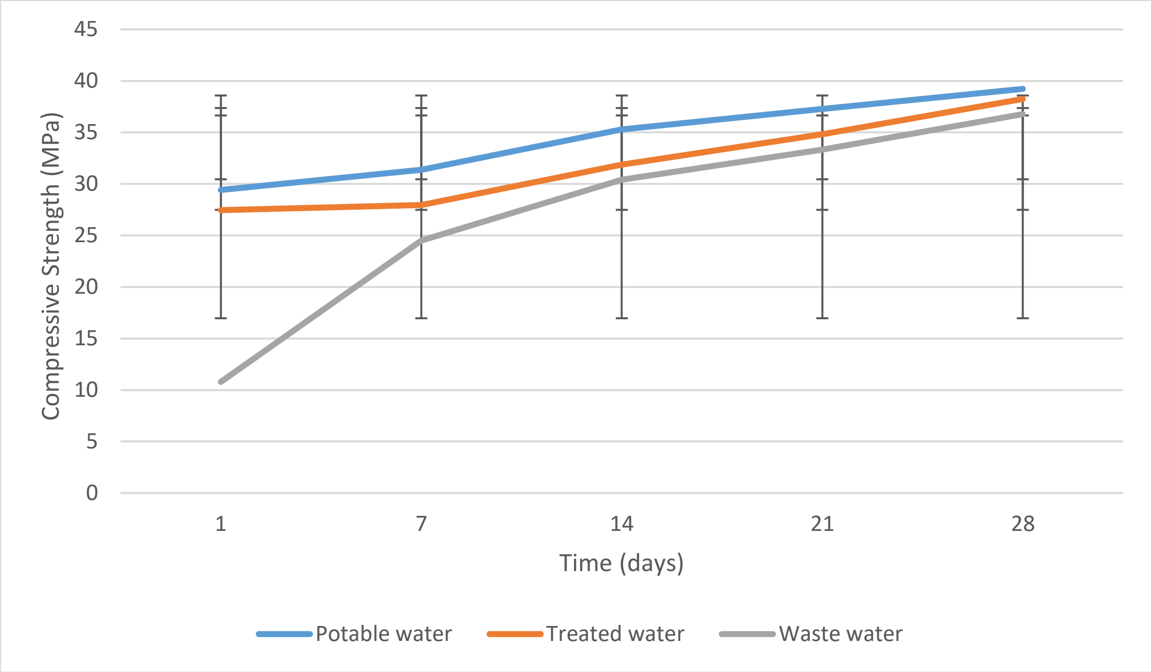


Figure 2.8: Curing time and compressive strength of concrete mixed with various water types.
Source: Mahasneh (2014)

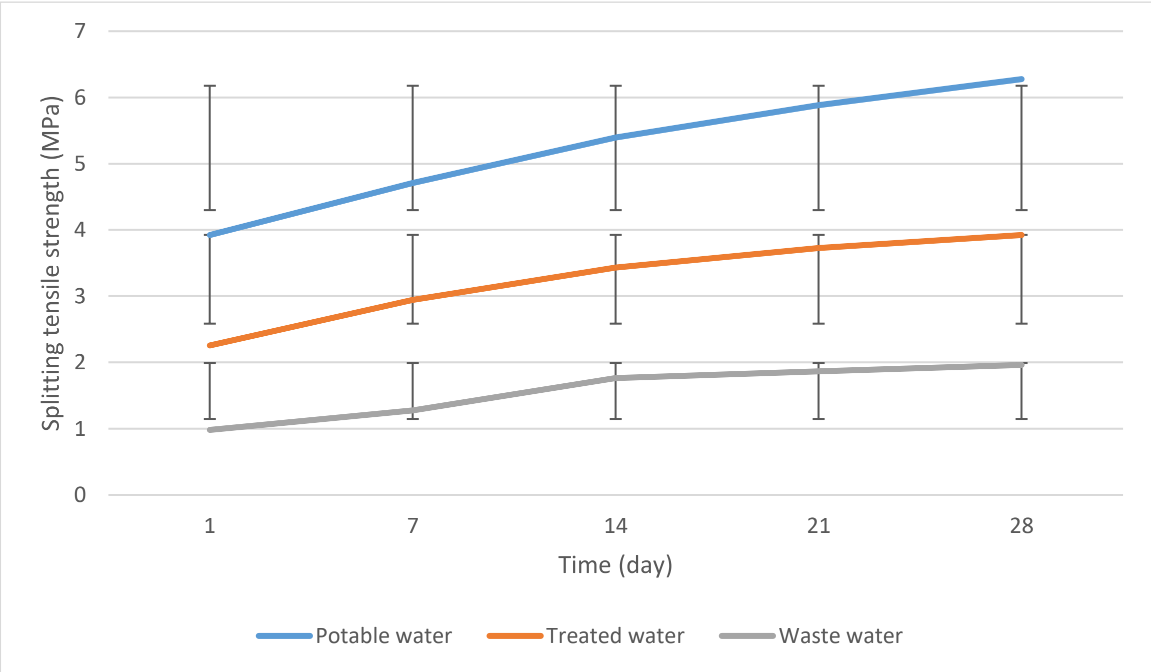


Figure 2.9: Relation of curing time and splitting tensile strength for concrete made from various types of water.
Source: Mahasneh (2014)

Mahasneh's (2014) results appear to show that treated water and potable water differed greatly in composition even though chemically the composition of treated water is very similar to that of potable water (this is shown and discussed in detail in Chapter 4). Therefore, there needs to be a scientific reason for why there is a noticeable drop in the strength of concrete mixed using treated water.

Even though there is a decrease in strength outcomes between concrete mixed with potable water and concrete mixed with treated water, ASTM specifications allow for treated water to be used in the place of potable water (Mehr and Ghatte, 2019). Mahasneh's (2014) results demonstrated that treated water may be utilised during concrete production instead of potable water. The splitting tensile strength and compressive strength obtained by Mahasneh (2014) from the use of treated water in concrete differed by no more than 40 % from the figures that were obtained when using potable water.

2.7 Properties of expanded polystyrene concrete vs conventional concrete

EPS concrete is a type of concrete that carries numerous environmental and structural benefits and was therefore considered for this study.

EPS foam is a polymer that is regarded as a thermoplastic due to its insulation properties (Assaad and Mir, 2020). EPS has a closed cellular structure (Cronin and Ouellet, 2016) and is biologically inert and not toxic. Due to the capillary absorption coefficient of EPS, the inclusion of EPS in mortars improves their durability (Assaad and Mir, 2020).

Hernandez-Zaragoza et al. (2013) conducted an investigation in Mexico into the strength of cellular concrete using mortar mixed with recycled EPS beads instead of sand. After calculating the tensile stresses, absorption and compressive strength of the samples, the researchers concluded that the bricks tested met the masonry standards as per Mexico's requirements.

When EPS beads are used as a substitute for conventionally mined aggregates, the concrete that is produced is found to have densities that vary from 1 500 kg/m^3 to 2 000 kg/m^3 (Tayal et al., 2018). The compressive strength variances for such concrete is from 10 MPa to 21 MPa (Tayal et al., 2018).

Hernandez-Zaragoza et al. (2013) tested two specimens of EPS concrete in order to investigate their absorption potential as well as their average rupture stress. The specimens were labelled as 'Brick A' and 'Brick B' with dimensions of 100 mm × 200 mm × 60 mm. Brick A had a weight of 0.600 kg of EPS and a water-to-cement ratio of 0.4, and the results for Brick A were captured at 28 days. Brick B contained 0.520 kg of EPS and a water-to-cement ratio of 0.4. The results for Brick B were captured at 14 days. The results are represented in Table 2.8.

Table 2.8: Specimen A & B versus conventional parameters.

Property	Brick A	Brick B	Burned clay brick	Mortar brick
Dimensions: thickness, width and length (cm)	6, 10, 20	6, 10, 20	5.5, 11.5, 23	18, 12, 38
Volumetric weight (kg/m^3)	1 568	1 236	1 580	1 890
Average absorption (%)	9.3	4.3	17.8	25.2
Compressive strength (MPa)	9.69	6.92	11.16	4.69

Average rupture stress (MPa)	2.94	1.65	0.755	0.794

Source: Hernandez-Zaragoza et al. (2013)

The findings of this investigation showed that when EPS is used in the production of concrete, the resultant product may be used as masonry blocks in the construction industry.

The strength and durability characteristics of EPS concrete depend on the quantity of each constituent as well as the type of superplasticiser that has been used in the mix. Although increasing the EPS content may improve the flexural modulus of the concrete, an excessive amount leads to a reduction in compressive strength (Ali and Ansari, 2013). In order to achieve a concrete strength of between 60 MPa to 70 MPa, Ali and Ansari (2013) found that the best range of substitution for cement with polymers should be between 12 % and 14 %. This not only ensures that a workable mix is attained, but also that the mix is mechanically sound. Table 2.9 tabulates the differences between EPS concrete and conventional concrete made from unsubstituted ordinary Portland cement. One of the biggest differences between EPS concrete and conventional concrete is that EPS concrete is highly resistant to chemicals and moisture (Ali and Ansari, 2013).

Table 2.9: Properties of conventional concrete made with Portland cement versus EPS concrete also made with Portland cement.

Property	Portland Cement Concrete	EPS Concrete
Compressive	10 MPa to 60 MPa	40 MPa to 150 MPa
Flexural strength	1.5 MPa to 7 MPa	4 MPa to 50 MPa
Tensile strength	0.6 MPa to 3.0 MPa	4 MPa to 20 MPa
Water absorbability	4 % to 10 %	0.5 % to 3 %
Chemical resistance	Poor to Average	Very Good to Excellent

Source: Ali and Ansari (2013)

Amongst the many benefits and advantages of EPS concrete, the four major ones are: high compressive strength, rapid curing, high specific stiffness, and high resistance to chemical attack. The biggest influencers in the properties of EPS concrete are parameters such as amount and type of polymer used in the mix. Other factors that influence the final characteristics of EPS concrete are the proportions, the moisture content of the aggregates used, and the type of curing methods used (Bedi et al., 2013).

According to the Expanded Polystyrene Association of Southern Africa (2018), EPS concrete is advantageous compared to conventional concrete due to its seismic performance, low density, and thermal insulation. During the production of EPS concrete, EPS beads are easily integrated with mortar to produce a strong lightweight concrete (Chen and Liu, 2004).

The roots of EPS concrete can be traced back to 1972 when Cook (1972) set out to understand how EPS beads could perform when used as aggregate in concrete. In modern day applications EPS concrete has been widely used to form curtain walls, load-bearing blocks, subbase material, cladding, and floating marine structures (Perry et al., 1991).

Chen and Liu (2004) studied the effects of steel fibre and fine silica fume on the properties of EPS concrete. Results showed that with the addition of a maximum of 15 % of fine silica fume, the compressive strength of EPS concrete was increased. Upon analysis of the interaction of the EPS beads with the concrete constituents, Chen and Liu (2004) found that the silica fume improved the diffusion of the EPS beads within the cement paste. Furthermore, the addition of silica fume to EPS concrete yielded the best results when the aggregates were substituted with EPS beads to a maximum of 25 %. When there was a substitution of aggregates by EPS of 55 %, the results showed that even with the addition of silica fume the compressive strength remained very low at 12 MPa, as shown in Figure 2.13 (Chen and Liu, 2004).

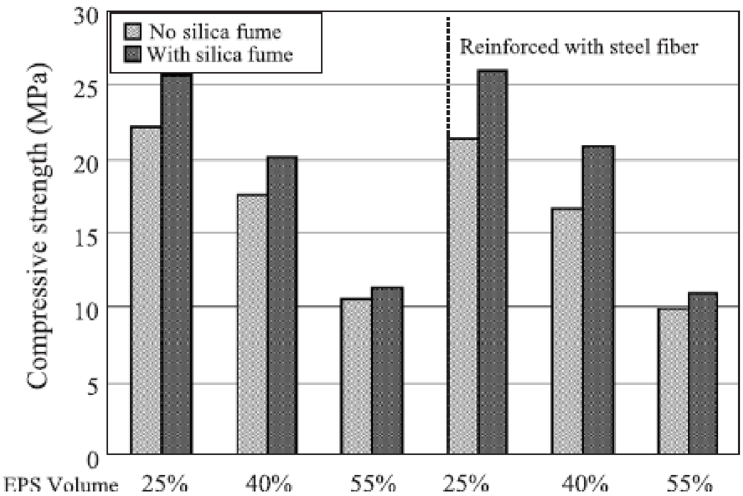


Figure 2.10: Effect of silica fume on the compressive strength of EPS concrete.
Source: Chen and Liu (2004)

2.8 The need to investigate eggshell/EPS concrete further

A review of literature highlighted the following gaps:

1) Most research focused on how much aggregate can be replaced using EPS in the presence of various superplasticisers in a concrete mix. However, there are other factors worth investigating such as whether or not there are other materials which can additionally be substituted in a concrete mix and which can complement the substitution by EPS. The researcher addressed this in the current research by exploring how the inclusion of eggshell powder as a substitute in concrete can complement concrete which includes EPS as a substitute for aggregate.
2) Existing literature regarding eggshell concrete has only looked at the performance of eggshell concrete to a maximum testing period of 28-days. However, it is necessary to also show the longer term performance of the concrete in order to have greater understanding of the strength

qualities of this type of concrete, considering that the concrete mix itself falls outside of conventional norms. This research has addressed this by also performing tests at 90 days.

3) In a world of increasing material scarcity, it is becoming more and more apparent that material re-use is a major theme even in construction. Existing research in both eggshell concrete and EPS concrete neglects the aspect of resource scarcity in relation to water scarcity. Up until now research in both eggshell concrete and EPS concrete has assumed that there are adequate water resources which explains the use of potable water in the respective research studies. Previous research in eggshell concrete and EPS concrete assume the availability of clean potable water in all sectors of society whereas this is not accurate since many poorer societies only have rivers and streams within their localities as their primary source of water for all their needs inclusive of their drinking needs. This research has addressed this by investigating the production of eggshell concrete and EPS concrete using unprocessed river water.

CHAPTER 3: METHODOLOGY

3.1 Research approach

The experimental approach used in this research was that of characterising the different components of concrete with EPS and eggshell powder. EPS and eggshell powder were used in different configurations to partially substitute the various elements in concrete such as coarse aggregate and cement. The mechanical effects of substitution on the concrete samples were interrogated and assessed.

The concrete samples were all subjected to the same curing standards as per SANS 878 (South African National Standards [SANS], 2012) which include curing for 7 days and 28 days. The researcher went further to test a set of concrete samples at 90 days. This was done in order to be able to accurately extrapolate a quarterly growth path of the characterised concrete. The optimal mix ratios for each of the various concrete configurations was obtained by assessment of the samples with the best mechanical property results.

Upon studying the microstructural interactions of each of the samples with the substitutions of EPS and eggshell powder in different configurations, the mixes were also modelled through the representation of mathematical equations. To further investigate the growth trend potential of each tested mix category, regression analysis was conducted in order to compute the estimated values of compressive and flexural strength.

3.2 Materials

The materials used for concrete production were cement, sand (fine aggregate), stone (coarse aggregate), potable water, river water, eggshell powder and EPS. The equipment used to mix these materials was an electric concrete mixer as shown in Figure 3.1.

Figure 3.1: Electric concrete mixer.

3.2.1 Cement

The type of cement used during the research was NPC Original Blue CEM III/A 32.5N cement. NPC Original Blue conforms to the SANS 50197-1 standard (SANS, 2013). This type of cement is used for applications such as concrete, mortar, plaster and any other domestic applications. The relative density of the cement is 2.90.

3.2.2 Aggregates

Coarse aggregate of 19 mm size as well as fine aggregate of river sand was used. Coarse aggregate of 19 mm size is the most popular aggregate that is used in concrete and is used in a variety of construction projects such as road construction.

3.2.3 Water

The potable water used was acquired from the Department of Civil Engineering laboratory, Durban University of Technology. This water was free from any acids/chlorides, organic matter or any alkalis and therefore was in conformity with the minimum requirements for potable water as detailed in SANS 241-1 (SANS, 2015).

The study also investigated the use of natural river water for concrete production. The river water was obtained from the Msunduzi River that runs through Pietermaritzburg (a town in the midlands of the KwaZulu-Natal province).

3.2.4 Expanded polystyrene

EPS was sourced from Iso Moulders in Durban, KwaZulu-Natal. The densities that were used during the experiment were 15 kg/m^3, 20 kg/m^3, and 30 kg/m^3. The EPS beads were all virgin material. The typical characteristic values of EPS are shown in Table 3.1.

Table 3.1: Typical characteristic values of EPS.

	15D	**20D**	**30D**
Density (kg/m^3)	15	20	30
Thermal conductivity at 10 %	0.038	0.035	0.033
Compressive strength (kPa)	70	110	200
Tensile strength (kPa)	200	280	440
Water absorption % Volume	0.5-1.5	0.5-1.5	0.5-1.5
Temperature limits	-110 °C to 70 °C		

Source: Isover (2021)

3.2.5 Eggshell powder

The average eggshell of a chicken weighs 5.5 grams (Butcher and Miles, 2019), therefore 4 182 eggs were used during the research in order to obtain the required 23 kg of eggshell powder. Brown eggshells were used for the experiment as shown in Figure 3.2.

There are commonly two types of coloured eggshells, namely, white and brown (Soria et al., 2013). The eggshell colour is dependent on the chicken that has produced the egg. According to consumer brands such as Get Cracking (2021), “white and brown eggs have no nutritional difference; however, they have a noticeable price variance on store shelves”.

(a) (b)

Figure 3.2: Eggshells used for research during preparation as they were being washed (a) and dried (b).

Although it may not be noticeable with the human-eye, chicken eggshells have pores. Pores allow the eggshell to diffuse metabolic gases as well as water vapour (Hincke et al., 2012). A diagram of the cross-sectional layout of an eggshell is shown in Figure 3.3.

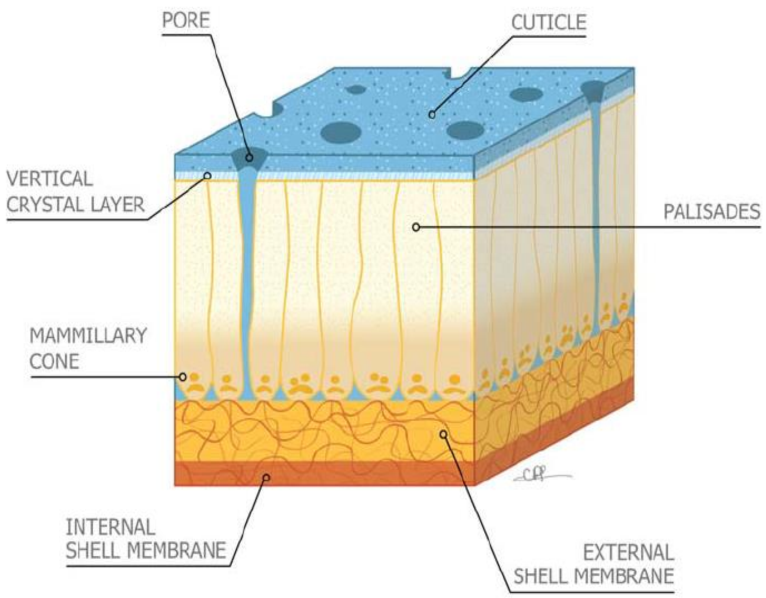


Figure 3.3: Cross-sectional layout of a chicken eggshell.
Source: Hincke et al. (2012)

3.3 Characterisation of materials for concrete production

3.3.1 Sieve analysis of fine and coarse aggregates

Coarse aggregate and fine aggregate were evaluated. The specifications that were used for the sieve analysis are the ASTM C33 (American Society for Testing and Materials [ASTM], 2016) and the SANS 1083 (SANS, 2018). Both specifications are descriptive of the percentage of aggregates that pass the selected set of sieves. The purpose of conducting the sieve analysis was to ensure that the aggregates used for concrete production were in compliance with local norms as well as international standards. Sieves used during the research are shown in Figure 3.4.

Figure 3.4: Sieves used to conduct the sieve analysis.

3.3.2 Fineness modulus of fine aggregates

The fineness modulus of the sand used during the experiment was calculated in order to determine what percentage of sand would be retained on sieves between 4.75 mm and 150 µm. This was conducted in line with SANS 1083 (SANS, 2018).

3.3.3 Moisture content of sand and stone

The importance of determining the moisture content in the stone and sand was to ensure that the overall water content in the concrete remained controlled. Moisture content tests were conducted in line with SANS 3001-GR20 (SANS, 2010).

3.3.4 Apparent relative density of sand and stone

The apparent relative density is the ratio of the mass of air for a specific volume of material (this includes any impermeable voids, but excludes any permeable voids). The apparent relative density of the stone and sand were tested at a temperature of 40 °C as per SANS 3001-AG23 (SANS, 2014b).

The importance of the apparent relative density of aggregate was to determine the compactness of the particles of the aggregates. Aggregate samples with large voids possess less relative density while ones with a compact microstructure have greater relative density (Zhang et al., 2019). The apparent relative density is also commonly referred to as the absolute volume of the aggregate (Zhang et al., 2019).

3.3.5 Bulk density of sand and stone

Bulk density is dependent on a number of factors, including size and particle shape of the aggregate, moisture content, and grading (Gameiro et al., 2014). Bulk density testing of the stone and sand was conducted in order to ascertain the mass of each aggregate. Stone aggregates with a higher bulk density generally have fewer voids to be filled by sand and cement. The bulk density test was conducted in line with SANS 5845 (SANS, 2006a).

3.3.6 pH of water

The pH of water is a measure of how acidic or basic water is (United States Geological Survey, 2019). The pH level range can go from 0 to 14. Any pH less than 7 indicates acidity while a pH greater than 7 indicates a base (United States Geological Survey, 2019). The pH of water is a measure of the relative amount of free hydrogen and hydroxyl ions in water (Rojas-Carbonell et al., 2018). The test for the pH of water was carried out in line with American Public Health Association (APHA) standards (American Public Health Association [AHPA], 1998).

3.3.7 Conductivity of water

The conductivity of water is a measure of the ability of water to pass electrical flow (Thanh et al., 2019). The conductivity of water is dependent on the concentration of conductive ions that are present in the water (Thanh et al., 2019). These conductive ions originate due to inorganic materials such as chlorides, alkalis, carbonate and sulfide compounds, and dissolved salts. The test was conducted in line with APHA (1998) standards.

3.4 Experimental investigation of the mechanical properties of concrete

The mechanical properties of concrete mixes with the substitution of cement with eggshell powder and sand with EPS were investigated by conducting the tests described below.

3.4.1 Slump of fresh concrete

According to Chandwani et al. (2015), slump is a measurement of the workability or consistency of concrete. Slump of concrete is meant to measure how easy it is to either push, mould or smooth out the concrete. Chandwani et al. (2015) state that the slump rating of concrete is an indicator of what construction application the concrete is good for. The higher the slump, the more workable the concrete mix. If the slump of concrete is too low, it will shape with great difficulty.

The concept of viscosity is a measure of how a material performs under stress (Hu and Wang, 2011). For a Newtonian fluid, the relationship may be written as:

$$\tau = \eta D \tag{3.1}$$

where τ is the shear stress, η is the viscosity, and $\boldsymbol{D}$ is the rate of shear or velocity gradient (Rheosense, 2021).

The workability of the concrete mixes for this research was determined in line with SANS 5862-1 (SANS, 2006c).

3.4.2 Bulk density of hardened concrete

The bulk density of concrete is the mass that is necessary for it to fill a container of a unit volume (Bedeković et al., 2019). The bulk density for all the concrete specimens was tested in line with BS 1881 (British Standard Institution, 1983). Bulk density is typically expressed in kilograms per cubic metre (kg/m^3).

3.4.3 Compressive strength of concrete

The compressive strength of any material is defined as the resistance to failure under the action of compressive forces (Vu et al., 2020). Compressive strength is an important parameter to determine the behaviour of a material during service conditions. Compressive strength is calculated by dividing the failure load with the area of application of load, usually after 28 days of curing. The compressive strength test was conducted in line with SANS 5863 (SANS, 2006d). The loading rate for the test specimens was in line with SANS 5863:2006 at 0.3 MPa/s +/- 0.1 MPa/s. The machine used to conduct the compressive strength test is shown in Figure 3.5.

Figure 3.5: Compressive strength testing machine.

3.4.4 Flexural strength of concrete

The flexural strength of concrete is one of the most basic and important properties which greatly affects the extent and size of cracking in structures (Regal and Hanus, 2017). As stated by Regal and Hanus (2017), "Concrete is very weak in tension due to its brittle nature. Hence, it is not expected to resist direct tension, so concrete develops cracks when tensile forces exceed its tensile strength. Therefore, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack". Tensile splitting strength tests were conducted in line with SANS 5864 (SANS, 2006e). The loading rate for the test specimens was in line with SANS 5864:2006 at 0.03 MPa/s +/- 0.01 MPa/s. The machine used to conduct the flexural strength test is shown in Figure 3.6.

Figure 3.6: Flexural strength testing machine.

3.4.5 Morphology and elemental composition of concrete and concrete constituent materials

The characterisation of concrete with different materials brought about a need to understand the microstructural interaction of its constituents. The tests conducted were X-ray diffraction (XRD), energy dispersive x-ray spectroscopy (EDXS or EDS) and scanning electron microscopy (SEM). A Carl Zeiss Augiga Cobra fib-fesem was used to conduct the micro-analyses as shown in Figure 3.7 and Figure 3.8.

SEM uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens (Mohammed and Abdullah, 2018). Mohammed and Abdullah (2018) state that the “signals that derive from electro-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample”.

EDS or EDX is a chemical microanalysis technique used in conjunction with SEM. The detector is typically a lithium-drifted silicon, solid-state device. When an incident x-ray strikes the detector it creates a charge pulse that is proportional to the energy of the x-ray (Mohammed and Abdullah, 2018). The charge pulse is converted to a voltage pulse (which remains proportional to the x-ray energy) by a charge-sensitive preamplifier.

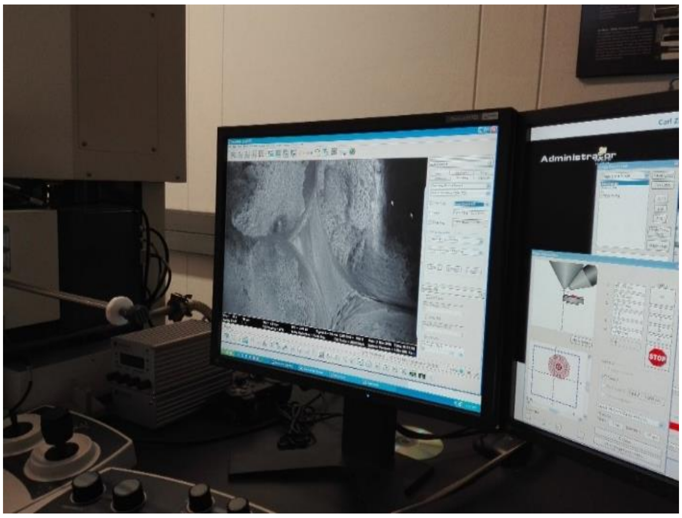


Figure 3.7: Carl Zeiss Agugiga Cobra fib-fesem control station.

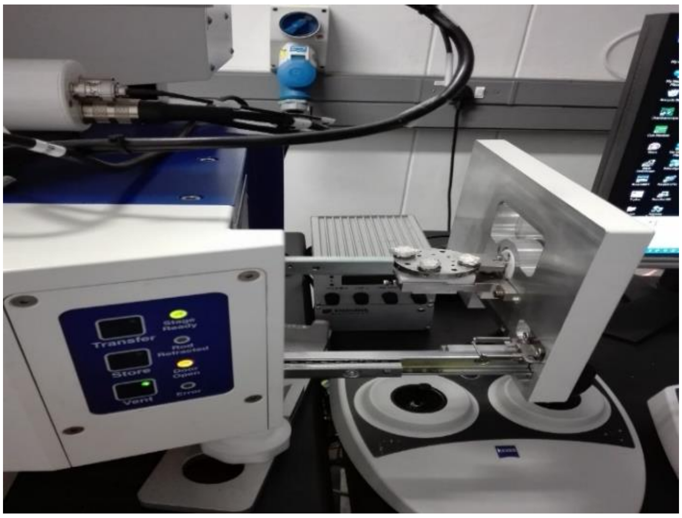


Figure 3.8: Carl Zeiss Agugiga Cobra fib-fesem control station sample feed.

3.5 Evaluation of the optimal mix proportions

Researchers such as Verma and Jain (2020) and Tamut et al. (2014) have shown beyond reasonable doubt that the most suitable percentage to use in substituting coarse aggregate in a concrete mix by EPS is a percentage of between 5 % to 10 %. This assertion is further confirmed by Adeala and Soyemi (2020) and Murugesan et al. (2015) who assert that at a maximum of 10 % replacement of coarse aggregate with EPS, the resultant concrete still has good compressive, tensile and flexural strength. Any substitution that is beyond 10 % produces results which significantly differ from what would be achieved had no EPS been used in the mix. Although numerous researchers have shown the suitability of a preferred substitution bracket of between 5 % to 10 % when coarse aggregate is substituted by EPS, they have only done this within the confines of using potable water as the mixing agent. This research therefore sought to bridge these gaps by investigating how a concrete mix that contains a maximum commonly accepted substitution percentage of 10 % for coarse aggregate by EPS mixed with potable water differs in strength outcomes from a similar mix that has been mixed with non-potable water. The researcher further experimented with how the strength qualities of a concrete mix would fare if the amount of EPS used to substitute coarse aggregate was kept at a lower preferred percentage of 5 % in order to accommodate the use of eggshell powder in substituting cement at 5 %, mixed with non-potable water.

Research thus far has demonstrated a commonly accepted percentage range of 5 % to 10 % when substituting coarse aggregate with EPS, but there are insufficient studies in the sphere of eggshell powder usage in concrete technology to have an acceptable known substitution percentage for its replacement of cement. Therefore this research considered how a concrete mix that contained up to 10 % substitution of cement by eggshell powder performed when not only compared to conventional concrete, but also to a purely EPS concrete mix and to a concrete mix that contained a mixture of both EPS and eggshell powder as substitutes in the concrete mix. To this end, five sets of varying concrete types were produced.

The mix proportion for the various mix designs was in the form of 1:2:3 for cement, sand and stone with the water-to-cement ratio being 0.5, as follows:

1. The first mix was conventional concrete which was considered as the control mix. Conventional concrete that is produced using traditionally recognised materials is the most authoritative reference point of comparison in any matter that pertains to concrete research. Therefore the control mix contained 1 part cement, 2 parts of sand, and 3 parts of stone, mixed with non-potable water in order to produce M20 grade concrete.
2. The second mix category had the stone quantity substituted by 10 % with EPS and clean potable water was used. Therefore the mix had 1 part cement mixed with 2 parts of sand and 2.7 parts of stone along with 0.3 parts of EPS.
3. The third mix category had the same mix proportions as the second mix category, namely, 1 part cement mixed with 2 parts of sand along with 2.7 parts of stone and 0.3 parts of EPS. However, non-potable water in the form of river water was used in the mix in place of potable water.
4. The fourth category mix had the cement quantity substituted with eggshell powder by 5 % and the stone quantity substituted with EPS by 5 % along with the use of river water instead of potable water. The proportions were 0.95 parts of cement mixed with 2 parts of sand along with 2.85 parts of stone, 0.15 parts of EPS and 0.05 parts of eggshell powder.
5. The fifth category mix had cement substituted with eggshell powder by 10 % and river water was used in the mix in place of potable water. The proportions were 0.9 parts of cement mixed with 2 parts of sand along with 3 parts of stone and 0.1 parts of eggshell powder.

Each of the concrete samples were cured to three different ages, namely, 7 days, 28 days and 90 days.

Each mix category had 18 samples each, of which 9 samples were tested for compressive strength and 9 for flexural strength. The total number of 150 mm x 150 mm x 150 mm cubes tested for compressive strength was 45 cubes. The total number of 100 mm x 100 mm x 500 mm beams tested for flexural strength was 45.

The mix design quantities for the various mix categories in terms of mass are represented in Tables 4.60, 4.63, 4.66, 4.69 and 4.72. The varying quantities of materials such as eggshell powder and EPS were measured to the desired weights in terms of kilograms as shown in Tables 4.60, 4.63, 4.66, 4.69 and 4.72. Upon reaching the desired quantities, mixing was carefully managed in order to ensure that all the materials blended well together. Upon mixing all the materials together, the combined weight of each mix was verified in order to ensure that there was no loss of any of the constituent materials.

The best mix in terms of the substituted materials for the five mix categories was determined by assessing which of the mixes resulted in the highest compressive and flexural strength. The growth trend potential of each tested mix category was investigated using logarithmic regression in order to capture the estimated values of compressive and flexural strength for ages which were not physically tested. Logarithmic regression is a statistical method that is used to estimate the value of a variable based on the value of another variable. An important part of using logarithmic regression is firstly the determination of whether the data to be analysed can be analysed using logarithmic regression. This forms part of the assumptions of logarithmic regression such as linearity which were checked during the research using methods such as scatter plots in order to ascertain the appropriateness of using logarithmic regression. The variable that is to be estimated is called the dependent variable. The variable that is being used to estimate the other variable's value is called the independent variable (Stanton, 2001).

CHAPTER 4: CHARACTERISATION OF MATERIALS FOR CONCRETE PRODUCTION

4.1 Introduction

The role played by stone aggregate as well as fine aggregate in concrete is the main reason why concrete possesses so much strength. However, due to the over-exploitation and depletion of natural resources, it is essential to investigate the combination and qualities of various alternative materials. The characterisation of concrete with eggshell powder and EPS was therefore investigated.

4.1.1 Sieve analysis of sand and stone samples

In order to ensure that the fine aggregate and the coarse aggregate that were used for the research were in compliance with SANS 1083 (SANS, 2018), the fine and coarse aggregates were tested by way of a sieve analysis in order to ensure that any material that was not compliant was sieved out and that the remaining material was compliant.

The initial sieve analyses for both fine aggregate and coarse aggregate was in accordance with SANS 1083 (SANS, 2018) which states that any aggregate that is intended for use in concrete must be of one of the classes stipulated below:

a) Aggregate produced by the regular fragmentation of rock;
b) Aggregate formed by the motorised crushing or grinding of rock; and
c) Aggregate obtained from a blend of (a) and (b) above.

Both the fine aggregate and the coarse aggregate that were used in this research were produced by regular fragmentation of rock and therefore were in line with the requirements of SANS 1083 (SANS, 2018).

The definition of fine aggregate as per SANS 1083 (SANS, 2018) states that the particle size of fine aggregate must be such that "at least 90 % of its mass passes a sieve that has a square aperture of nominal size of 4 750 µm or 5 mm as referenced in SANS 3001-AG1 (SANS, 2014a) and is retained on a sieve that has square apertures of nominal size 75 µm".

When initially tested, only 77.8 % of the fine aggregate fragmented rock passed through a sieve that has a square aperture of nominal size of 4 750 µm or 5 mm, instead of 90 %. This was due to the material at source containing a high volume of coarser material within its composition. The results are represented in Figure 4.1. Material was sieved several times and only suitable material that met the minimum threshold of 90 % as specified by SANS 1083 (SANS, 2018) was used for the research.

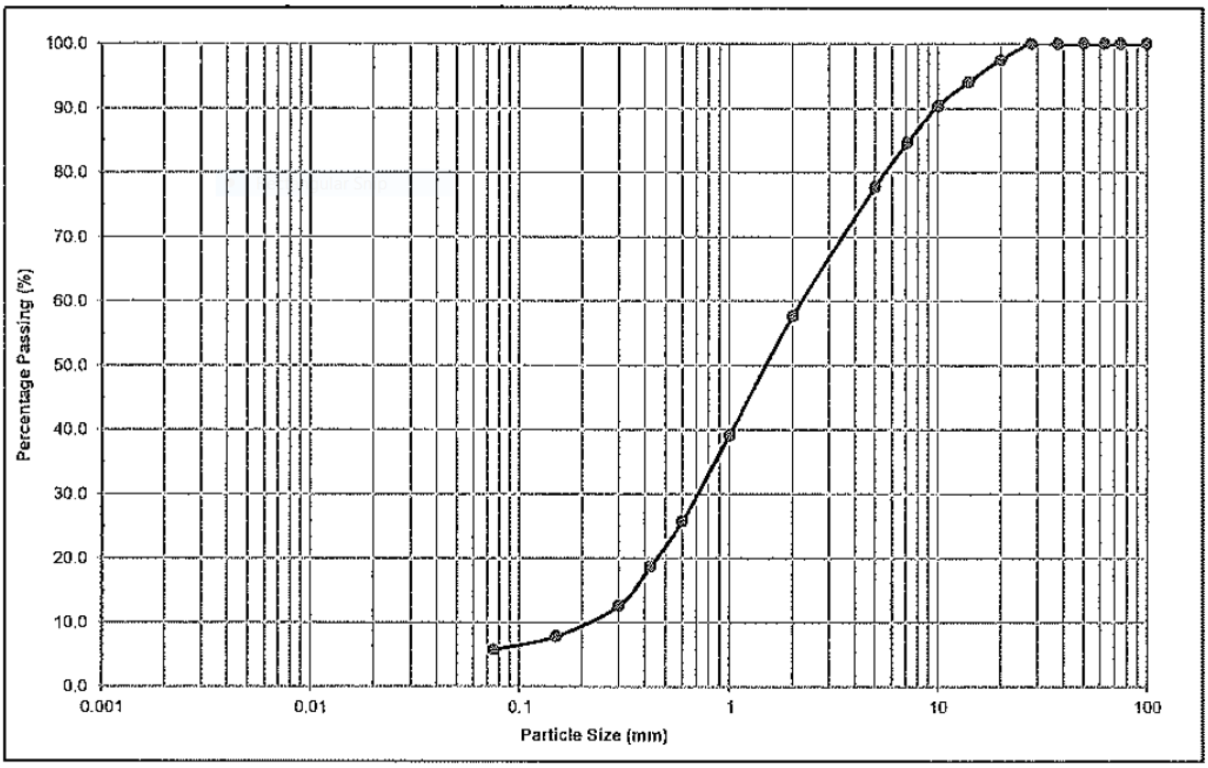


Figure 4.1: Sieve analysis of percentage passing versus particle size for fine aggregate.

The definition of coarse aggregate as per SANS 1083 (SANS, 2018) states that coarse aggregate should be of particle size such that it is retained on a sieve that has square apertures of nominal size either 4 750 µm or 5 mm as referenced in SANS 3001-AG1 (SANS, 2014a). When initially tested from the source, only 22.8 % of the coarse aggregate passed a sieve that has a square aperture of nominal size of 4 750 µm or 5 mm. This was due to the material at source having a high volume of coarser material within its composition. The results are represented in Figure 4.2. Material was sieved several times and only suitable material that met the minimum threshold as specified by SANS 1083 (SANS, 2018) was used for the research.

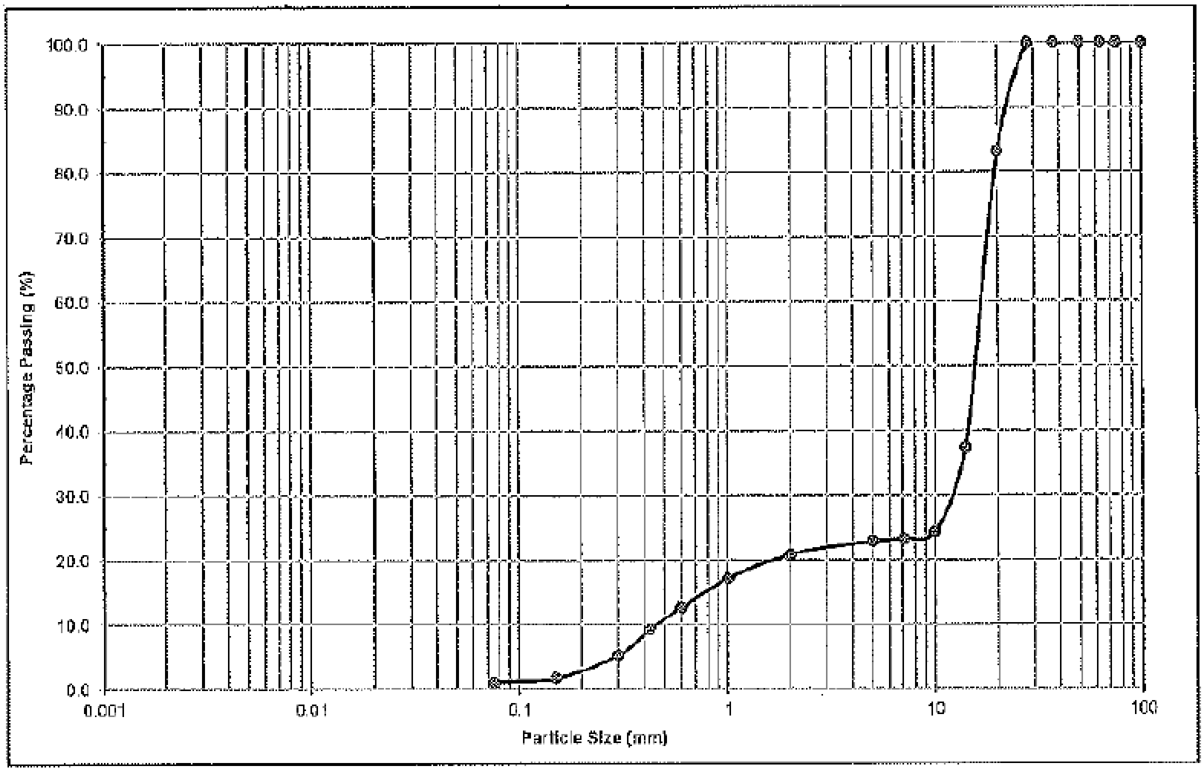


Figure 4.2: Sieve analysis of percentage passing versus particle size for coarse aggregate.

4.1.2 Fineness modulus of fine aggregate and coarse aggregate

The fineness modulus that was obtained for fine aggregate was 3.8. This is represented in Table 4.1. The fine aggregate used for all the samples was a coarse sand. Classification of the fineness modulus as well as the physical characteristics of the sand sample revealed that it fell within the coarse sand range.

Table 4.1: Fineness modulus analysis for fine aggregate.

Sieve analysis (% Passing)	100.0 mm	100.0
	75.0 mm	100.0
	63.0 mm	100.0
	50.0 mm	100.0
	37.5 mm	100.0
	28.0 mm	100.0
	20.0 mm	97.5
	14.0 mm	94.1
	10.0 mm	90.4
	7.1 mm	84.6
	5.00 mm	77.8
	2.00 mm	57.7
	1.00 mm	39.2
	0.600 mm	25.8
	0.425 mm	18.7
	0.300 mm	12.6

	0.150 mm	7.8
	0.075 mm	5.7
Fineness Modulus		3.8

The fineness modulus that was obtained for coarse aggregate was 5.2. This is represented in Table 4.2. The coarse aggregate used for all the samples was partially flaky in nature. Classification of the fineness modulus as well as the physical characteristics of the coarse aggregate revealed that it fell within the coarse stone aggregate range.

Table 4.2: Fineness modulus analysis for coarse aggregate.

Sieve analysis (% Passing)	100.0 mm	100.0
	75.0 mm	100.0
	63.0 mm	100.0
	50.0 mm	100.0
	37.5 mm	100.0
	28.0 mm	100.0
	20.0 mm	83.2
	14.0 mm	37.4
	10.0 mm	24.3
	7.1 mm	23.2
	5.00 mm	22.8
	2.00 mm	20.8
	1.00 mm	17.1
	0.600 mm	12.6
	0.425 mm	9.2
	0.300 mm	5.2
	0.150 mm	1.6
	0.075 mm	1.0
Fineness Modulus		5.2

4.1.3 Physical properties of fine aggregate

Surface texture, moisture content, apparent relative density, particle shape and compacted bulk density for fine aggregate are shown in Table 4.3. The moisture content of fine aggregate was found to be 1.17 %. All the fine aggregate that was used was oven dried at 110 ℃ in order to ensure that it was completely dry for usage in the production of the concrete samples.

Table 4.3: Physical properties of fine aggregate.

Characteristics	**Results**
Surface texture	Coarse
Compacted bulk density (kg/m^3)	1664
Uncompacted bulk density (kg/m^3)	1507
Particle shape	Irregular
Relative density	2.69

Moisture content (%)	1.17

4.1.4 Physical properties of coarse aggregate

Surface texture, moisture content, apparent relative density, particle shape and compacted bulk density for the coarse aggregate are shown in Table 4.4. The moisture content of coarse aggregate was found to be 0.52 %. All coarse aggregate that was used was oven dried at 110 ℃ in order to ensure that it was completely dry for usage in the production of the concrete samples.

Table 4.4: Physical properties of coarse aggregate.

Characteristics	**Results**
Surface texture	Coarse
Compacted bulk density (kg/m^3)	2072
Uncompacted bulk density (kg/m^3)	1942
Particle shape	Irregular
Relative density	2.91
Moisture content (%)	0.52

4.1.5 Mixing proportions and mixing strategy

In this study there were a total of five concrete mixes. All the mixes were mixed according to the mix ratio of 1:2:3. The water-to-cement ratio that was used was 0.5 which is a similar ratio used in other research studies investigating concrete for use in construction. Ede et al. (2017) state that it is possible to opt for a concrete ratio of either 1:2:4, 1:2:3 or 1:3:6, depending on the purpose. The ratio of 1:2:4 is a suitable mix for what can be considered to be normal average strength concrete. The ratio of 1:2:3 is suitable for construction related purposes, while the ratio of 1:3:6 is not suitable for casting of major structural elements since it often yields the lowest compressive strength out of the three different mix ratios. An electronic mixer was used to mix all the different mixes and is shown in Figure 4.3a. An example of the concrete samples produced is shown in Figure 4.3b.

Figure 4.3a: Electronic concrete mixer.

Figure 4.3b: An example of the concrete samples produced.

All the concrete mixes were produced according to SANS 5861-1 (SANS, 2006b) guidelines. The only two components that remained constant in quantity in all the five different mixes were the water-to-cement ratio as well as the sand content. A portion of the stone quantity for mix 2, mix 3 and mix 4 were substituted by EPS, and a portion of the cement for mix 4 and mix 5 was substituted by eggshell powder. Only mix 2 was mixed using potable water, while the control mix as well as mix 3, mix 4 and mix 5 were mixed using river water. Concrete mix 1 was the control mix for the research with the main focus of the research being mix 2, mix 3, mix 4 and mix 5.

4.2 Morphology and chemical compositions of concrete constituents

The morphology of the crushed concrete samples that included components such as eggshell powder, EPS, cement, sand and stone are discussed in the following section.

4.2.1 Visual section of each concrete mix

In order to better understand the interaction of all the different materials within the different concrete samples, it was necessary to break each sample into a sectional piece. From the section of mix 1 (Figure 4.4) it is evident that all the concrete constituents appeared to be moderately represented hence appeared to be much denser than the other samples. The sectional piece of concrete mix 2 (Figure 4.5) had visibly less stone which was due to the replacement of a portion of the stone with EPS. The sectional piece of concrete mix 3 (Figure 4.6) was similar in appearance to concrete mix 2 since the mix ratios were identical except that the hue of concrete mix 3 was a darker shade than that of concrete mix 2, due to the use of river water for mix 3 instead of potable water. The sectional piece of concrete mix 4 (Figure 4.7) parted in an irregular manner compared to the other concrete mixes. This was due to the reduced quantity of cement and the introduction of eggshell powder as a replacement for a portion of the cement. This can also be seen for the last mix, mix 5 (Figure 4.8). However, mix 5 broke off much more easily compared to mix 4, this being due to the use of an increased quantity of eggshell powder in mix 5 compared to mix 4.

Figure 4.4: Concrete sample of mix 1.

Figure 4.5: Concrete sample of mix 2.

Figure 4.6: Concrete sample of mix 3.

Figure 4.7: Concrete sample of mix 4.

Figure 4.8: Concrete sample of mix 5.

4.2.2 Morphology of eggshell powder in comparison to cement

Eggshell powder as well as NPC Original Blue CEM III/A 32.5N cement was studied under microscopic conditions through SEM. The purpose of this was to investigate the topography as well as the microscopic structure of both materials in terms of their void potential. The magnification of eggshell powder as shown in Figures 4.9, 4.11, 4.13 and 4.15 shows that voids are present throughout all the observed points under SEM. This differs significantly from what was observed for cement since very few voids were observed for cement as shown in Figures 4.10, 4.12, 4.14 and 4.16.

Eggshell powder	**NPC Original Blue CEM III/A 32.5N Cement**
1 µm	

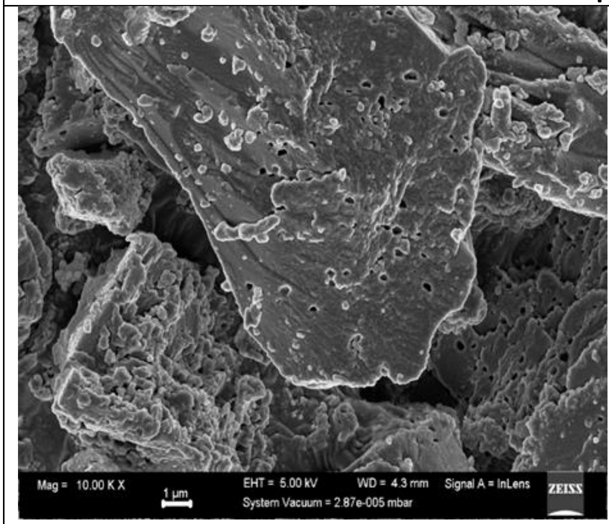
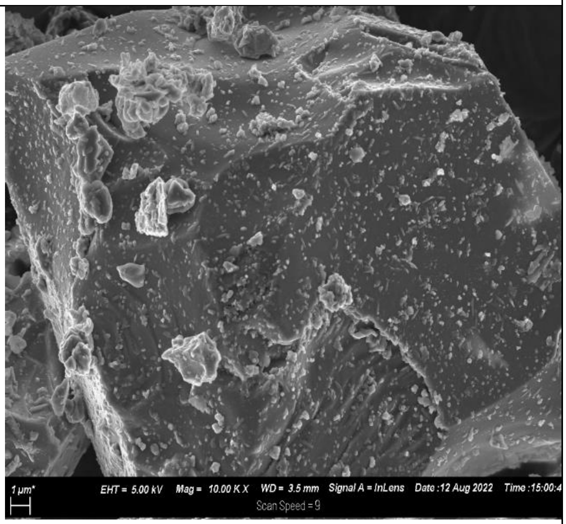

	

Figure 4.9: 1 µm image of eggshell powder (angle 1).	**Figure 4.10: 1 µm image of cement (angle 1).**

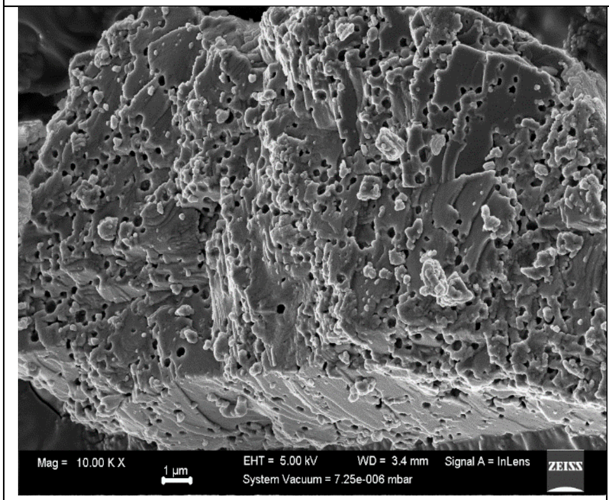
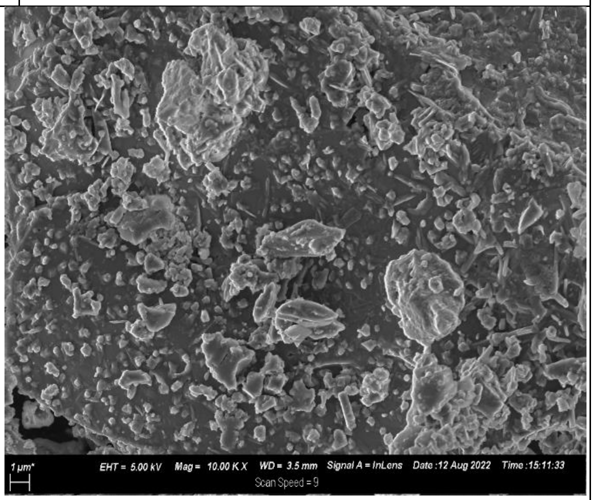

	

Figure 4.11: 1 µm image of eggshell powder (angle 2).	**Figure 4.12: 1 µm image of cement (angle 2).**

2 µm

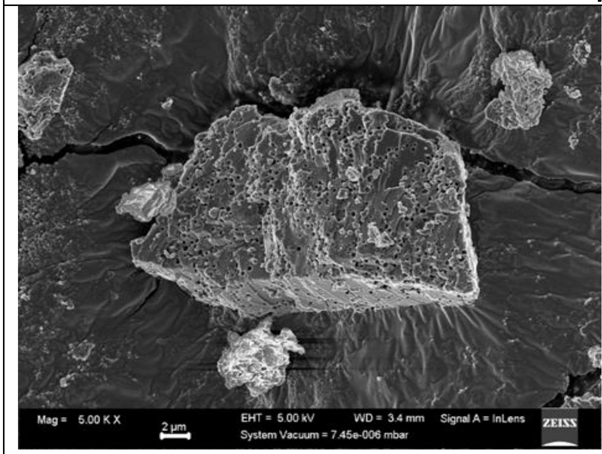


Figure 4.13: 2 µm image of eggshell powder.

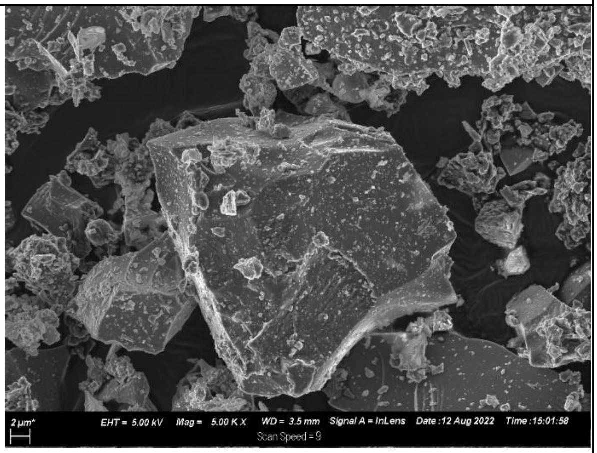


Figure 4.14: 2 µm image of cement.

200 nm

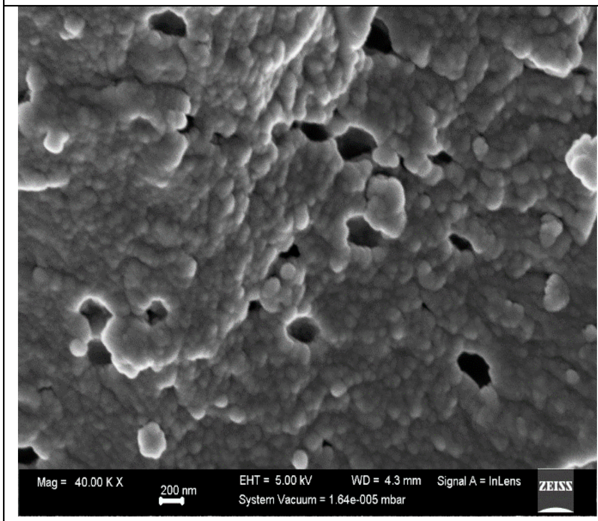


Figure 4.15: 200 nm image of eggshell powder.

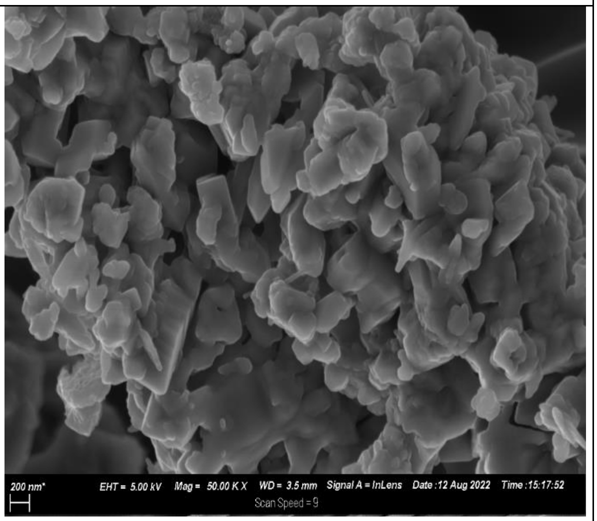


Figure 4.16: 200 nm image of cement.

In later sections of this chapter the results of the compressive and flexural tests show that the control mix on average achieved slightly higher strength values than the experimental samples of mix 2 to mix 5. This may be due to the arrangement of the micro-structural constituents in NPC Original Blue CEM III/A 32.5N cement in which not many voids were observed at the chosen points on the sample.

4.2.3 Chemical composition of concrete materials

The XRD scans were conducted on cement, sand, stone and eggshell powder to examine the percentage of relative chemicals present in each material. Enlarged XRD images are shown in Annexure A.

4.2.3.1 Stone

The XRD results show that the mineral constituents of the stone were quartz, albite, microcline, calcite, muscovite, and kaolinite. The most common mineral constituent was quartz at a percentage of 80.2 %, as shown in Figure 4.17.

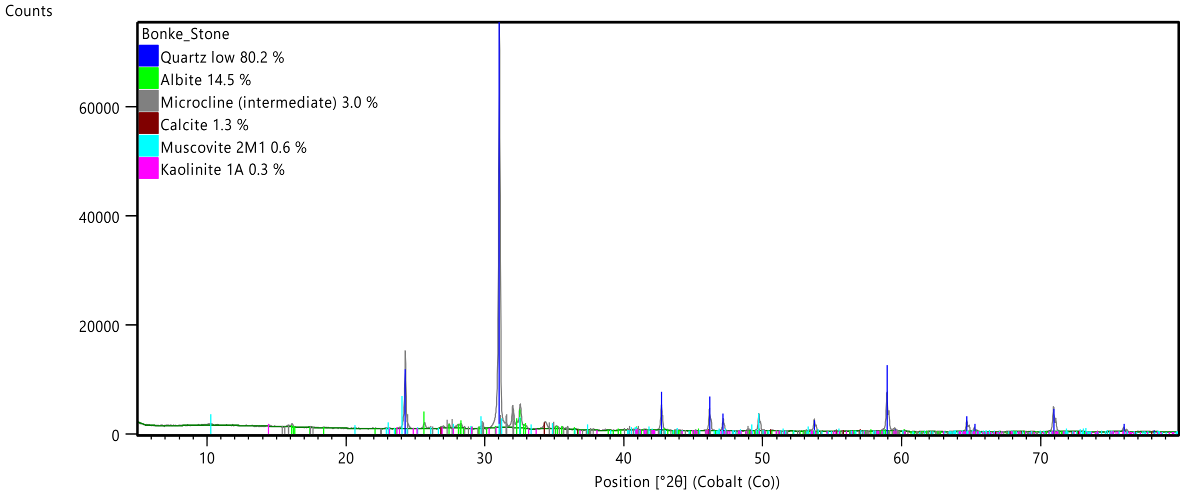


Figure 4.17: XRD analysis of stone sample.

4.2.3.2 River sand

The XRD results show that the mineral constituents of river sand were quartz, albite, microcline, and muscovite. The most common mineral constituent was quartz at a percentage of 97.7 % as shown in Figure 4.18.

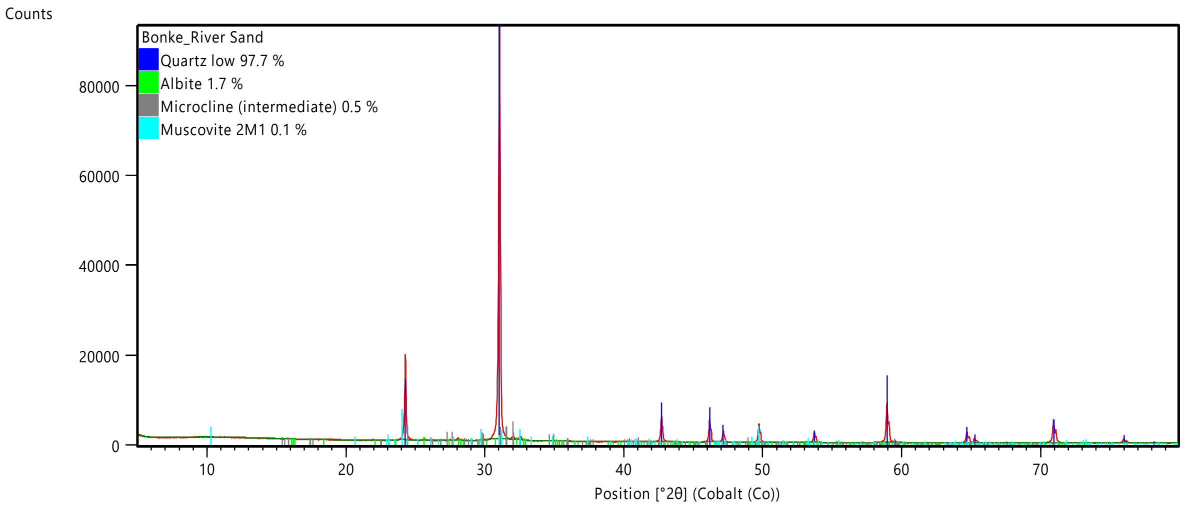


Figure 4.18: XRD analysis of sand sample.

4.2.3.3 Eggshell powder

The XRD results show that there was only one mineral present in eggshell powder, namely, calcite. The XRD graph for eggshell powder is shown in Figure 4.19.

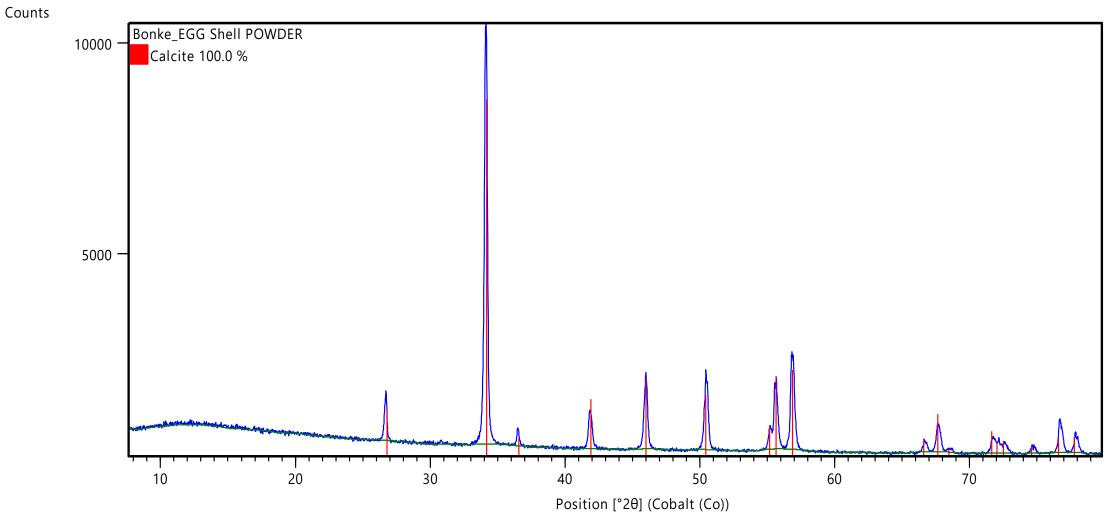


Figure 4.19: XRD analysis of eggshell powder sample.

4.2.3.4 Cement

The XRD results show that the mineral constituents of cement were alite, belite, ferrite, cubic, ortho, freelime, portlandite, periclase, arcanite, aphthitalite, calciolangbeinite, gypsum, bassanite, anhydrite, calcite, quartz, and mullite. The most common mineral constituent was alite at a percentage of 47.3 % as shown in Figure 4.20.

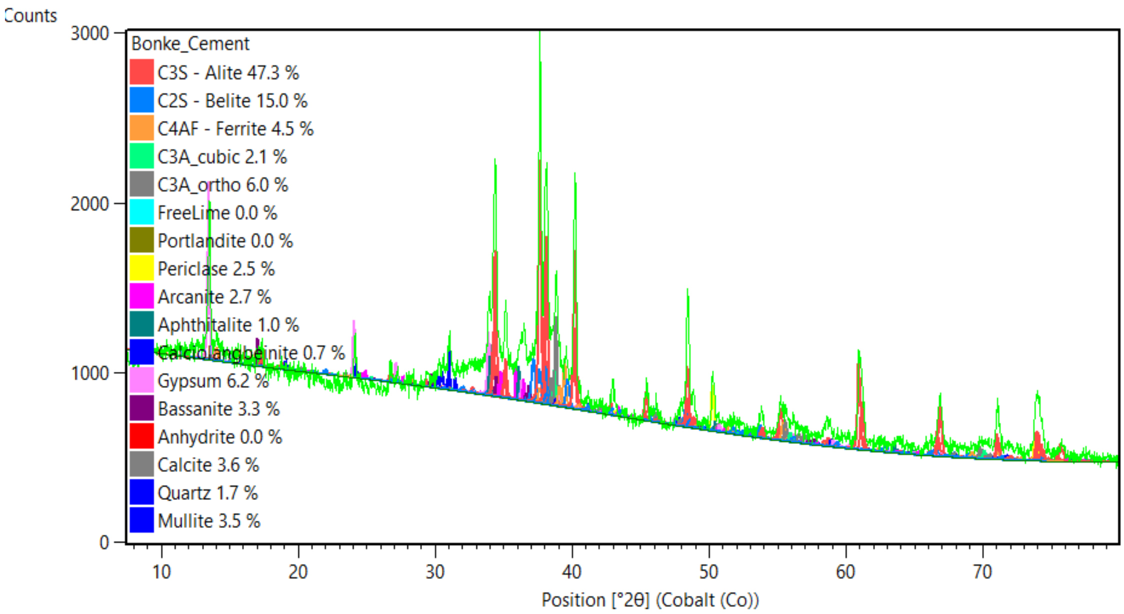


Figure 4.20: XRD analysis of cement powder sample.

The XRD scans reveal that eggshells contain 100 % calcite as also shown in Figure 4.19. The XRD scans also show that calcite exists within cement at a proportion of 3.6 % and in stone at 1.3 %.

4.2.4 Elemental composition of concrete constituents

EDS was used to obtain the weight and atomic percentage of stone, river sand and cement. Elemental concentrations were also collected during the process in order to be able to visualize the distribution of the constituent elements.

4.2.4.1 Stone

The EDS of stone in Table 4.5 shows that the greatest atomic percentage was that of oxygen. According to Independent (2013), oxygen is an important binder in concrete structures since it ensures that the compounds within concrete hold their rigidity.

Table 4.5: Energy dispersive x-ray spectroscopy of stone material.

Element line	Weight %	Weight % error	Atom %	Atom % error
C K	15.70	± 0.67	24.50	± 1.05
O K	39.84	± 0.34	46.66	± 0.40
Al K	1.34	± 0.08	0.93	± 0.06
Si K	40.43	± 0.19	0.97	± 0.13
Si L	-	-	-	-
K K	0.28	± 0.04	0.13	± 0.02
K L	-	-	-	-
Fe K	2.41	± 0.29	0.81	± 0.10
Fe L	-	-	-	-
Total	100.00	± 0.67	100.00	± 1.05

Corresponding concentration mapping of the stone specimens as shown from Figure 4.21a to Figure 4.21e illustrates how the dispersion patterns of each element differ. The results show that silicon was the most agglomerated element at the test point within the stone specimen tested compared to the other identified elements.

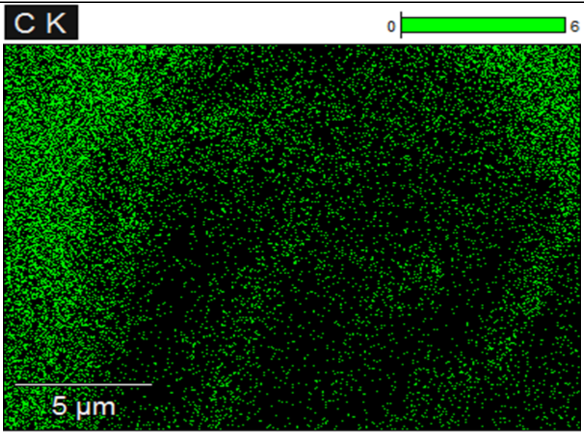


Figure 4.21a: Distribution of carbon.

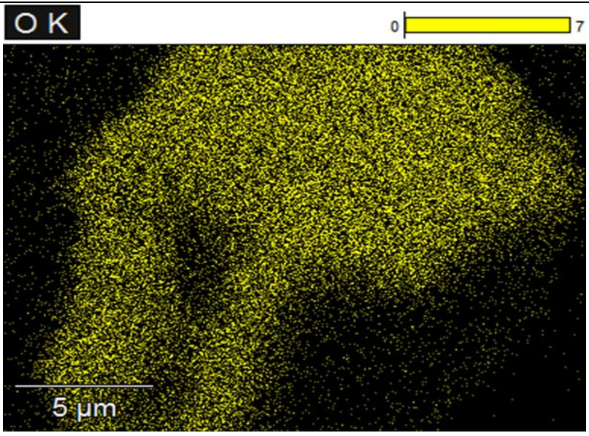


Figure 4.21b: Distribution of oxygen.

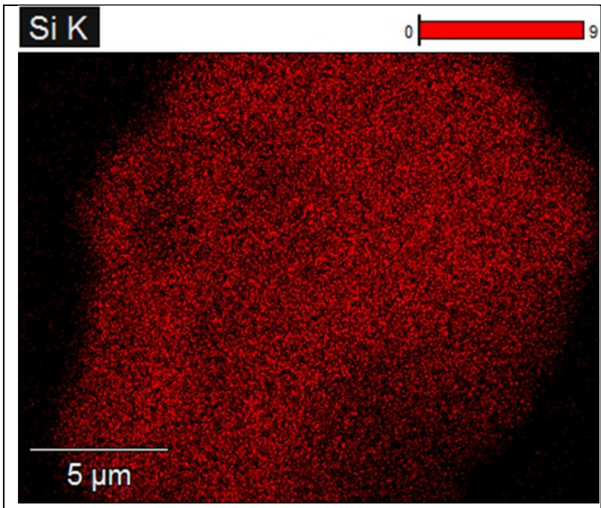


Figure 4.21c: Distribution of silicon.

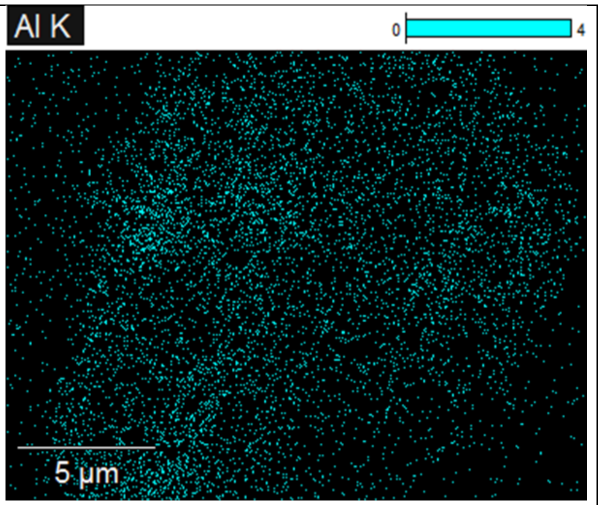


Figure 4.21d: Distribution of aluminium.

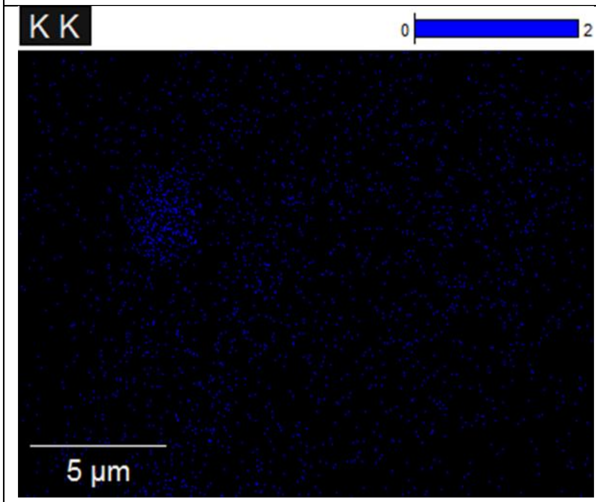


Figure 4.21e: Distribution of potassium.

4.2.4.2 River sand

The EDS of the river sand in Table 4.6 shows that the greatest atomic percentage was that of oxygen.

Table 4.6: Energy dispersive x-ray spectroscopy of river sand material.

Element line	**Weight %**	**Weight % error**	**Atom %**	**Atom % error**
C K	13.98	± 0.17	22.42	± 0.27
O K	50.07	± 0.37	60.26	± 0.44
Mg K	0.07	± 0.02	0.05	± 0.02
Al K	0.12	± 0.02	0.08	± 0.01
Ca K	35.77	± 0.20	17.18	± 0.10
Ca L	-	-	-	-
Total	100.00		100.00	

Corresponding concentration mapping of the river sand specimen as shown from Figure 4.22a to Figure 4.22g illustrates how the dispersion patterns of each element differ. The results show that oxygen was the most agglomerated element at the test point within the river sand specimen tested compared to the other identified elements.

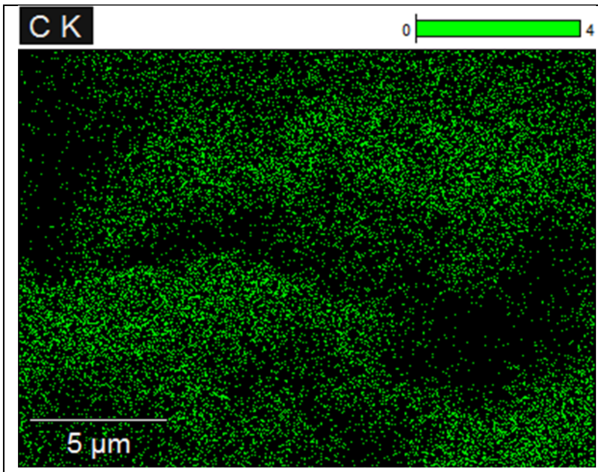


Figure 4.22a: Distribution of carbon.

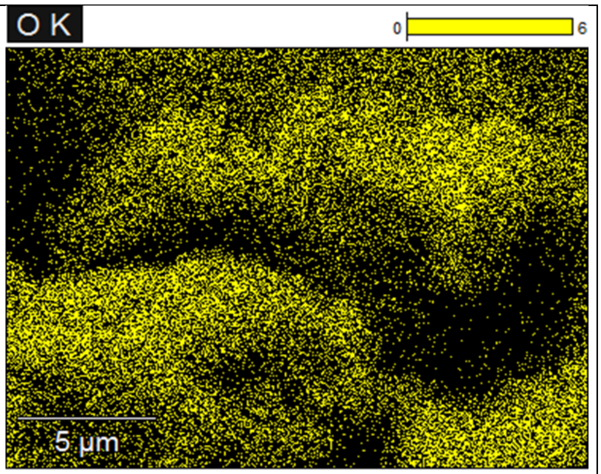


Figure 4.22b: Distribution of oxygen.

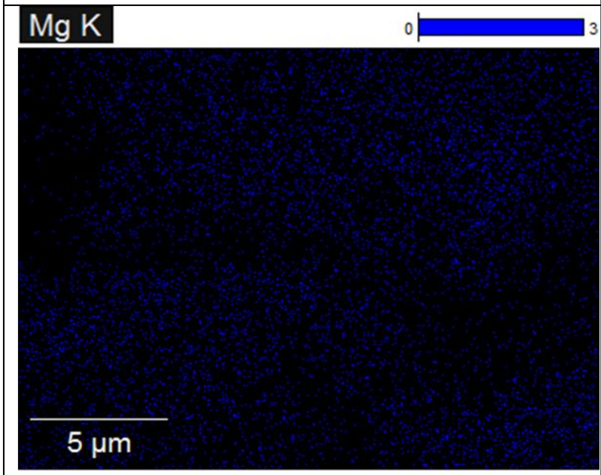


Figure 4.22c: Distribution of magnesium.

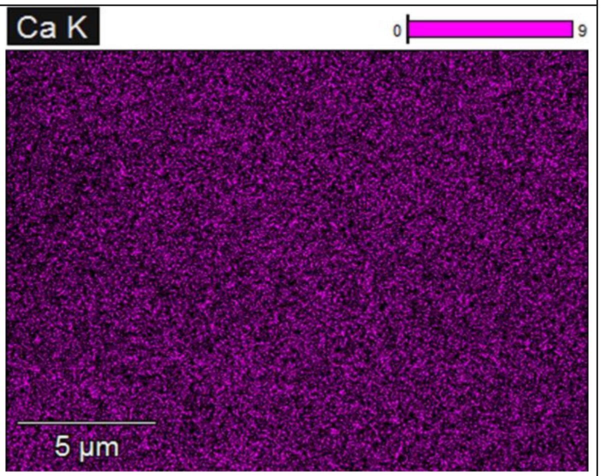


Figure 4.22d: Distribution of calcium.

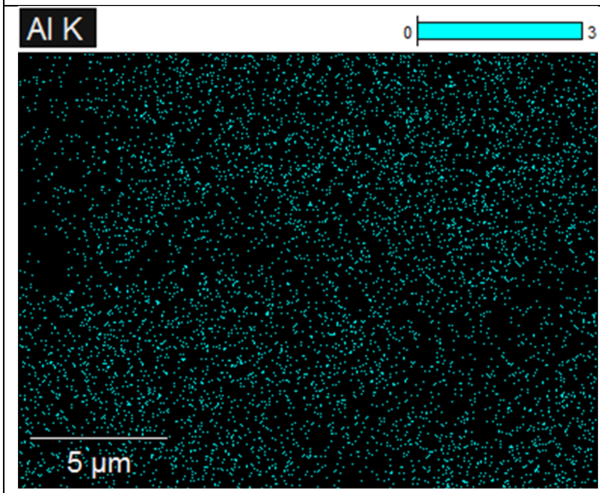


Figure 4.22e: Distribution of aluminium.

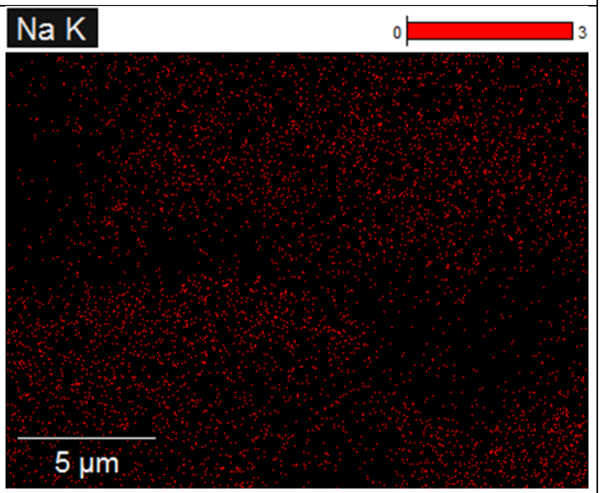


Figure 4.22f: Distribution of sodium.

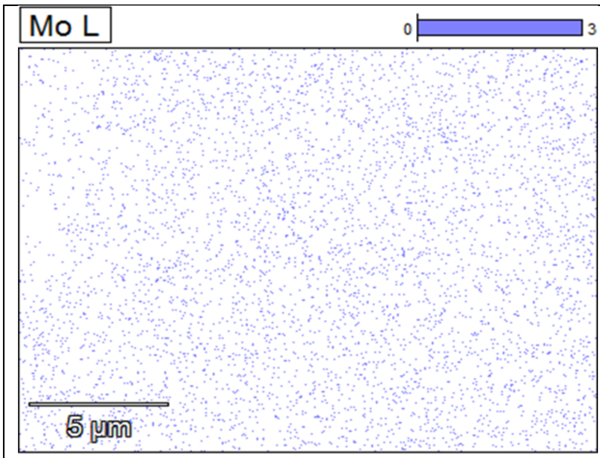


Figure 4.22g: Distribution of molybdenum.

4.2.4.3 Cement

The EDS of cement in Table 4.7 shows that the greatest atomic percentage was that of carbon.

Table 4.7: Energy dispersive x-ray spectroscopy of cement material.

Element line	Weight %	Weight % error	Atom %	Atom % error
C K	44.39	± 0.34	60.18	± 0.46
O K	26.34	± 0.45	26.81	± 0.45
Mg K	0.50	± 0.03	0.33	± 0.02
Al K	2.13	± 0.06	1.28	± 0.04
Si K	3.68	± 0.06	2.14	± 0.04
Si L	-	-	-	-
S K	0.57	± 0.05	0.29	± 0.02
S L	-	-	-	-
K K	0.28	± 0.03	0.12	± 0.01
K L	-	-	-	-
Ca K	20.98	± 0.18	8.52	± 0.07
Ca L	-	-	-	-
Fe K	1.13	± 0.18	0.33	± 0.05
Fe L	-	-	-	-
Total	100.00		100.00	

Corresponding concentration mapping of the cement specimen as shown from Figure 4.23a to Figure 4.23h illustrates how the dispersion patterns of each element differs. The results show that carbon was the most agglomerated element at the test point within the cement specimen tested.

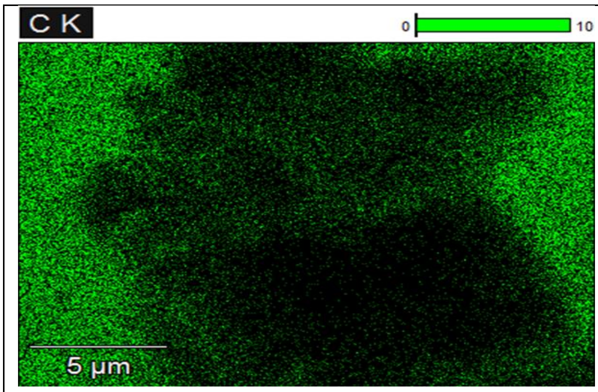


Figure 4.23a: Distribution of carbon.

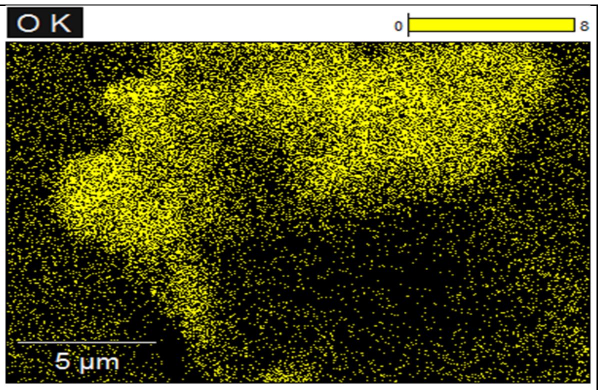


Figure 4.23b: Distribution of oxygen.

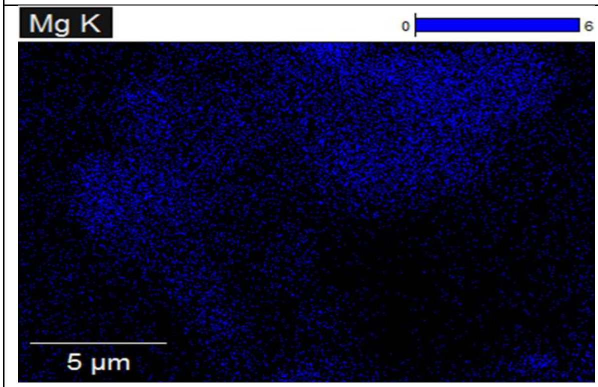


Figure 4.23c: Distribution of magnesium.

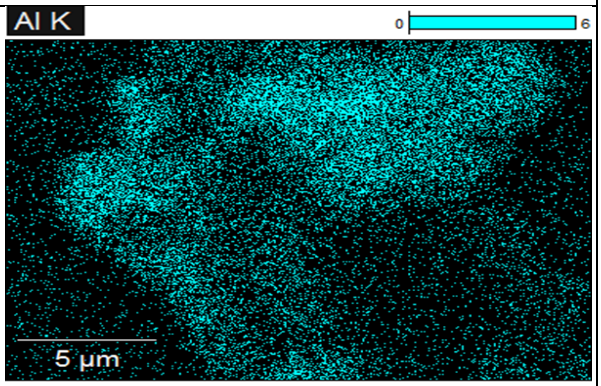


Figure 4.23d: Distribution of aluminium.

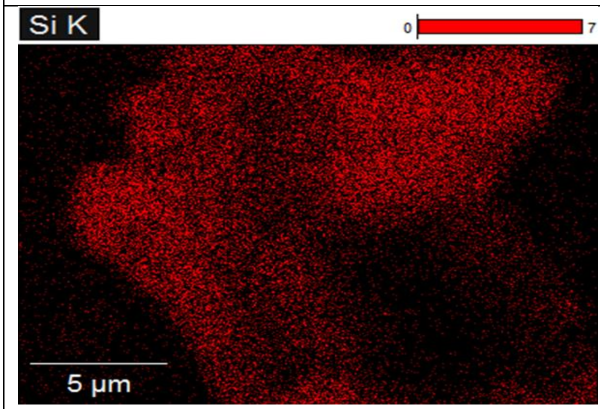


Figure 4.23e: Distribution of silicon.

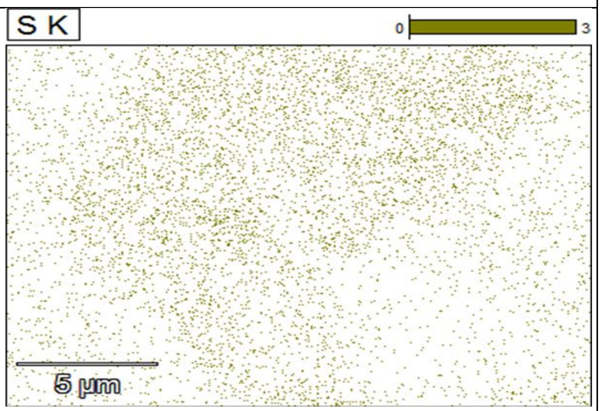


Figure 4.23f: Distribution of sulfur.

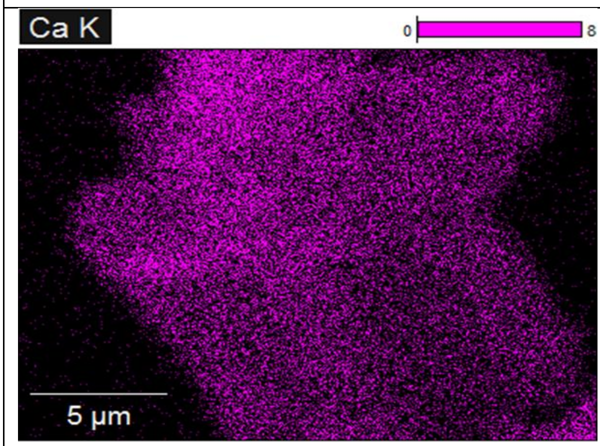


Figure 4.23g: Distribution of calcium.

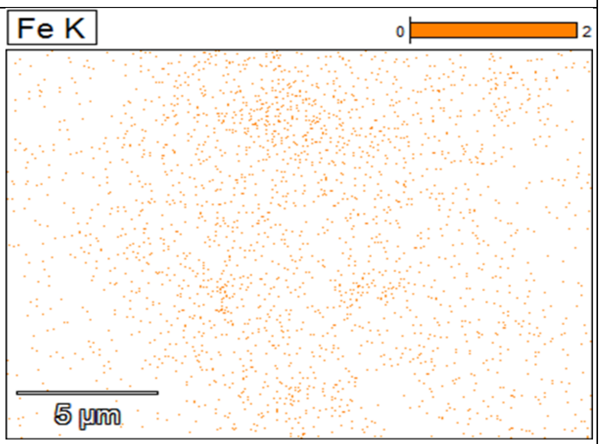


Figure 4.23h: Distribution of iron.

From the XRD conducted on stone, river sand and cement, it is evident that calcium, which is available in eggshell powder, is also available in river sand and cement at an atomic percentage of 17.18 % and 8.52 % respectively. The calcium content of eggshells is significant and is easily accessible as a waste material, so it should be considered for other uses instead of simply being discarded.

4.2.5 Evaluation of water for concrete production

The river water used for concrete sample production was obtained from the Msunduzi river which runs through Pietermaritzburg. The river water used for the control mix as well as for mix 2 to mix 5 was taken from the same source but at different times. The chemical and bacteriological analysis of the river water collected and used for the control mix is shown in Table 4.8. The chemical and bacteriological analysis of the river water collected and used for mix 2 to mix 5 is shown in Table 4.9.

Table 4.8: Msunduzi river water chemical and bacteriological analysis of the river water collected and used for the control mix.

Variable	Units	SANS 241-1:2015 Drinking Water Standard- (SABS, 2015)	Monitoring Localities
			Msunduzi River Water
Physical Variables			
pH @ 25 ℃	pH	5.0/9.7	7.34
Electrical conductivity (EC) @ 25 ℃	mS/m	170	18.4
Total dissolved solids (TDS)	mg/l	1200	107
Chemical Variables			
Chloride (Cl)	mg/l	300	24.2
Sulphate (SO_4)	mg/l	500	6.80
Nitrate (NO_3) as N	mg/l	11	2.84
Ammonium (NH_4) as N	mg/l	1.5	< 0.10
Flouride (F)	mg/l	1.5	< 0.10
Calcium (Ca)	mg/l	-	11.4
Magnesium (Mg)	mg/l	-	7.49
Sodium (Na)	mg/l	200	14.7
Potassium (K)	mg/l	-	1.19
Aluminium (Al)	mg/l	0.3	< 0.15
Iron (Fe)	mg/l	0.3	< 0.10
Manganese (Mn)	mg/l	0.1	1.28
Chromium (Cr)	mg/l	0.05	3.34
Copper (Cu)	mg/l	2	1.34
Nickel (Ni)	mg/l	0.07	2.35
Zinc (Zn)	mg/l	5	< 0.06
Cobalt (Co)	mg/l	-	< 0.20
Cadmium (Cd)	mg/l	0.003	< 0.10
Lead (Pb)	mg/l	0.01	< 1.00
Microbiological Variables			

E.Coli	CFU/100 ml	0	200.5
Total coliform	CFU/100 ml	10	2005

Table 4.9: Msunduzi river water chemical and bacteriological analysis of the river water collected and used for mix 2 to mix 5.

Variable	Units	SANS 241-1:2015 Drinking Water Standard- (SABS, 2015)	Monitoring Localities
			Msunduzi River Water
Physical Variables			
pH @ 25 ℃	pH	5.0/9.7	7.5
Electrical conductivity (EC) @ 25 ℃	mS/m	170	31.8
Total dissolved solids (TDS)	mg/l	1200	196
Chemical Variables			
Chloride (Cl)	mg/l	300	44.9
Sulphate (SO_4)	mg/l	500	13.6
Nitrate (NO_3) as N	mg/l	11	3.48
Ammonium (NH_4) as N	mg/l	1.5	0.127
Flouride (F)	mg/l	1.5	< 0.263
Calcium (Ca)	mg/l	-	17.7
Magnesium (Mg)	mg/l	-	9.64
Sodium (Na)	mg/l	200	36.6
Potassium (K)	mg/l	-	2.35
Aluminium (Al)	mg/l	0.3	< 0.002
Iron (Fe)	mg/l	0.3	< 0.004
Manganese (Mn)	mg/l	0.1	< 0.001
Chromium (Cr)	mg/l	0.05	< 0.003
Copper (Cu)	mg/l	2	< 0.002
Nickel (Ni)	mg/l	0.07	< 0.002
Zinc (Zn)	mg/l	5	< 0.002
Cobalt (Co)	mg/l	-	< 0.003
Cadmium (Cd)	mg/l	0.003	< 0.002
Lead (Pb)	mg/l	0.01	< 0.004
Microbiological Variables			
E.Coli	CFU/100ml	0	2 000
Total coliform	CFU/100ml	10	9 000

Examination of the water test analyses presented in Table 4.8 and Table 4.9 for the Msunduzi water samples show that the river water used during the research met most of the chemical requirements as per SANS 241-1 (SANS, 2015). A point of concern from the samples analysed was the bacteriological quantities that were present in the water, but this is a phenomenon that is to be expected from raw river water samples.

4.2.6 General summary

The elemental composition, mineral composition and morphological appearance of eggshell powder, cement, stone and river sand have been discussed. The chemical and bacteriological composition of the river water has also been extensively analysed in order to ascertain the variance from the requirements of SANS 241-1 (SANS, 2015) for normal potable water. This was an important consideration since mix 3, mix 4 and mix 5 for the research were all produced using river water instead of potable water. Considering the elemental and chemical compositions of eggshell powder, cement, stone, river sand, and river water, the material capabilities of each material present a strong enough case for testing to assess whether a lightweight concrete can be produced using eggshell powder, EPS and river water. This also compelled the researcher to consider:

- Whether the composition of eggshell powder, EPS and river water in concrete can produce a minimum compressive strength of at least 20 MPa after 28 days as per conventional M20 grade concrete; and
- How the removal of EPS and an increase of eggshell powder in the same mix would alter the compressive and flexural strength.

4.3 Compressive strength, flexural strength and mass of the control mix

Before substitutions are discussed for mix 2 to mix 5, the results for the control mix are presented from Table 4.11 to Table 4.19.

The intention of the control mix was to have a concrete mix that was produced without any substitutions of EPS or eggshell powder. The non-potable water used for the control mix was collected from the same source but taken at a different time from the non-potable water used for mix 2 to mix 5. The control mix was also intended to meet the requirements of being regarded as an M20 grade concrete mix which means one of the most important criteria is that the mix must at least achieve 20 MPa at 28 day compressive strength.

The control mix can be considered as mix 1. The proportioning of this mix followed the ratio of 1:2:3 with water-to-cement ratio of 0.5. The sample nomenclature for the individual cubes can be interpreted as shown in Table 4.10.

Table 4.10: Days tested as well as nomenclature of mix 1.

Days to be tested at:	**Nomenclature for each sample:**
7 (3 cubes)	C_1, C_2, C_3
28 (3 cubes)	C_4, C_5, C_6
90 (3 cubes)	C_7, C_8, C_9

The slump test for all the mixes was conducted in line with SANS 5862-1 (SANS, 2006c). The slump of the control mix was found to be 70 mm. This was consistent with the guidelines of the Cement & Concrete Institute (2021), that when sufficient water is used, a workable mix of 60 mm to 100 mm slump will be produced. The bulk density of the set of samples produced for each testing age are shown in Table 4.11 to Table 4.13. From the densities below it is evident that even though the control mix was composed of non-potable water instead of potable water, all the produced samples fell within the density range of normal weight concrete which is between 2 200 kg/m^3 to 2 600 kg/m^3 as supported by Iffat (2015) in her study of the relationship between density and compressive strength in concrete. Cement & Concrete South Africa (2022) also confirm that "standard" concrete should have a density of approximately 2 400 kg/m^3. The ability of concrete produced using non-potable water to meet the specified density for "standard" concrete is largely dependent on the chemical and bacteriological limits of the non-potable water used.

Table 4.11: Bulk density of sample C_1 to C_3.

Sample ID for 7 day test result samples	**Bulk density (kg/m^3)**
C_1	2 426
C_2	2 407
C_3	2 384
Average	**2 406**
Standard deviation	**21.03**

Table 4.12: Bulk density of sample C_4 to C_6.

Sample ID for 28 day test result samples	**Bulk density (kg/m^3)**
C_4	2 420
C_5	2 404
C_6	2 427
Average	**2 417**
Standard deviation	**11.79**

Table 4.13: Bulk density of sample C_7 to C_9.

Sample ID for 90 day test result samples	**Bulk density (kg/m^3)**
C_7	2 425
C_8	2 415
C_9	2 483
Average	**2 441**
Standard deviation	**36.72**

The masses of the individual cube samples in Figure 4.24 show how mix 1 cube samples differed from each other. The largest variance of the cubes made for mix 1 was 0.334 kg.

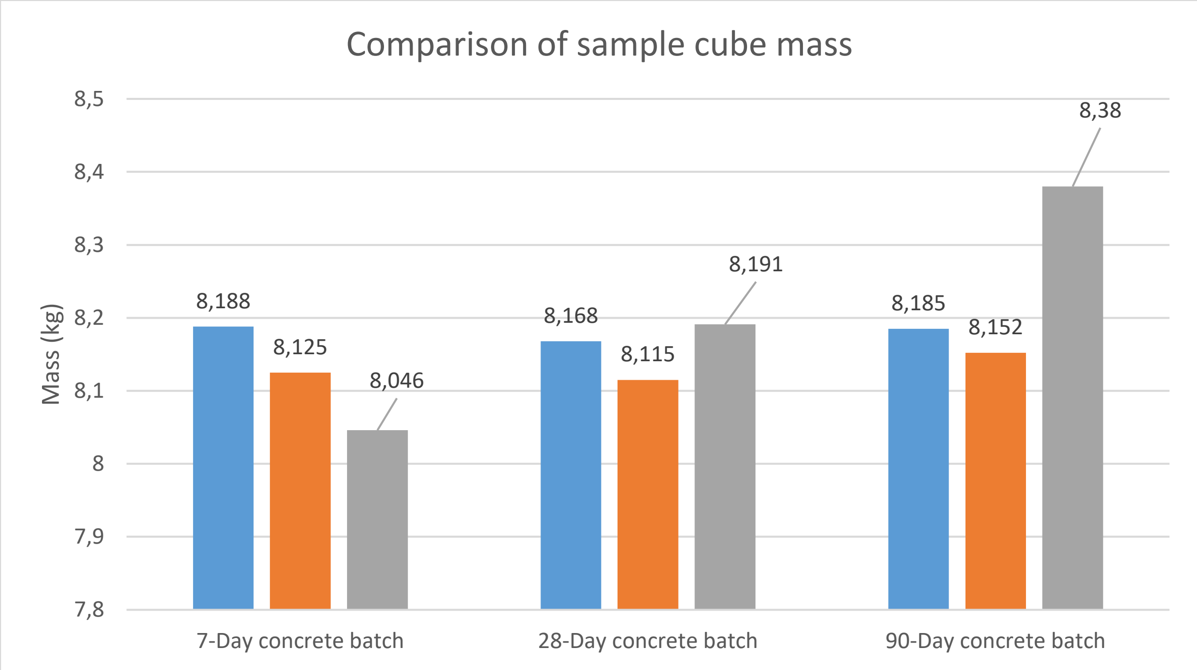


Figure 4.24: Comparison of the masses of cube samples for mix 1 for compressive strength tests.

The masses of the individual beam samples are shown in Figure 4.25 where it can be seen that the largest variance of the beams made for mix 1 was 1.86 kg.

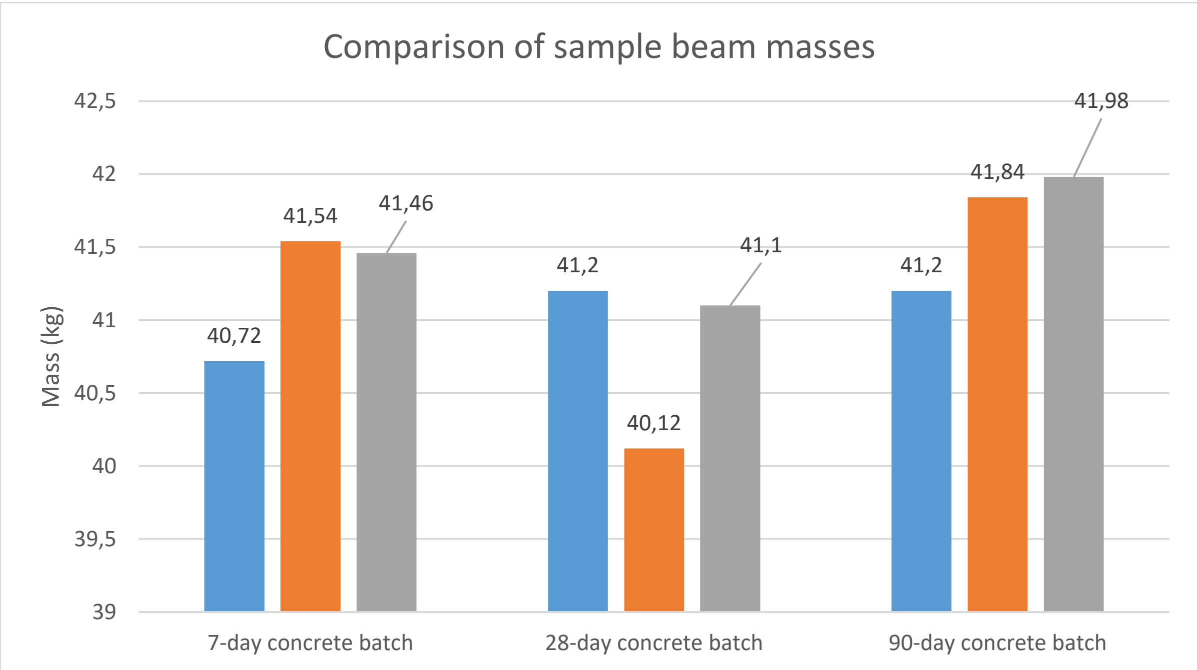


Figure 4.25: Comparison of the masses of the beam samples of mix 1 for flexural strength tests.

The intention of the control mix was to test a concrete mix produced without any substitutions of EPS or eggshell and for this to be the reference result for comparison with the other mixes. It was envisaged that this mix should at least meet or exceed a target compressive strength of 20 MPa at 28-days. This was indeed the case. The compressive strength test results are shown from Table 4.14 to Table 4.16.

Table 4.14: Compressive strength of C_1 to C_3.

Sample ID for 7 day test result samples	**Compressive Strength (MPa)**
C_1	12.7
C_2	11.9
C_3	11.3
Average	**12**
Standard deviation	**0.70**

Table 4.15: Compressive strength of C_4 to C_6.

Sample ID for 28 day test result samples	**Compressive Strength (MPa)**
C_4	24.6
C_5	24.9
C_6	26.2
Average	**25.2**
Standard deviation	**0.85**

Table 4.16: Compressive strength of C_7 to C_9.

Sample ID for 90 day test result samples	**Compressive Strength (MPa)**
C_7	33.6
C_8	31.3
C_9	36.2
Average	**33.7**
Standard deviation	**2.45**

Numerous researchers such as Raza et al. (2021), Elchalakani and Elgaali (2012), Gadzama et al. (2015), Ghrair et al. (2018), Saxena and Tembhurkar (2018), Kaboosi and Emami (2019), Babu and Ramana (2018), and Mahasneh (2014), have investigated the effects of using non-potable water instead of potable water for concrete production. Although the control mix in the current study met and exceeded the targeted compressive strength of 20 MPa at 28-day compressive strength as shown in Figure 4.26, the above mentioned researchers noted that the compressive strength of concrete will decline by approximately 0 % to 20 % when potable water is replaced with non-potable water.

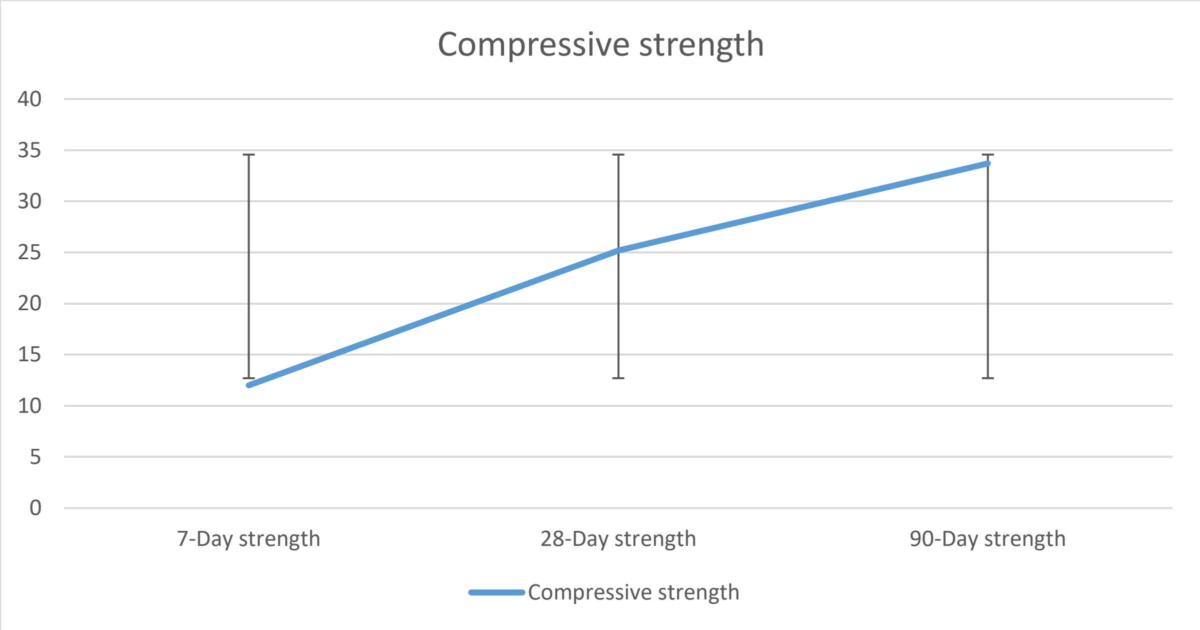


Figure 4.26: Compressive strength of control mix.

The intention of the control mix was to have a concrete mix produced without any substitutions of EPS or eggshell to be tested for flexural strength. It was envisaged that this mix should at least meet a flexural strength of 2.71 MPa at 28-days in order to be comparable to similar results obtained by researchers such as Gulve et al. (2018). The flexural strength test results obtained are shown from Table 4.17 to Table 4.19.

Table 4.17: Flexural strength of C_1 to C_3.

Sample ID for 7 day test result samples	**Flexural Strength (MPa)**
C_1	2.4
C_2	2.3
C_3	2.4
Average	**2.4**
Standard deviation	**0.06**

Table 4.18: Flexural strength of C_4 to C_6.

Sample ID for 28 day test result samples	**Flexural Strength (MPa)**
C_4	3.1
C_5	3.0
C_6	3.6
Average	**3.2**
Standard deviation	**0.32**

Table 4.19: Flexural strength of C_7 to C_9.

Sample ID for 90 day test result samples	**Flexural Strength (MPa)**
C_7	5.2

C_8	4.7
C_9	4.5
Average	**4.8**
Standard deviation	**0.36**

Figure 4.27 shows that the control mix met and surpassed the targeted flexural strength of 2.71 MPa at 28-day strength. The flexural strength values of concrete produced using non-potable water are lower than the known flexural strength values of concrete produced using potable water. Chatveera et al. (2006) found that a reason for this is that the bond strength between the cement paste and the aggregate is weaker when non-potable water is used in concrete production.

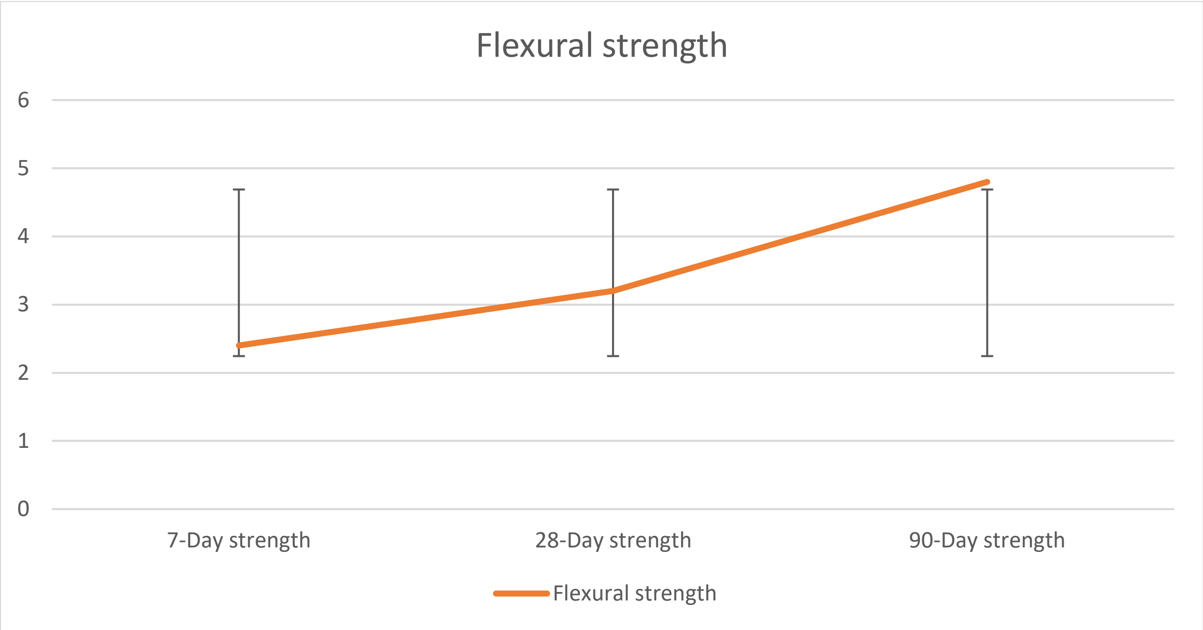


Figure 4.27: Flexural strength of control mix.

In order to ensure consistency as well as comparability, the cubes and beams prepared for compressive and flexural strength testing for mix 2 to mix 5 were strictly checked so as to not exceed the variances allowed in the control mix. This is demonstrated in Figures 4.29, 4.30, 4.31, 4.32, 4.34, 4.35, 4.38 and 4.39.

4.4 Influence of substituting coarse aggregate with EPS using potable water in concrete

4.4.1 Concrete mix proportioning for EPS concrete using potable water in concrete

This mix can be considered as mix 2. The proportioning of this mix followed the ratio of 1:2:3 with water-to-cement ratio of 0.5. The sample nomenclature for the individual cubes can be interpreted as shown in Table 4.20.

Table 4.20: Days tested as well as nomenclature of mix 2.

Days to be tested at:	Nomenclature for each sample:
7 (3 cubes)	E_1, E_2, E_3
28 (3 cubes)	E_4, E_5, E_6
90 (3 cubes)	E_7, E_8, E_9

4.4.2 Effects of partial substitution of coarse aggregate with EPS on the slump of concrete

The slump of any concrete is a determinant of its consistency and workability. The slump that was achieved for mix 2 was 100 mm. This was consistent with the guidelines of the Cement & Concrete Institute (2021) which is that when sufficient water is used, a workable mix of 60 mm to 100 mm slump will be produced. This is important since an excessive amount of water reduces the strength of concrete. Therefore, the effect of partially substituting coarse aggregate with EPS in this particular case was not noticeable. This lack of effect is similar to what Shraddha et al. (2014) found during the investigation of partially substituting coarse aggregate with coconut shells. They concluded that even replacing the quantity of coarse aggregate with coconut shells by up to 22.50 % did not affect the workability of the concrete. The slump of mix 2 was higher than that of the control mix which is an indication that mix 2 was more fluid and therefore more workable than the control mix.

4.4.3 Effects of partial substitution of coarse aggregate with EPS on the bulk density of concrete

The bulk density of concrete is the weight of the concrete mixture that fills a container of a specific volume. Each of the concrete cubes and beams were cured at a length of between 7 days, 28 days and 90 days. The curing bath used to cure the samples is shown in Figure 4.28.

Figure 4.28: Curing bath used to cure the different samples.

The bulk density of each cube was tested individually and the results are presented in Table 4.21 to Table 4.23. The bulk density of the samples were analysed at 7 days, 28 days and 90 days. The relevant averages found were 2 385 kg/m^3 at 7 days, 2 351 kg/m^3 at 28 days and 2 380 kg/m^3 at 90 days. The bulk density decreased by 34 kg/m^3 from the samples tested at 7 days to the samples tested at 28 days.

This phenomenon was not observed in the control mix since from the literature it is known that bulk density increases with time although the rate of density change is low (Iffat, 2015). The only difference between mix 2 and the control mix was the use of potable water along with the substitution of coarse aggregate with EPS. The fluctuation of the bulk density as observed from Table 4.21 to Table 4.23 can therefore only be attributable to this change in mix composition. When comparing the 7 day, 28 day and 90 day bulk density averages of mix 2 to the 7 day, 28 day and 90 day bulk density averages of the control mix, the finding was that the averages of mix 2 were all lower than the control mix. This means that mix 2 was a lighter weight concrete than the control mix. Previous researchers have found a decrease in bulk density as an outcome in experimental tests regarding the effects of partial substitution of some of the most common constituents of concrete such as cement, coarse aggregate and potable water. An example of such a finding is the study by Malesev et al. (2010) which investigated the alteration of concrete properties when recycled concrete was used as an aggregate for concrete production. The researchers found that the bulk density of the concrete decreased slightly as the quantity of recycled aggregate used in the mix increased.

Table 4.21: Bulk density of sample E_1 to E_3.

Sample ID for 7 day test result samples	**Bulk density (kg/m^3)**
E_1	2 419
E_2	2 363
E_3	2 373
Average	**2 385**
Standard deviation	**29.87**

Table 4.22: Bulk density of sample E_4 to E_6.

Sample ID for 28 day test result samples	**Bulk density (kg/m^3)**
E_4	2 365
E_5	2 343
E_6	2 345
Average	**2 351**
Standard deviation	**12.17**

Table 4.23: Bulk density of sample E_7 to E_9.

Sample ID for 90 day test result samples	**Bulk density (kg/m^3)**
E_7	2 363
E_8	2 372
E_9	2 405
Average	**2 380**
Standard deviation	**22.11**

The masses of the individual cube samples in Figure 4.29 show how mix 2 cube samples differed from each other. The largest variance of the cubes made for mix 2 was 0.258 kg, which was within the allowable variance of 0.334 kg as per the control mix.

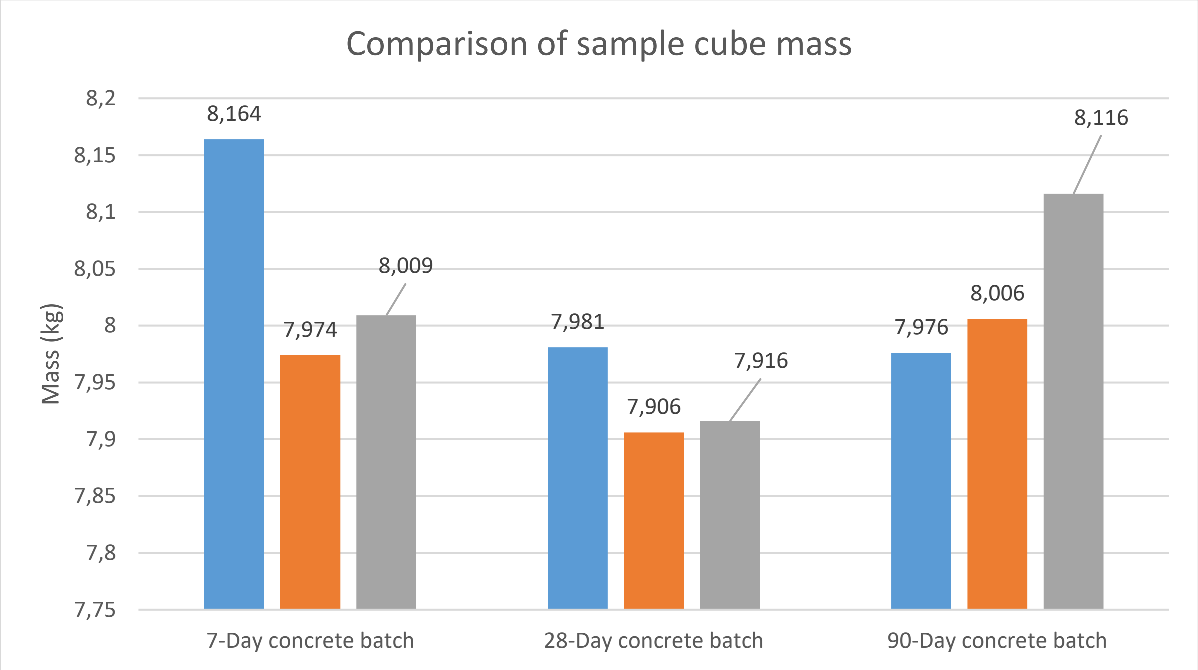


Figure 4.29: Comparison of the masses of cube samples for mix 2 for compressive strength tests.

Figure 4.30 shows that the largest variance of the beams made for mix 2 was 1.23 kg, which was within the allowable variance of 1.86 kg as per the control mix.

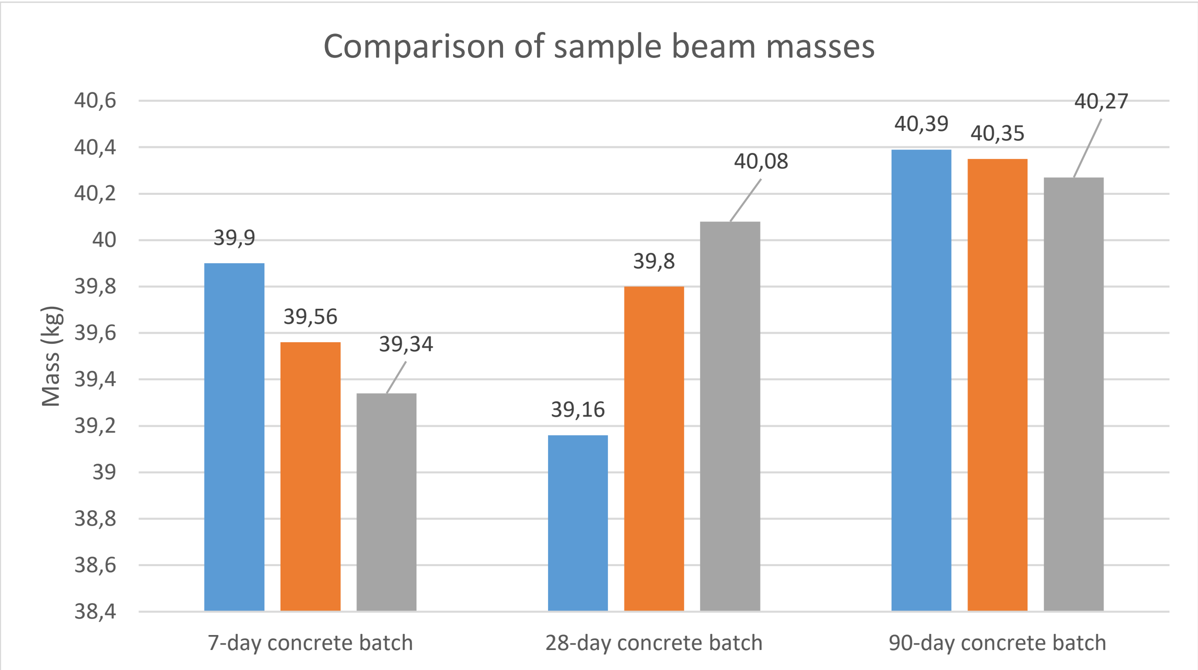


Figure 4.30: Comparison of the masses of the beam samples of mix 2 for flexural strength tests.

4.4.4 Effects of partial substitution of coarse aggregate with EPS on the compressive strength of concrete

The compressive strength of each cube was tested individually and the results are presented from Table 4.24 to Table 4.26. The average compressive strengths of the samples at 7 days, 28 days and 90 days, were 7.4 MPa at 7 days, 21.2 MPa at 28 days and 27.8 MPa at 90 days. The results show an increase in compressive strength as the curing age of the samples increased. It is important to note that mix 2 only contained a substitution of coarse aggregate with EPS by 10 %, based on Sayadi et al.'s (2016) findings that increasing the quantity of EPS in a concrete mix directly affects the compressive strength of the mix. This is also supported by Adeala and Soyemi (2020) who found that there is a strong correlation between compressive strength and the percentage of EPS used as a substitute material in a concrete mix.

Table 4.24: Compressive strength of E_1 to E_3.

Sample ID for 7 day test result samples	Compressive Strength (MPa)
E_1	7.3
E_2	7.3
E_3	7.6
Average	**7.4**
Standard deviation	**0.17**

Table 4.25: Compressive strength of E_4 to E_6.

Sample ID for 28 day test result samples	Compressive Strength (MPa)
E_4	20.7
E_5	21.1
E_6	21.8
Average	**21.2**
Standard deviation	**0.56**

Table 4.26: Compressive strength of E_7 to E_9.

Sample ID for 90 day test result samples	Compressive Strength (MPa)
E_7	27.6
E_8	28
E_9	27.8
Average	**27.8**
Standard deviation	**0.2**

4.4.5 Effects of partial substitution of coarse aggregate with EPS on flexural strength

The flexural strength of each beam was tested individually and the results are presented from Table 4.27 to Table 4.29. The average flexural strengths of the samples at 7 days, 28 days and 90 days were 1 MPa at 7 days, 3.3 MPa at 28 days and 3.7 MPa at 90 days. The averages at the different curing ages show that there was an increase in flexural strength as the curing age of the samples increased. This increase was specifically significant from the 7 day age to the 28 day age, where there was a gain of 2.3 MPa, whereas from the 28 day age to the 90 day age, the gain was only 0.4 MPa. This concurs with the research conducted by Supe and Gupta (2014) into the flexural strength gain of concrete. These researchers found that the gain of flexural strength in concrete was higher during the initial stage after being cast.

Table 4.27: Flexural strength of E_1 to E_3.

Sample ID for 7 day test result samples	Flexural Strength (MPa)
E_1	1.2
E_2	0.9
E_3	1
Average	**1**
Standard deviation	**0.15**

Table 4.28: Flexural strength of E_4 to E_6.

Sample ID for 28 day test result samples	Flexural Strength (MPa)
E_4	3.4
E_5	3.1
E_6	3.5
Average	**3.3**
Standard deviation	**0.21**

Table 4.29: Flexural strength of E_7 to E_9.

Sample ID for 90 day test result samples	Flexural Strength (MPa)
E_7	3.6
E_8	3.9
E_9	3.6
Average	**3.7**
Standard deviation	**0.17**

4.5 Influence of substituting coarse aggregate with EPS using river water in concrete

4.5.1 Concrete mix proportioning for EPS concrete using river water

This mix can be considered as mix 3. The proportioning of this mix followed the ratio of 1:2:3 with a water-to-cement ratio of 0.5. The sample nomenclature for the individual cubes can be interpreted as shown in Table 4.30:

Table 4.30: Days tested as well as nomenclature of mix 3.

Days to be tested at:	Nomenclature for each sample:
7 (3 cubes)	F_1, F_2, F_3
28 (3 cubes)	F_4, F_5, F_6
90 (3 cubes)	F_7, F_8, F_9

4.5.2 Effects of partial substitution of coarse aggregate with EPS on the slump of concrete

The slump that was achieved for mix 3 was 60 mm slump. This was consistent with the guidelines of the Cement & Concrete Institute (2021) that when sufficient water is used, a workable mix of 60 mm to 100 mm slump will be produced. Mix 3 was the first mix to have been mixed with river water in the group of concrete mixes from mix 2 to mix 5. It is interesting to note how the slump of concrete mixed with river water differed when compared to concrete mixed with other sources of non-potable water such as wastewater collected from car wash stations. Al-Jabri et al. (2011) conducted research into the effect of using car wash station wastewater on the properties of concrete. These researchers found that when the concrete was mixed only with the wastewater and not a mixture of both wastewater and potable water, the slump reduced to 10 mm. This differs significantly from the situation of mix 3 where river water was used since the slump of the mix was 60 mm. This also emphasizes the extreme differences in concrete mix outcomes that can be obtained depending on the chosen source of non-potable water. It was also observed that the slump of mix 3 is slightly lower than that of the control mix which is an indication that mix 3 was less fluid and therefore slightly less workable than the control mix.

4.5.3 Effects of partial substitution of coarse aggregate with EPS on the bulk density of concrete

The bulk density of each cube was tested individually and the results are presented from Table 4.31 to Table 4.33. The average bulk densities of the samples at 7 days, 28 days and 90 days were 2 324 kg/m^3 at 7 days, 2 356 kg/m^3 at 28 days and 2 334 kg/m^3 at 90 days. When considering the average bulk density at 28 days and comparing it to the average at 90 days, there was a noticeable decrease in bulk density. This is similar to what was observed for mix 2 where the bulk density decreased by 34 kg/m^3 from the samples tested at 7 days to the samples tested at 28 days. Mix 2 and mix 3 are similar in composition with the only difference being the type of mixing water used. Mix 2 showed an initial decrease in bulk density from 7 days to 28 days, however, mix 3 showed an increase from 7 days to 28 days but a later decrease from 28 days to 90 days. This means that the substitution of coarse aggregate by EPS in concrete mixed using potable water (as in the case of mix 2) displays an early initial decrease in bulk density when compared to a similar mix where the only difference is the use of river water (as in the case of mix 3) which displayed a later decrease in bulk density. The decrease in bulk density from a curing age of 28 days to 90 days for mix 3 can be attributable to the use of river water. However, in terms of severity, this slight decrease in bulk density was not severe since it still fell comfortably within the category of normal weight concrete according to the European specification EN 206 (European Standards, 2006). The density results obtained for mix 3 are consistent with those obtained by Al-Ghusain and Terro (2003) who found that the different types of mixing water do not significantly affect the density of concrete. During their research these authors found that there was less than 5 % variation in the density of concrete made with potable water compared to concrete made with treated wastewater. When comparing the 7 day, 28 day and 90 day averages of mix 3 to the 7 day, 28 day and 90 day averages of the control mix it is evident that the bulk density results for the control mix are higher at all test ages which signifies the impact of the introduction of EPS on the bulk density of concrete.

Table 4.31: Bulk density of sample F_1 to F_3.

Sample ID for 7 day test result samples	Bulk density (kg/m^3)
F_1	2 328
F_2	2 333
F_3	2 312
Average	**2 324**
Standard deviation	**10.97**

Table 4.32: Bulk density of sample F_4 to F_6.

Sample ID for 28 day test result samples	Bulk density (kg/m^3)
F_4	2 345
F_5	2 362
F_6	2 362
Average	**2 356**
Standard deviation	**9.81**

Table 4.33: Bulk density of sample F_7 to F_9.

Sample ID for 90 day test result samples	Bulk density (kg/m^3)
F_7	2 340
F_8	2 334
F_9	2 329
Average	**2 334**
Standard deviation	**5.51**

The masses of the individual cube samples in Figure 4.31 show how the cubes for mix 3 differed from each other. The largest variance of the cubes made for mix 3 was 0.170 kg, which was within the allowable variance of 0.334 kg as per the control mix.

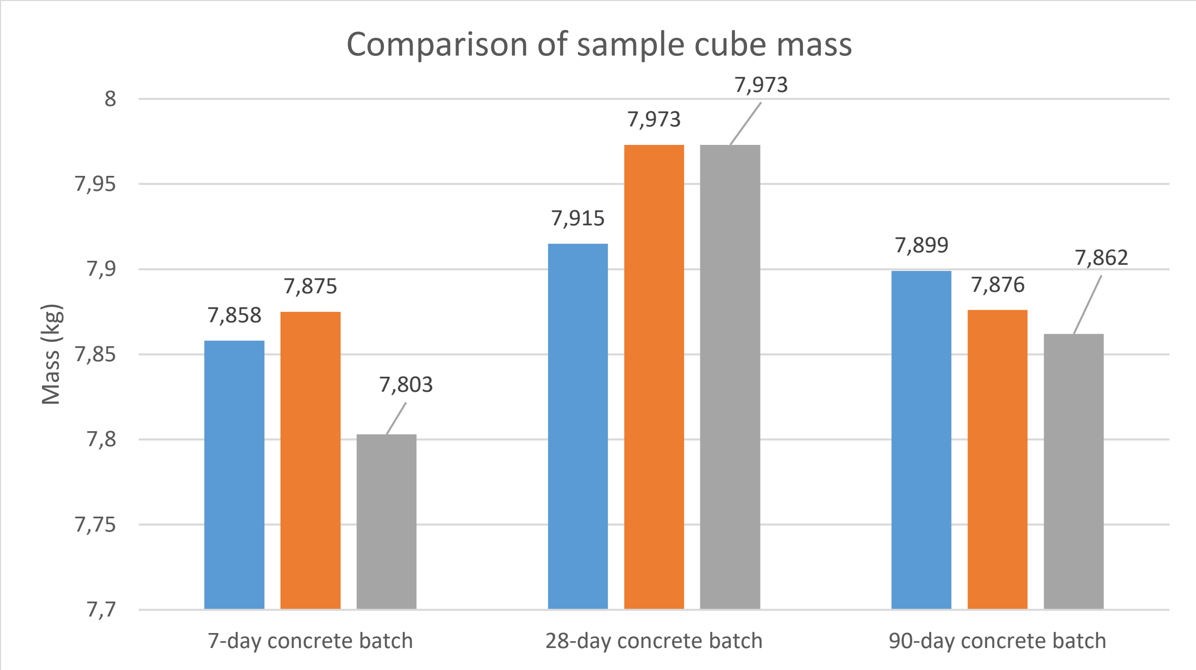


Figure 4.31: Comparison of the masses of cube samples for mix 3 for compressive strength tests.

Figure 4.32 shows that the largest variance of the beams made for mix 3 was 1.44 kg, therefore this was within the allowable of 1.86 kg as per the control mix.

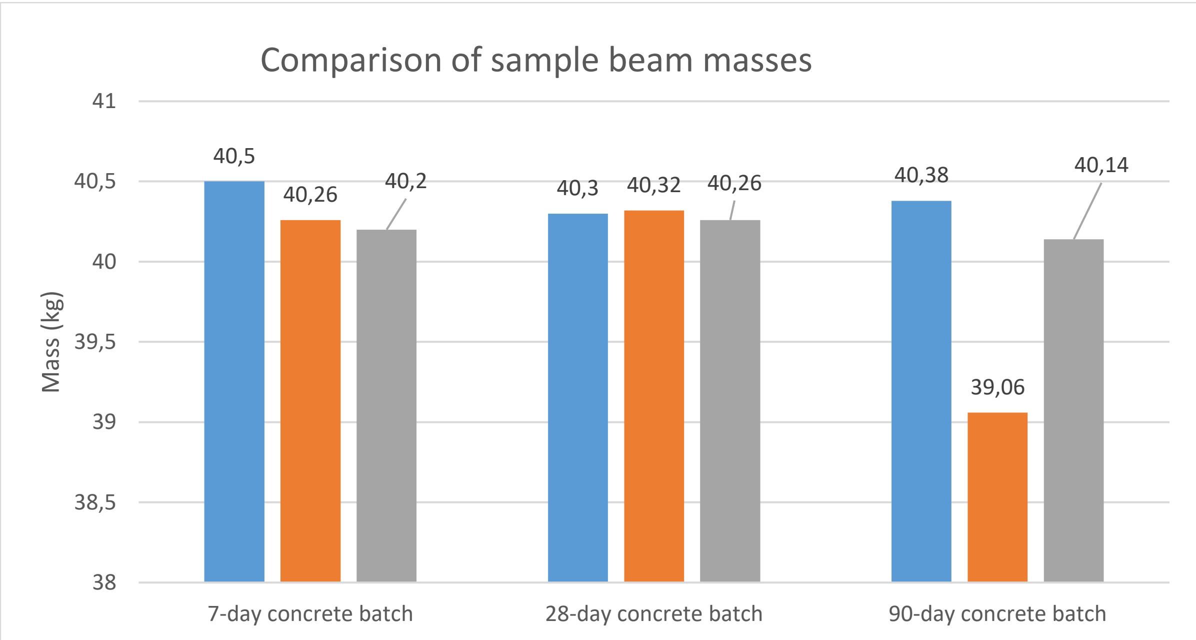


Figure 4.32: Comparison of the masses of the sample beams of mix 3 for flexural strength tests.

4.5.4 Effects of partial substitution of coarse aggregate with EPS on the compressive strength of concrete

The compressive strength of each cube was tested individually and the results are presented from Table 4.34 to Table 4.36. The average compressive strengths of the samples at 7 days, 28 days and 90 days were 7.9 MPa at 7 days, 19.8 MPa at 28 days and 26.7 MPa at 90 days. The results showed that there was an increase in compressive strength as the curing age of the samples increased. When comparing the compressive strength averages of mix 3 to the compressive strength averages of mix 2, it was observed that the initial compressive strength gain of a mix such as mix 3 (which is similar in composition to mix 2 but only differs with the type of mixing water used) was higher than the initial compressive strength gain of mix 2 even though mix 2 was composed of potable water. Although the initial strength gain of mix 3 was higher than that of mix 2, mix 2 still achieved a higher compressive strength at the 28 day and 90 day mark. The compressive strength results for mix 3 were also found to be lower than the compressive strength results of the control mix at all the test ages. This is consistent with the findings of Olugbenga (2014) who found that when substitutes for the conventional materials used for concrete have been introduced, the compressive strength of the resulting concrete mixed with non-potable water is lower than concrete mixed with potable water at all test ages.

Table 4.34: Compressive strength of F_1 to F_3.

Sample ID for 7 day test result samples	**Compressive Strength (MPa)**
F_1	8.4
F_2	7.9
F_3	7.5
Average	**7.9**
Standard deviation	**0.45**

Table 4.35: Compressive strength of F_4 to F_6.

Sample ID for 28 day test result samples	**Compressive Strength (MPa)**
F_4	20
F_5	20.2
F_6	19.1
Average	**19.8**
Standard deviation	**0.59**

Table 4.36: Compressive strength of F_7 to F_9.

Sample ID for 90 day test result samples	**Compressive Strength (MPa)**
F_7	24.9
F_8	29.1
F_9	26.2
Average	**26.7**
Standard deviation	**2.15**

4.5.5 Effects of partial substitution of coarse aggregate with EPS on the flexural strength of concrete

The flexural strength of each beam was tested individually and the results are presented in Table 4.37 to Table 4.39. The average flexural strengths of the samples at 7 days, 28 days and 90 days were 1.3 MPa at 7 days, 3 MPa at 28 days and 3.4 MPa at 90 days. The results showed that there was an increase in flexural strength as the curing age of the samples increased. When comparing the flexural strength averages of mix 3 to the flexural strength averages of mix 2, it was observed that the initial flexural strength gain of mix 3 (which was similar in composition to mix 2 but only differed in the type of mixing water used) was higher than the initial flexural strength gain of mix 2 even though mix 2 was composed of potable water. Although the initial flexural strength gain of mix 3 was higher than that of mix 2, mix 2 still achieved a higher flexural strength at the 28 day and 90 day mark. This means that a mix such as mix 3 that has been mixed with river water has the advantage of higher initial flexural strength gain but this does not translate into an overall higher flexural strength over time. The flexural strength results for mix 3 were also found to be lower than the flexural strength results of the control mix at all the test ages. This is consistent with the findings of Ali et al. (2021) who found that when substitutes for concrete's conventional materials have been introduced into concrete, the flexural strength of the resulting concrete mixed with non-potable water is lower than that of concrete mixed with potable water at all test ages.

Table 4.37: Flexural strength of F_1 to F_3.

Sample ID for 7 day test result samples	**Flexural Strength (MPa)**
F_1	1.4
F_2	1.3
F_3	1.3
Average	**1.3**
Standard deviation	**0.06**

Table 4.38: Flexural strength of F_4 to F_6.

Sample ID for 28 day test result samples	**Flexural Strength (MPa)**
F_4	2.8
F_5	3
F_6	3.2
Average	**3**
Standard deviation	**0.2**

Table 4.39: Flexural strength of F_7 to F_9.

Sample ID for 90 day test result samples	**Flexural Strength (MPa)**
F_7	2.7
F_8	3.8

F_9	3.7
Average	**3.4**
Standard deviation	**0.61**

4.6 Influence of substituting cement, coarse aggregate and potable water with eggshell powder, EPS and river water in concrete

4.6.1 Concrete mix proportioning for EPS eggshell concrete using river water

This mix can be considered as mix 4. The proportioning of this mix followed the ratio of 1:2:3 with a water-to-cement ratio of 0.5. The sample nomenclature for the individual cubes can be interpreted as shown in Table 4.40:

Table 4.40: Days tested as well as nomenclature of mix 4.

Days to be tested at:	**Nomenclature for each sample:**
7 (3 cubes)	G_1, G_2, G_3
28 (3 cubes)	G_4, G_5, G_6
90 (3 cubes)	G_7, G_8, G_9

4.6.2 Effects of partial substitution of cement, coarse aggregate and potable water with eggshell powder, EPS and river water on the slump of concrete

The slump that was achieved for mix 4 was a slump of 35 mm. Although this was not consistent with the guidelines of the Cement & Concrete Institute (2021) which state that when sufficient water is used, a workable mix of 60 mm to 100 mm slump will be produced, it is still important to note that in construction there are certain instances where a lower slump concrete is more suitable than a moderate to high slump concrete. This is explained by EduRev (2021) which states that slump mixes of low workability such as those that range between 10 mm to 40 mm are typically more suitable for foundations with light reinforcement in construction. The slump of mix 4 is considerably lower than that of the control mix which is an indication that mix 4 is less fluid and is therefore less workable than the control mix.

The effect of partially substituting three components in concrete (cement, coarse aggregate and potable water) on the slump of the concrete is considerable, however this is not unique since it is common with substitutions made to concrete to find that the slump is altered by a noticeable degree. An example of this is the study by Ismail and Al-Hashmi (2008) who investigated the effects of coarse aggregate substitution in concrete with waste plastic. They found that the slump decreased proportionally to the increase in plastic content. Their observation was that this occurs by a minimum of 30 mm to a maximum of 60 mm. The slump decrease that Ismail and Al-Hashmi (2008) witnessed is demonstrated in Figure 4.33 which shows how concrete is affected by the increase in waste plastic content.

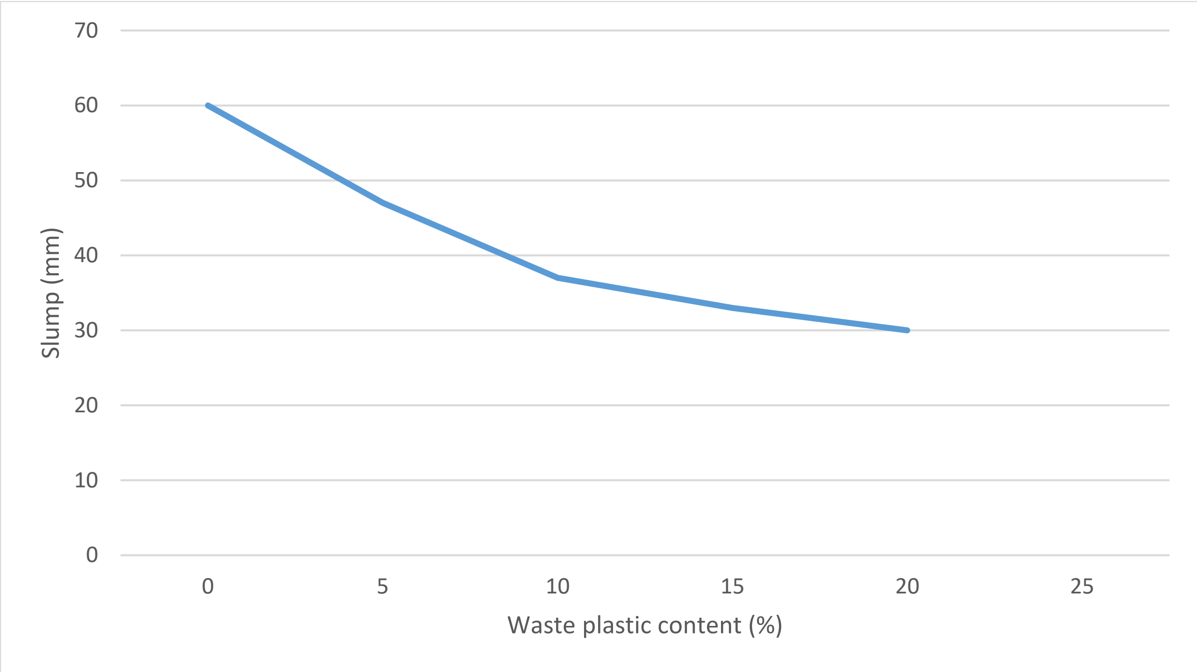


Figure 4.33: Slump versus waste plastic content percentage in concrete.
Source: Ismail and Al-Hashmi (2008)

4.6.3 Effects of partial substitution of cement, coarse aggregate and potable water with eggshell powder, EPS and river water on the bulk density of concrete

Table 4.41 to Table 4.43 show that the average bulk densities of the samples at 7 days, 28 days and 90 days were 2 366 kg/m^3 at 7 days, 2 374 kg/m^3 at 28 days and 2 378 kg/m^3 at 90 days. The average results obtained at each test age indicate that the bulk density of the samples increased as the curing age increased. When comparing the 7 day, 28 day and 90 day averages of mix 4 to the 7 day, 28 day and 90 day averages of the control mix it is evident that the bulk density results for the control mix are higher at all test ages, which shows the impact of the introduction of substitutes such as EPS, eggshell powder and river water on the bulk density of mix 4. It is also interesting to note that although mix 4 contains more substitutions than mix 3, the average bulk density results obtained at all the test ages were higher than that of mix 3. However, the average bulk density results for mix 2 were higher than that of mix 4 at the 7 day and 90 day test period even though mix 2 and mix 3 were similar in composition and only differed in the type of mixing water used in the composition of the mixes.

Table 4.41: Bulk density of sample G_1 to G_3.

Sample ID for 7 day test result samples	**Bulk density (kg/m^3)**
G_1	2 388
G_2	2 326
G_3	2 384
Average	**2 366**
Standard deviation	**34.70**

Table 4.42: Bulk density of sample G_4 to G_6.

Sample ID for 28 day test result samples	**Bulk density (kg/m^3)**
G_4	2 404
G_5	2 400
G_6	2 318
Average	**2 374**
Standard deviation	**48.54**

Table 4.43: Bulk density of sample G_7 to G_9.

Sample ID for 90 day test result samples	**Bulk density (kg/m^3)**
G_7	2 387
G_8	2 377
G_9	2 369
Average	**2 378**
Standard deviation	**9.02**

The masses of the individual cube samples in Figure 4.34 show how mix 4 cube samples differed from each other. The largest variance of the cubes made for mix 4 was 0.290 kg, which was within the allowable variance of 0.334 kg as per the control mix.

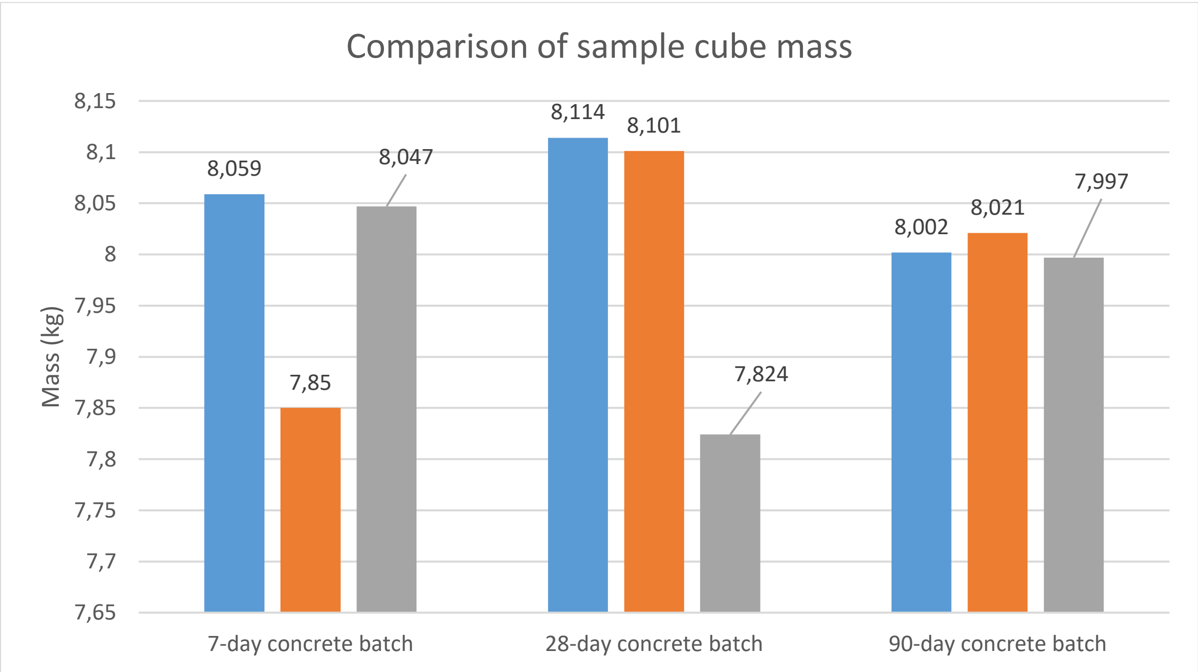


Figure 4.34: Comparison of the masses of cube samples for mix 4 for compressive strength tests.

Figure 4.35 shows that the largest variance of the beams made for mix 4 was 1.7 kg, which was within the allowable variance of 1.86 kg as per the control mix.

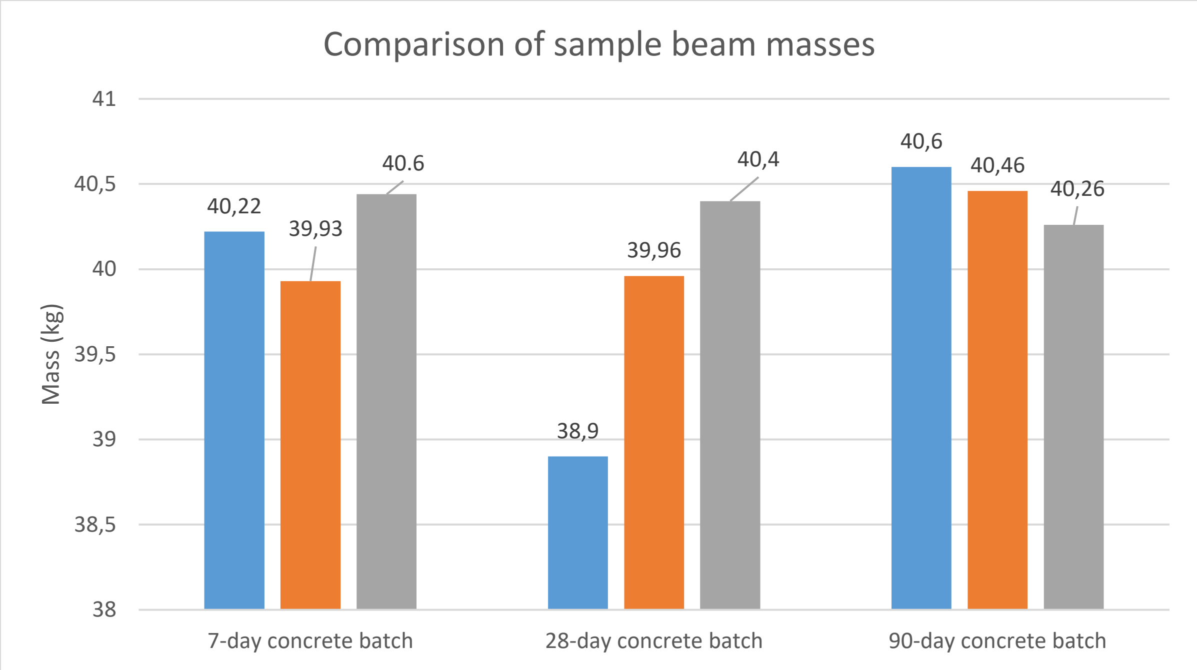


Figure 4.35: Comparison of the masses of the sample beams of mix 4 for flexural strength tests.

4.6.4 Effects of partial substitution of cement, coarse aggregate and potable water with eggshell powder, EPS and river water on the compressive strength of concrete

The compressive strength of each cube was tested individually and the results are presented in Table 4.44 to Table 4.46. The average compressive strengths of the samples at 7 days, 28 days and 90 days were 12.8 MPa at 7 days, 24.2 MPa at 28 days and 31.4 MPa at 90 days. The results show an increase in compressive strength as the curing age of the samples increased. Furthermore, the average compressive strength test results at all the test ages for mix 4 were higher than both those of mix 2 and mix 3. This was due to the percentage of EPS used in mix 4 being half of that used in mix 2 and mix 3 since mix 2 and mix 3 contained 10 % substitution of coarse aggregate with EPS instead of 5 %. The results obtained are consistent with the conclusions reached by Karthick et al. (2018) who found that the greater the percentage of EPS added to a concrete mix to replace aggregate, the lower the compressive strength. This is illustrated in Figure 4.36.

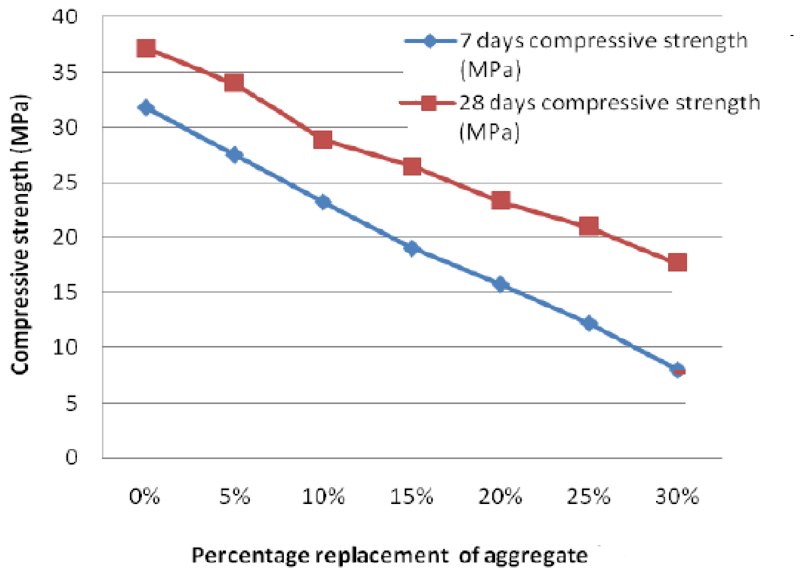


Figure 4.36: Percentage replacement of aggregate vs compressive strength.
Source: Karthick et al. (2018)

When comparing the average compressive strength test results at 7 days, 28 days and 90 days for mix 4 to those of the control mix, the finding was that the 7 day test results of mix 4 were higher than those of the control mix. However, both the 28 day and 90 day average compressive strength results of the control mix were higher than those of mix 4. This signifies that mix 4 had faster initial compressive strength gain when compared to the control mix.

Table 4.44: Compressive strength of G_1 to G_3.

Sample ID for 7 day test result samples	**Compressive Strength (MPa)**
G_1	12.4
G_2	12.7
G_3	13.2
Average	**12.8**
Standard deviation	**0.40**

Table 4.45: Compressive strength of G_4 to G_6.

Sample ID for 28 day test result samples	**Compressive Strength (MPa)**
G_4	23.2
G_5	23.8
G_6	25.6
Average	**24.2**
Standard deviation	**1.25**

Table 4.46: Compressive strength of G_7 to G_9.

Sample ID for 90 day test result samples	**Compressive Strength (MPa)**
G_7	31.4

G_8	29.7
G_9	33.2
Average	**31.4**
Standard deviation	**1.75**

4.6.5 Effects of partial substitution of cement, coarse aggregate and potable water with eggshell powder, EPS and river water on the flexural strength of concrete

The flexural strength of each beam was tested individually and the results are presented in Table 4.47 to Table 4.49. The average flexural strengths of the samples at 7 days, 28 days and 90 days were 1.4 MPa at 7 days, 3 MPa at 28 days and 4.1 MPa at 90 days. The results show that there was an increase in flexural strength as the curing age of the samples increased. The substitution of a portion of cement with eggshell powder for mix 4 had an interesting effect on the flexural strength of the mix at 28 days since the 28 day flexural strength of mix 4 was identical to that of mix 3 even though mix 4 contained a reduced quantity of substituted EPS. This being the case, the expected outcome was that it would be able to achieve a higher flexural strength than mix 3 at 28 days. This would have been consistent with the observations of Adeala and Soyemi (2020) who observed that the lesser the quantity of EPS that is used in a concrete mix as a substitute, the greater the flexural strength, as shown in Figure 4.37.

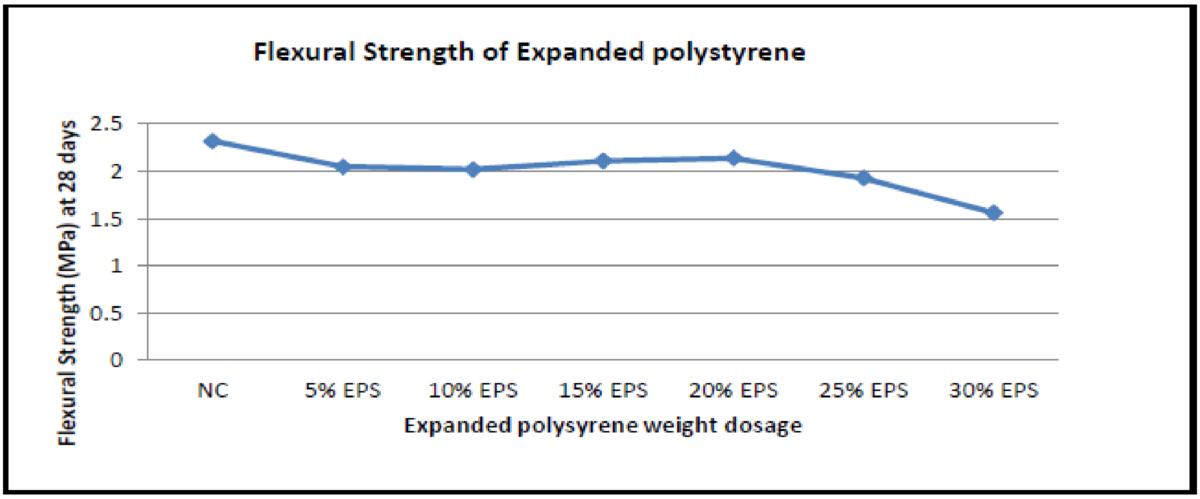


Figure 4.37: EPS weight dosage vs flexural strength gain at 28-days.
Source: Adeala and Soyemi (2020)

The observed phenomenon in mix 4 with regards to its flexural strength not increasing at the 28 day test mark even though the percentage of EPS was decreased, is due to the percentage of eggshell powder used in the mix in order to reduce the quantity of cement. This phenomenon emphasises that with the considered mixes of mix 2 to mix 5, it is possible for two different mixes in composition to achieve the same flexural strength outcomes with less cement being required in one of the mixes. The success of this is dependent on the quantity of EPS used to replace the coarse aggregate as well as the source of non-potable water used in the mix. The 7 day average flexural strength test result for mix 4 was also found to be higher than both that of mix 2 and mix 3. This signifies that mix 4 has higher initial flexural strength gain than both mix 2 and mix 3. However, when compared to the control mix, the average flexural strength test results for mix 4 at all test ages were found to be consistently lower than those of the control mix.

Table 4.47: Flexural strength of G_1 to G_3.

Sample ID for 7 day test result samples	Flexural Strength (MPa)
G_1	1.4
G_2	1.3
G_3	1.5
Average	**1.4**
Standard deviation	**0.1**

Table 4.48: Flexural strength of G_4 to G_6.

Sample ID for 28 day test result samples	Flexural Strength (MPa)
G_4	3
G_5	2.5
G_6	3.5
Average	**3**
Standard deviation	**0.5**

Table 4.49: Flexural strength of G_7 to G_9.

Sample ID for 90 day test result samples	Flexural Strength (MPa)
G_7	4.2
G_8	4.2
G_9	4.0
Average	**4.1**
Standard deviation	**0.12**

4.7 Influence of substituting cement with eggshell powder in concrete using river water

4.7.1 Concrete mix proportioning for eggshell concrete using river water

This mix can be considered as mix 5. The proportioning of this mix followed the ratio of 1:2:3 with a water-to-cement ratio of 0.5. The sample nomenclature for the individual cubes can be interpreted as shown in Table 4.50.

Table 4.50: Days tested as well as nomenclature of mix 5.

Days to be tested at:	Nomenclature for each sample:
7 (3 cubes)	H_1, H_2, H_3
28 (3 cubes)	H_4, H_5, H_6
90 (3 cubes)	H_7, H_8, H_9

4.7.2 Effects of partial substitution of cement and potable water with eggshell powder and river water on the slump of concrete

The slump that was achieved for mix 5 was 60 mm. This was within the guidelines of the Cement & Concrete Institute (2021), that when sufficient water is used, a workable mix of 60 mm to 100 mm slump will be produced. The slump obtained for mix 5 was greater than that obtained for mix 4 and was less than that obtained for mix 2 as well as the control mix. This means that mix 5 is more fluid and more workable than mix 4, however it is less fluid and less workable than mix 2 and the control mix. It was further noted that the slump obtained for mix 5 was equal to the slump obtained for mix 3 even though the material composition of the two mixes differ significantly.

4.7.3 Effects of partial substitution of cement and potable water with eggshell powder and river water on the bulk density of concrete

Table 4.51 to Table 4.53 show that the average bulk density of the samples at 7 days, 28 days, and 90 days were 2 227 kg/m^3 at 7 days, 2 186 kg/m^3 at 28 days and 2 227 kg/m^3 at 90 days. The substitution of cement and potable water with eggshell powder and river water on the bulk density of concrete is clearly evident since the average bulk density results of mix 5 were significantly lower than those of the control mix as well as all the other mixes considered. It was also observed that the average bulk density of mix 5 at 7 days was lower than the average bulk density at 28 days. This phenomenon was also only observed in mix 2 where the 7 day average bulk density decreased from 2 385 kg/m^3 to 2 380 kg/m^3 at 28 days even though the material composition of the mixes differed. A potential reason for the decrease in bulk density for mix 5 at 7 days to 28 days may be as a result of the increased eggshell powder content (10 %) used in combination with river water in the mix. Even though the substitution percentage of cement was high along with the use of river water instead of potable water, the average bulk density results achieved for mix 5 fell comfortably within the category of normal weight concrete according to the European specification EN 206 (European Standards, 2006).

Table 4.51: Bulk density of sample H_1 to H_3.

Sample ID for 7 day test result samples	Bulk density (kg/m^3)
H_1	2 218
H_2	2 250
H_3	2 214
Average	**2 227**
Standard deviation	**19.73**

Table 4.52: Bulk density of sample H_4 to H_6.

Sample ID for 28 day test result samples	Bulk density (kg/m^3)
H_4	2 219
H_5	2 205
H_6	2 135

Average	**2 186**
Standard deviation	**45**

Table 4.53: Bulk density of sample H_7 to H_9.

Sample ID for 90 day test result samples	**Bulk density (kg/m³)**
H_7	2 238
H_8	2 241
H_9	2 201
Average	**2 227**
Standard deviation	**22.28**

The masses of the individual cube samples in Figure 4.38 show how the cube samples for mix 5 differed from each other. The largest variance of the cubes made for mix 5 was 0.268 kg, which was within the allowable variance of 0.334 kg as per the control mix.

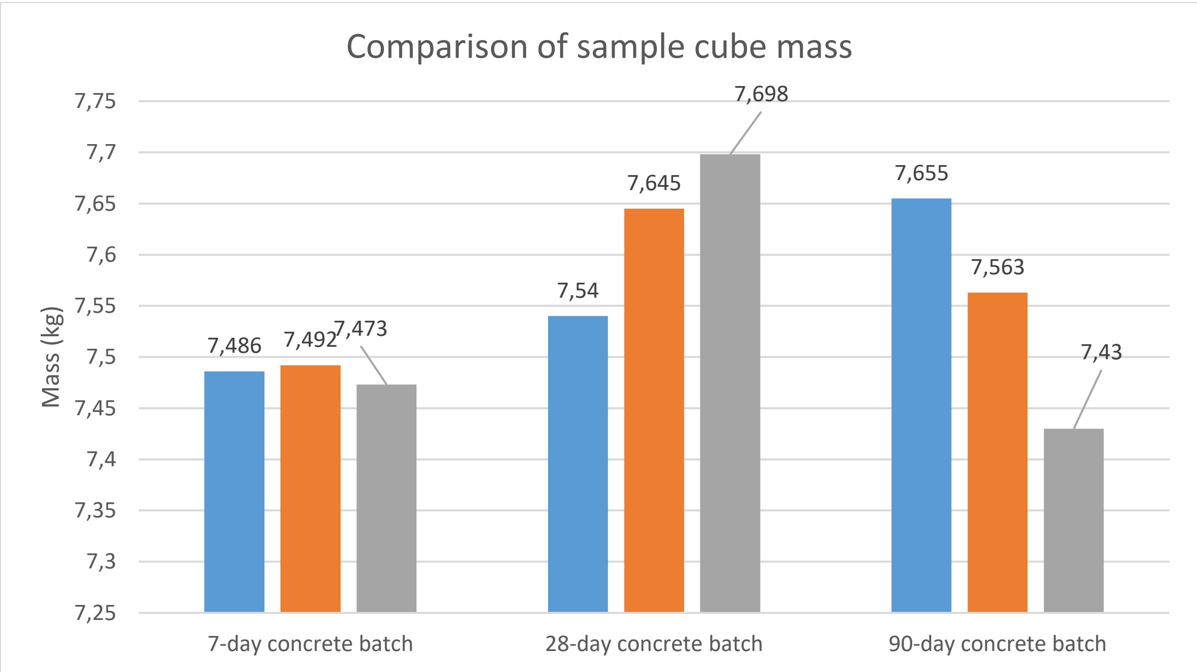


Figure 4.38: Comparison of the mass of cube samples for mix 5.

Figure 4.39 shows that the largest variance of the beams made for mix 5 was 1.81 kg, which was within the allowable variance of 1.86 kg as per the control mix.

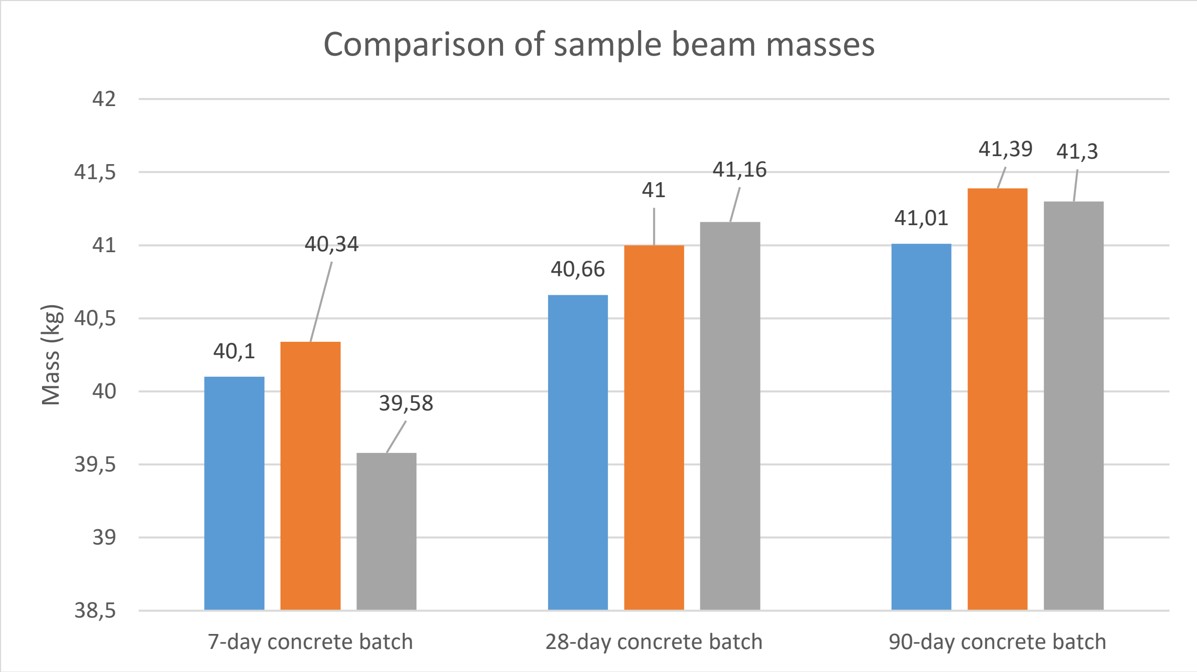


Figure 4.39: Comparison of the masses of the beam samples of mix 5 for flexural strength tests.

4.7.4 Effects of partial substitution of cement and potable water with eggshell powder and river water on the compressive strength of concrete

The compressive strength of each cube was tested individually and the results are presented from Table 4.54 to Table 4.56. The average compressive strengths of the samples at 7 days, 28 days and 90 days were 3.8 MPa at 7 days, 10 MPa at 28 days and 15 MPa at 90 days. The results showed that there was an increase in compressive strength as the curing age of the samples increased. From the results obtained it is clear that the substitution of cement with eggshell powder by a percentage of 10 % results in extremely slow strength gain in concrete. The average compressive strength test results for mix 5 were lower than the control mix and also much lower than any of the other mixes considered. Contrary to this, mix 4 exhibited excellent strength gain at all test ages since the average compressive strength at the different test ages was more than double that of mix 5. This is because mix 4 only had a substitution percentage of eggshell powder of 5 %, which was half that of mix 5. The differences in compressive strength between mix 4 and mix 5 show how much of a delicate exercise the issue of substitution is, because excessive substitution may result in a negative outcome. This is not only true for substitutions pertaining to eggshell powder and river water, but is also true for other materials that may be used for substitutions in concrete such as fly-ash. An example of this is an experimental investigation by Wankhede and Fulari (2014) into the effects of the usage of fly-ash on concrete. The authors found that the most suitable substitution percentage was between 10 % and 20 % and that if the replacement of cement with fly-ash was stepped up to 30 % this resulted in a significantly decreased compressive strength.

Table 4.54: Compressive strength of H_1 to H_3.

Sample ID for 7 day test result samples	**Compressive Strength (MPa)**
H_1	3.8
H_2	3.7
H_3	4
Average	**3.8**
Standard deviation	**0.15**

Table 4.55: Compressive strength of H_4 to H_6.

Sample ID for 28 day test result samples	**Compressive Strength (MPa)**
H_4	10.8
H_5	10
H_6	9.6
Average	**10.1**
Standard deviation	**0.61**

Table 4.56: Compressive strength of H_7 to H_9.

Sample ID for 90 day test result samples	**Compressive Strength (MPa)**
H_7	14.6
H_8	13.7
H_9	16.8
Average	**15**
Standard deviation	**1.59**

4.7.5 Effects of partial substitution of cement and potable water with eggshell powder and river water on the flexural strength of concrete

The flexural strength of each beam was tested individually and the results are presented from Table 4.57 to Table 4.59. The average flexural strengths of the samples at 7 days, 28 days and 90 days were 1.2 MPa at 7 days, 3.1 MPa at 28 days and 4 MPa at 90 days. The results show that there was an increase in flexural strength as the curing age of the samples increased. Contrary to the poor performance of mix 5 in terms of its compressive strength, mix 5 has a viable flexural strength outcome. The average 7 day flexural strength test result of mix 5 was higher than that of mix 2. Mix 5's average 90 day flexural strength test result outcome was also higher than both that of mix 2 and mix 3. Furthermore, the average 28-day flexural strength outcome of 3.1 MPa is comparable to that of Lakhiar et al. (2018) who obtained a flexural strength of 3.51 MPa at 28 days for a normal 20 MPa concrete mix. However, the average 7 day, 28 day and 90 day flexural strength test results of mix 5 remain significantly lower than those of the control mix.

Table 4.57: Flexural strength of H_1 to H_3.

Sample ID for 7 day test result samples	**Flexural Strength (MPa)**
H_1	1.2
H_2	1.1
H_3	1.2
Average	**1.2**
Standard deviation	**0.06**

Table 4.58: Flexural strength of H_4 to H_6.

Sample ID for 28 day test result samples	**Flexural Strength (MPa)**
H_4	2.8
H_5	3.3
H_6	3.2
Average	**3.1**
Standard deviation	**0.26**

Table 4.59: Flexural strength of H_7 to H_9.

Sample ID for 90 day test result samples	**Flexural Strength (MPa)**
H_7	3.8
H_8	3.8
H_9	4.5
Average	**4**
Standard deviation	**0.40**

4.8 Comparison of slump amongst all the different mixes

Figure 4.40 shows that the addition of EPS through the substitution of coarse aggregate for mix 2 did not significantly lower nor increase the slump. However, once river water began to be used from mix 3 to mix 5 as well as other substitutes were introduced, there was a noticeable drop in the slump. The biggest drop in slump can be seen in mix 4. This may be due to mix 4 having the highest number of substitutes in a single mix, therefore making its workability noticeably lower than that of the other mixes.

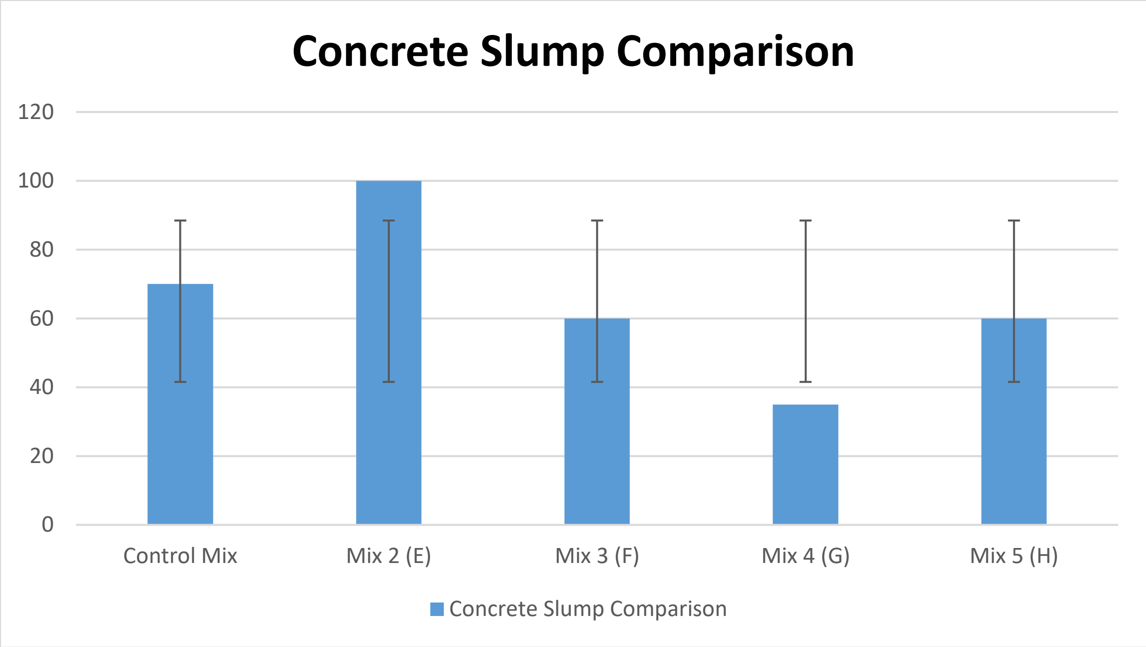


Figure 4.40: Column-graph of the different slumps obtained for the various mixes.

4.9 Comparison of bulk density amongst all the different mixes for cubes tested for compressive strength

The bulk density for all the samples from mix 2 to mix 5 decreased slightly from mix to mix at the different test ages as shown in Figure 4.41. However, even with the decrease in bulk density from mix 2 to mix 5, the average values of the individual mixes still fell within what can be considered to be the range of acceptance as per EN 206 (European Standards, 2006).

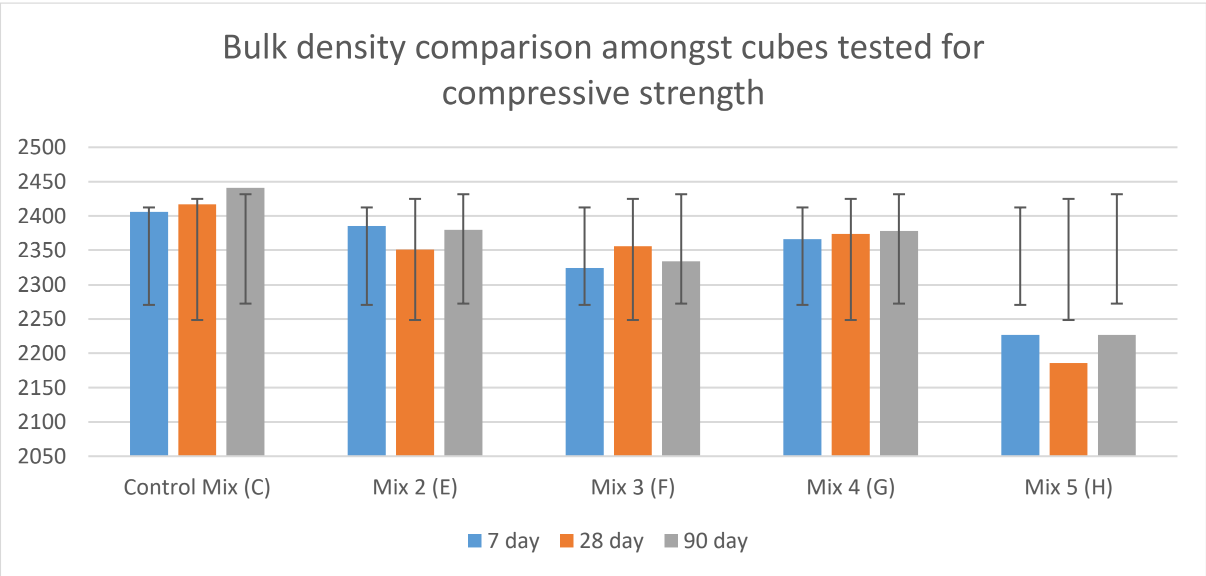


Figure 4.41: Bar-graph of the different bulk densities for the various mixes at different ages.

4.10 Comparison of bulk density amongst all the different mixes for beams

The bulk density of all the beams tested for flexural strength for all the mixes displayed a different trend to the bulk density of the cubes tested for compressive strength. Instead of a continuous slight decrease in each testing age within each different mix as was the case with the beams, the average bulk density results for the cubes slightly increased in each testing age within each different mix.

The importance of testing bulk density is to ensure that the samples prepared are within the range of acceptance in terms of weight; from the average values shown in Figure 4.42 it can be seen that the individual bulk densities for the prepared mixes all fell within what can be considered to be the range of acceptance as per EN 206 (European Standards, 2006).

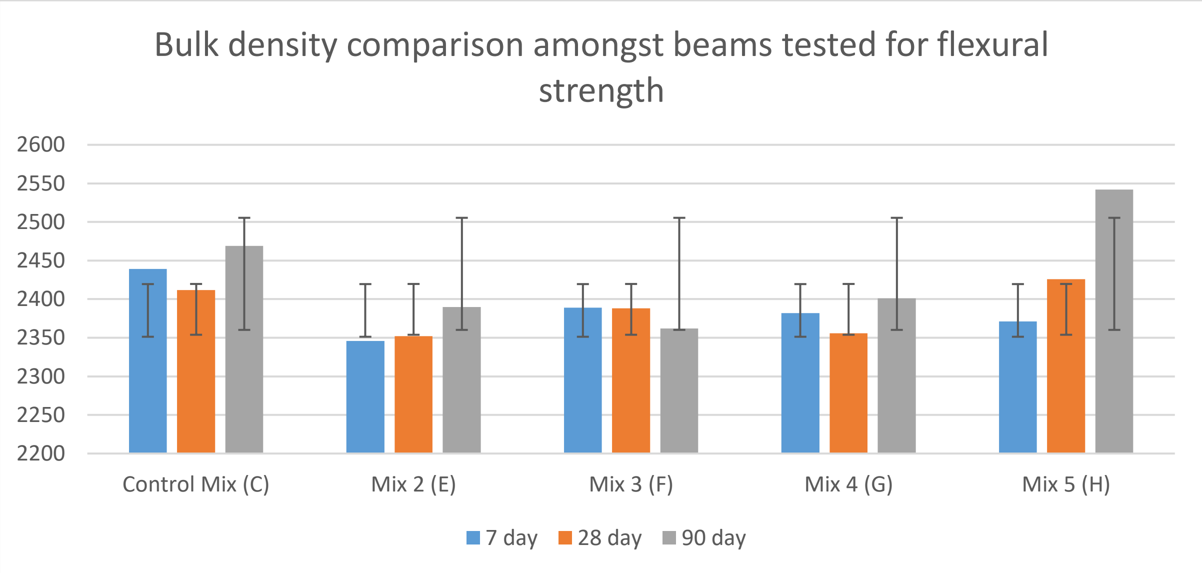


Figure 4.42: Bar-graph of the different bulk densities for the various mixes.

4.11 Comparison of compressive strength amongst all the different mixes

From Figure 4.43 it is evident that the only two mixes that managed to not only match the target compressive strength of 20 MPa at a test age of 28 days but also surpassed it, were mix 2 and mix 4. Mix 4 achieved an interesting compressive strength outcome considering that it contained half the substitution percentage of mix 3 in terms of EPS. Furthermore, it is important to note that mix 4 also contained an uncommon substitute within concrete, namely, eggshell powder. Considering that mix 4 was a complex mix containing three simultaneous substitutions instead of two, a natural expectation would have been that it would not reach the target strength, however, it not only reached it, but also surpassed it. The outcome of the compressive strength of mix 4 is commendable because in the real world of construction this means that when a mix such as mix 4 is used to construct various structural elements, 5 % of the total required volume of cement can be cut back and substituted with eggshell powder, 5 % of the total volume of coarse aggregate can be cut back and replaced by EPS, and potable water can also potentially be replaced by river water depending on the chemical and bacteriological characteristics of the river water. Although mix 2 also reached a similar compressive strength as mix 4 at 28 days, the main advantage that mix 4 had over mix 2 was the use of additional substitutes such as river water instead of potable water.

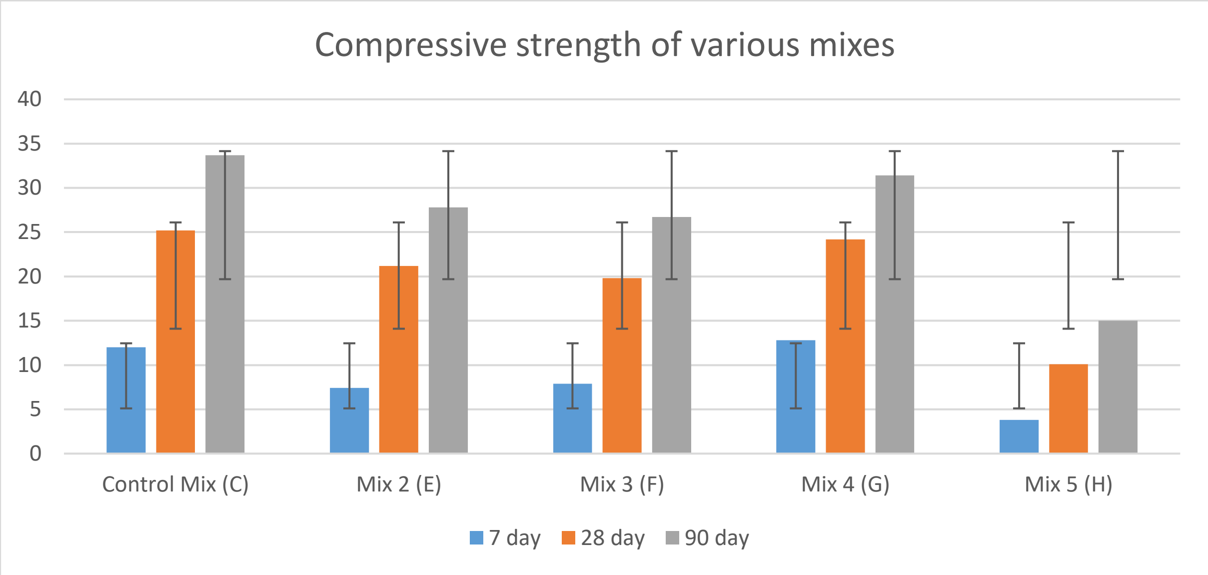


Figure 4.43: Bar-graph of the different compressive strengths for the various mixes.

4.12 Comparison of flexural strength amongst all the different mixes

The flexural performance of the various mixes largely lagged behind the flexural strength outcome of the control mix as shown in Figure 4.44. The only mix which managed to surpass the flexural strength of the control mix was mix 2 at a test age of 28 days. This means that a mix such as mix 2, which has 10 % of coarse aggregate substituted by EPS and was mixed using potable water, is capable of having a higher flexural strength than concrete which contains no substitutions but that has been mixed using river water. It is also important to note that mix 3 and mix 4 achieved the same flexural strength outcomes at a test age of 28 days. This means that although mix 3 contained 10 % substitution of coarse aggregate by EPS and was mixed using non-potable water, and mix 4 contained 5 % substitution of coarse aggregate by EPS and 5 % substitution of cement by eggshell powder and was mixed using non-potable water, they still were able to produce the same flexural strength outcome after 28 days. It was also observed that although mix 5 attained a substantially lower compressive strength when compared to the control mix as well as to all the other mixes, its flexural strength was observed to be higher than both mix 2 and mix 3 after 90 days. This is of significance when considering the different compositions of mix 2, mix 3 and mix 5. It means that a mix such as mix 5 which contains 10 % substitution of cement by eggshell powder mixed using river water instead of potable water is capable of surpassing the flexural strength of both of the mixes which contained no substitution of cement but only substitution of coarse aggregate by 10 % either mixed with river water or potable water, at a test age of 90 days.

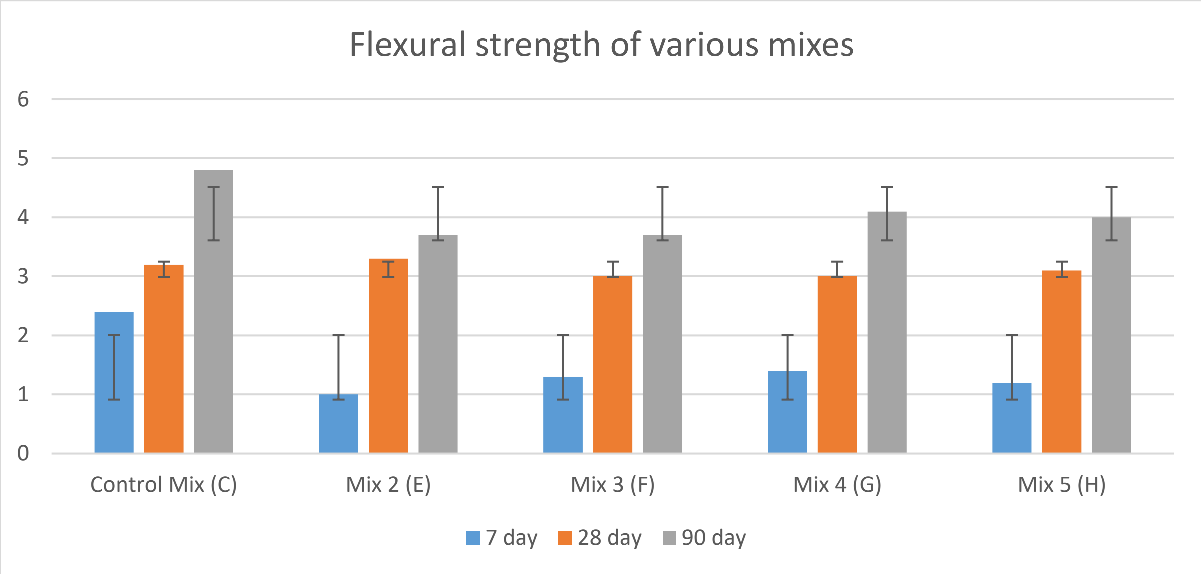


Figure 4.44: Bar-graph of the different flexural strengths for the various mixes.

4.13 Models for estimating the strength of different concrete mixes considered during the research

Considering the results presented above, the researcher developed mathematical models to be able to estimate the strength of the mixes at various ages. This would allow both the compressive and flexural strength of any of the mixes considered during the research to easily be approximated at any given age which was not physically tested during the research since the physical testing was confined to 7 days, 28 days and 90 days. Estimative models are not only a mathematical tool that can be used to generate further numerical analysis of the considered mixes, but can also be used to identify other trends which may not have been identified by the outcomes of the physical tests done at 7 days, 28 days and 90 days. It is also important to note that the models that have been developed can only be used as estimative models for the exact mixes that have been used in this research.

Logarithmic regression was used to generate models for estimating compressive and flexural strength. Individual test results (raw test database) were used for the regression analysis. Logarithmic regression is a statistical technique that is used for estimating the dependant variable's outcome based on the values of the possible independent variables (Stanton, 2001). The logarithmic regression equation used is as follows:

$$y = \ln(x)\, a + b \tag{4.1}$$

Where:

y = Response variable (this is either the compressive or flexural strength)

x= Predictor variable (this is the variable that is influencing y and will be the curing age)
a= Regression coefficient that describe the relationship between x and y
b= Regression coefficient that describe the relationship between x and y

The mathematical equations are elaborated hereunder.

4.13.1 Equations for finding the compressive and flexural strength of the various mixes at different ages

Five different mixes were considered during this research. Four of the mixes were investigated in greater detail, namely mix 2, mix 3, mix 4 and mix 5. Mix 2 contained 10 % replacement of coarse aggregate with EPS and was mixed using potable water. Mix 3 also contained 10 % of replacement of coarse aggregate with EPS, but was mixed with river water. Mix 4 contained 5 % replacement of coarse aggregate with EPS and 5 % replacement of cement with eggshell powder, mixed with river water. The last mix (mix 5) contained 10 % replacement of cement with eggshell powder, mixed with river water.

4.13.1.1 Modelling of control mix

The proportions of the control mix are shown in Table 4.60.

Table 4.60: Mix proportions of control mix.

Material	Quantity made for 1 m^3
Cement (kg)	154
Sand (kg)	308
Stone (kg)	462
Water (l)	77

The compressive strength test results obtained for the control mix are shown in Table 4.61.

Table 4.61: Compressive strength test results for the control mix.

$\boldsymbol{x}$ (no. of days)	0	7	7	7	28	28	28	90	90	90
$\boldsymbol{y}$ (Compressive strength)	0	12.7	11.9	11.3	24.6	24.9	26.2	33.6	31.3	36.2

In order to develop an estimative model for the compressive strength of the control mix, the data from Table 4.61 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm (formula = Compressive Strength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-2.9305 -0.6305 0.2865 0.6439 1.9695

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -4.2097 1.7891 -2.353 0.0509

log (Compstrength Days) 8.5426 0.5228 16.341 7.83e-07 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Residual standard error: 1.637 on 7 degrees of freedom

Multiple R-squared: 0.9745, Adjusted R-squared: 0.9708

F-statistic: 267 on 1 and 7 DF, p-value: 7.831e-07.

Output:

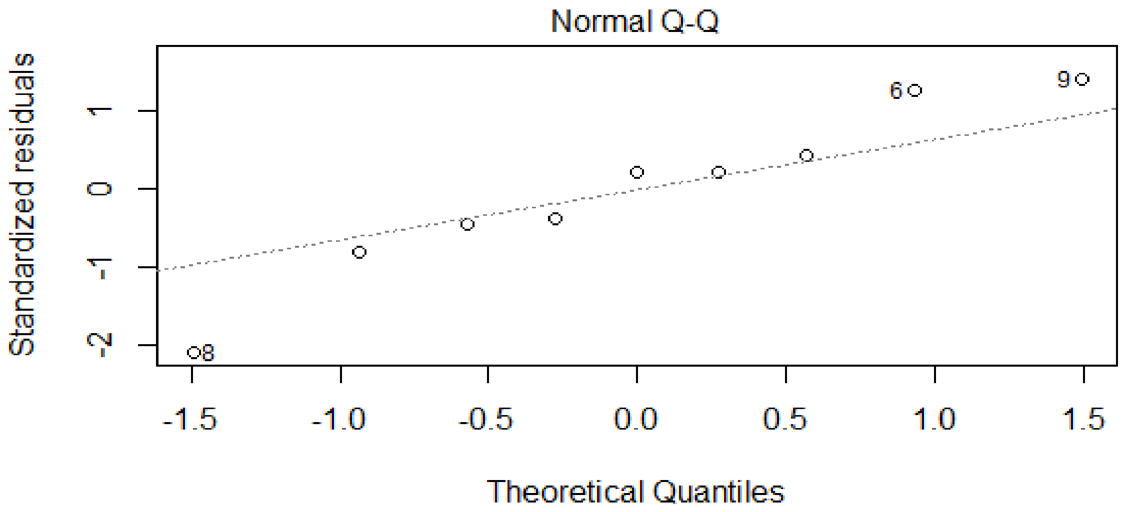


Figure 4.45: Q-Q plot of the compressive strength of the control mix.

The Points on the Normal Q-Q plot in Figure 4.45 lie around the diagonal line implying that the data follows a normal distribution though a bit skewed since some points are not close to the line. In order to visually depict the relationship between the compressive strength of the control mix over the 90 day period, a scatter plot was drawn as shown in Figure 4.46.

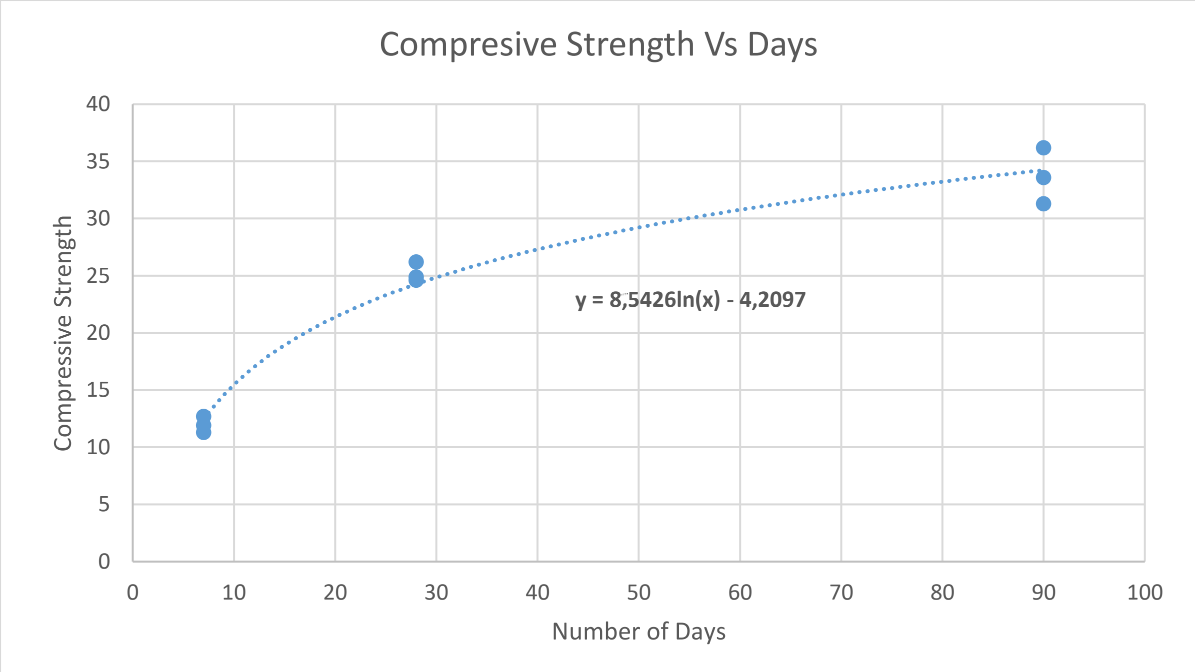


Figure 4.46: Scatter plot of the compressive strength of the control mix over the 90 day period.

The logarithmic regression model of the control mix for compressive strength over 90 days can be represented by:

$$y = 8{,}5426\ln(x) - 4{,}2097 \qquad (4.2)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of compressive strength over days for the control mix. There is a high positive logarithmic correlation between compressive strength and curing days of 91% and 97% of the variability observed in the target variable is explained by the regression model.

The flexural strength test results obtained for the control mix are shown in Table 4.62.

Table 4.62: Flexural strength test results for the control mix.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Flexural strength)	0	2.4	2.3	2.4	3.1	3.0	3.6	5.2	4.7	4.5

In order to develop an estimative model for the flexural strength of the control mix, the data from Table 4.62 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm (formula = Flexural Strength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-0.53538 -0.13604 0.06462 0.17143 0.56396

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 0.3942 0.3886 1.015 0.344

log(Flex Strength Days) 0.9427 0.1135 8.303 7.18e-05 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3555 on 7 degrees of freedom

Multiple R-squared: 0.9078, Adjusted R-squared: 0.8947

F-statistic: 68.94 on 1 and 7 DF, p-value: 7.183e-05

Output:

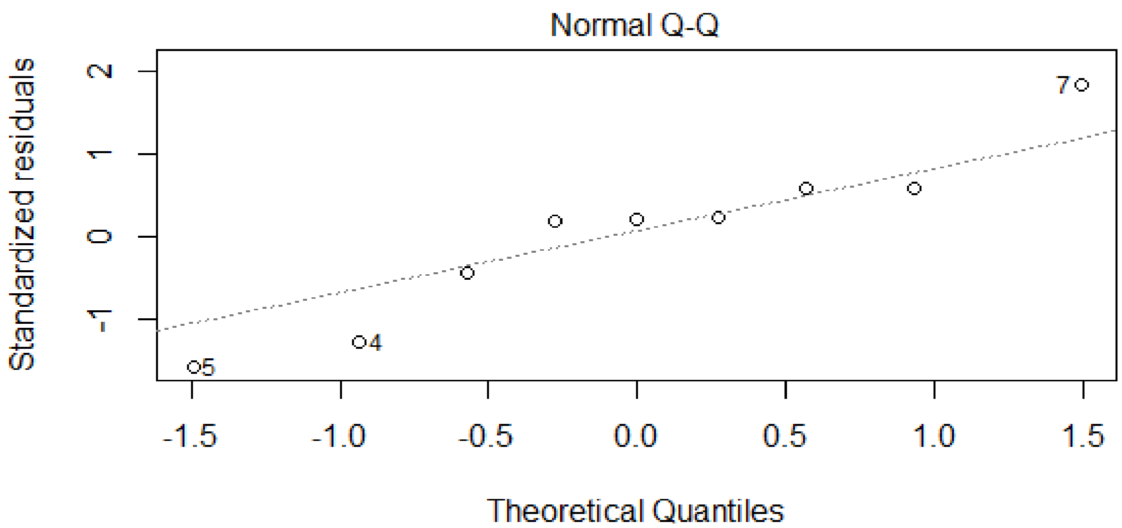


Figure 4.47: Q-Q plot of the flexural strength of the control mix.

The points on the Normal Q-Q plot in Figure 4.47 approximate a diagonal line implying that the data follows a normal distribution though a bit skewed since some points are not close to the line. In order to visually depict the relationship between the flexural strength of the control mix over the 90 day period, a scatter plot was drawn as shown in Figure 4.48.

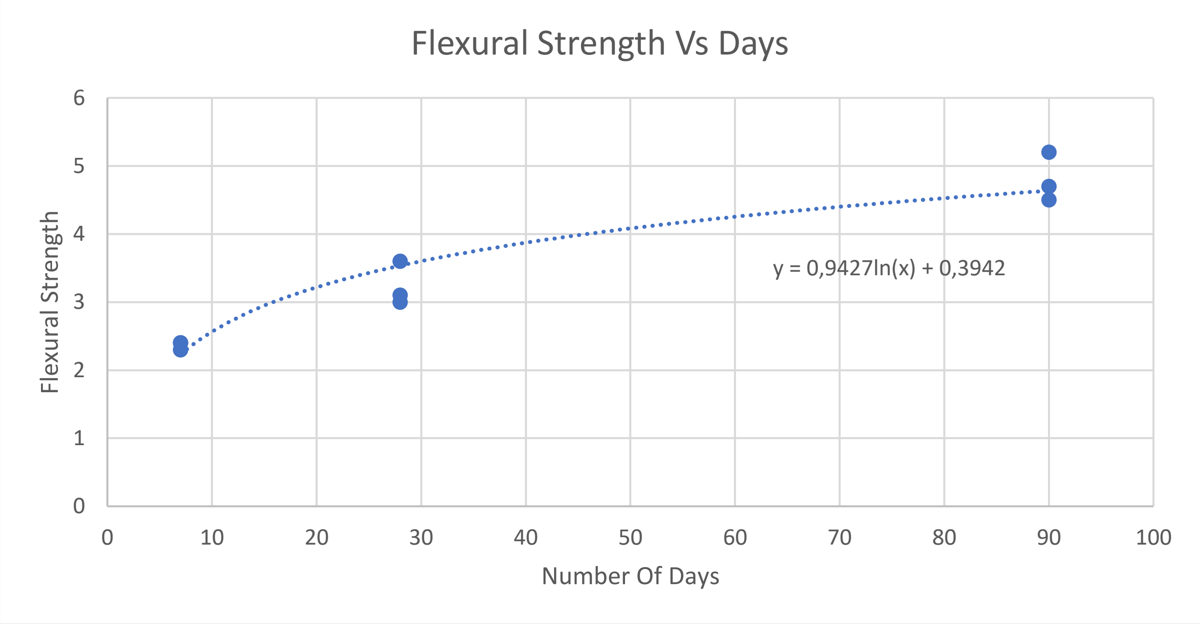


Figure 4.48: Scatter plot of the flexural strength of the control mix over the 90 day period.

The logarithmic regression model of the control mix for flexural strength over 90 days can be represented by:

$$y = 0{,}9427\ln(x) + 0{,}3942 \qquad (4.3)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of flexural strength over days for the control mix. There is a high positive logarithmic correlation between flexural strength and curing days of 97% and 90% of the variability observed in the target variable is explained by the regression model.

4.13.1.2 Modelling of concrete mix including EPS mixed using normal potable water

The proportions of the concrete mix that incorporated EPS for mix 2 are shown in Table 4.63.

Table 4.63: Mix proportions of mix 2.

Material	**Quantity made for 1 m^3**
Cement (kg)	150
Sand (kg)	310
Stone (kg)	420
Expanded Polystyrene (kg)	50
Water (l)	70

The compressive strength test results obtained for mix 2 are shown in Table 4.64.

Table 4.64: Compressive strength test results for mix 2.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Compressive strength)	0	7.3	7.3	7.6	20.7	21.1	21.8	27.6	28	27.8

In order to develop an estimative model for the compressive strength of mix 2, the data from Table 4.64 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\,a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm (formula = CompressiveStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-1.1843 -0.9290 -0.7843 1.3133 2.4133

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -7.4328 1.6310 -4.557 0.00261 **

log(Days) 8.0486 0.4766 16.889 6.25e-07 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Residual standard error: 1.492 on 7 degrees of freedom

Multiple R-squared: 0.976, Adjusted R-squared: 0.9726

F-statistic: 285.2 on 1 and 7 DF, p-value: 6.25e-07

Output:

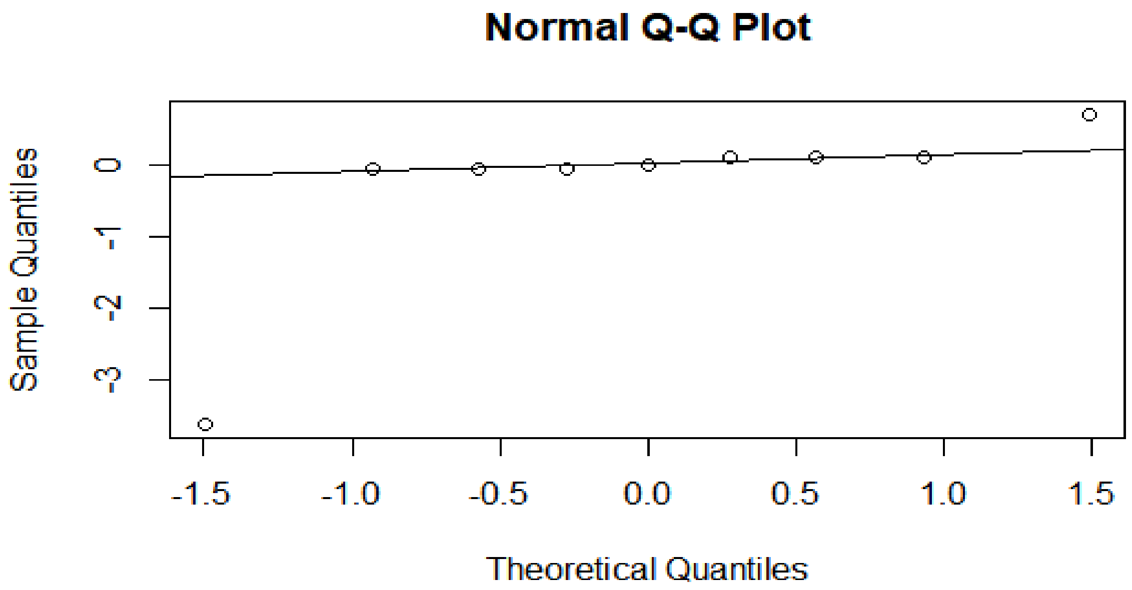


Figure 4.49: Q-Q plot of the compressive strength of mix 2.

The points on the Normal Q-Q plot in Figure 4.49 approximate a diagonal line except for two outliers implying that the data follows a normal distribution though a bit skewed since some points are not close to the line. In order to visually depict the relationship between the compressive strength of mix 2 over the 90 day period, a scatter plot was drawn as shown in Figure 4.50.

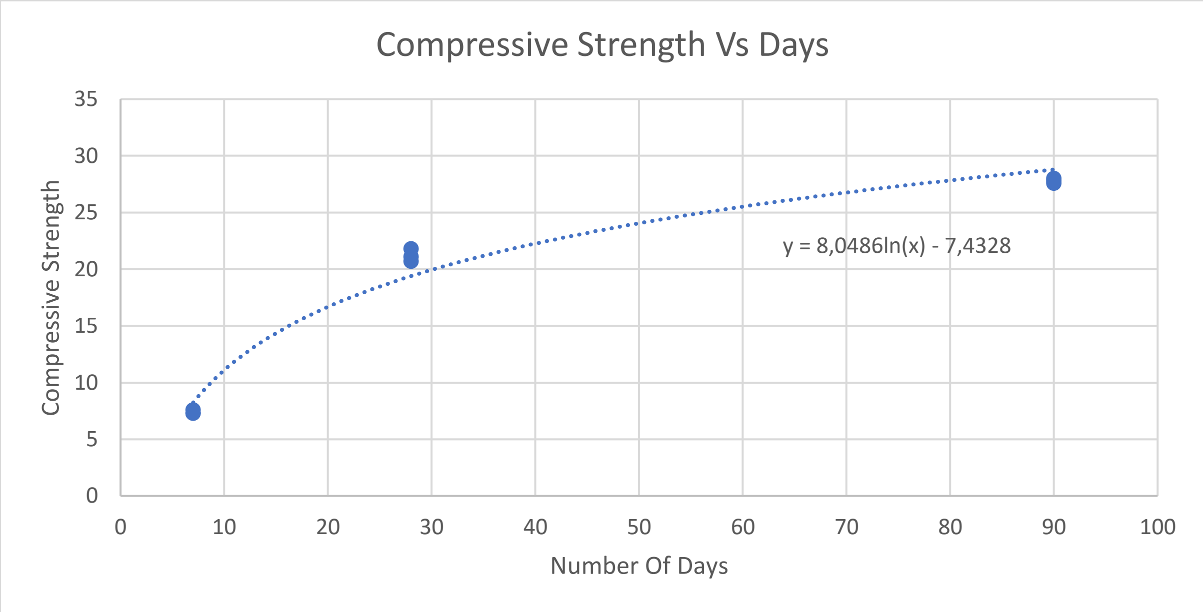


Figure 4.50: Scatter plot of the compressive strength of mix 2 over the 90 day period.

The logarithmic regression model of mix 2 for compressive strength over 90 days can be represented by:

$$y = 8{,}0486\ln(x) - 7{,}4328 \tag{4.4}$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of compressive strength over days for mix 2. There is a high positive logarithmic correlation between compressive strength and curing days of 89% and 97% of the variability observed in the target variable is explained by the regression model.

The flexural strength test results obtained for mix 2 are shown in Table 4.65.

Table 4.65: Flexural strength test results for mix 2.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Flexural strength)	0	1.2	0.9	1	3.4	3.1	3.5	3.6	3.9	3.6

In order to develop an estimative model for the flexural strength of mix 2, the data from Table 4.65 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\,a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula =FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-0.4078 -0.3925 -0.1077 0.3336 0.7336

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -0.7763 0.5295 -1.466 0.186047

log(Days) 1.0632 0.1547 6.872 0.000237 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Residual standard error: 0.4845 on 7 degrees of freedom

Multiple R-squared: 0.8709,   Adjusted R-squared: 0.8525

F-statistic: 47.22 on 1 and 7 DF, p-value: 0.0002373

Output:

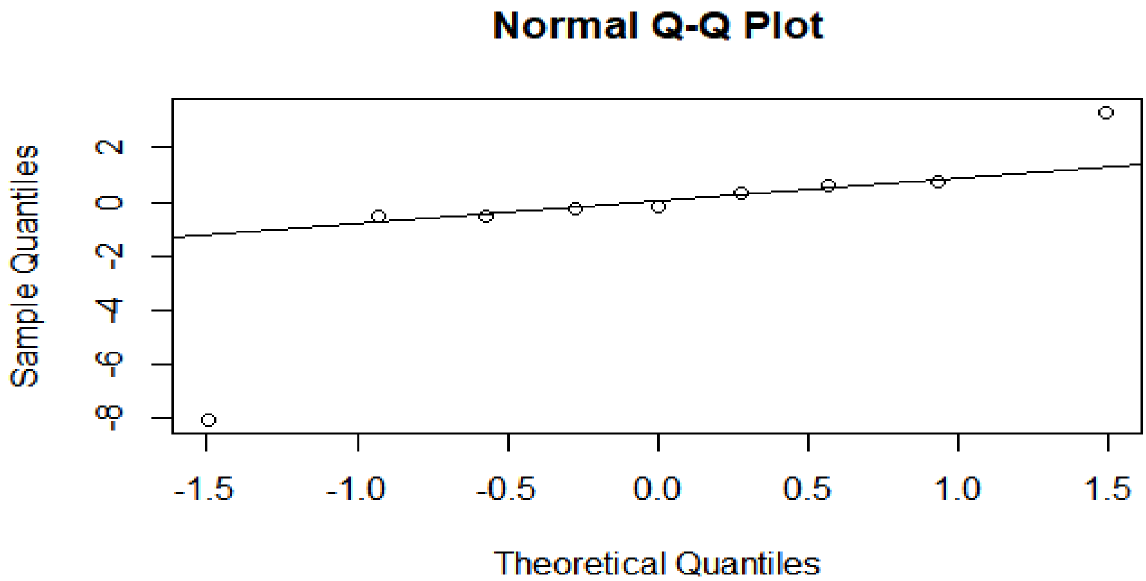


Figure 4.51: Q-Q plot of the flexural strength of mix 2.

The points on the Normal Q-Q plot in Figure 4.51 approximate a diagonal line except for two outliers implying that the data follows a normal distribution. In order to visually depict the relationship between the flexural strength of mix 2 over the 90 day period, a scatter plot was drawn as shown in Figure 4.52.

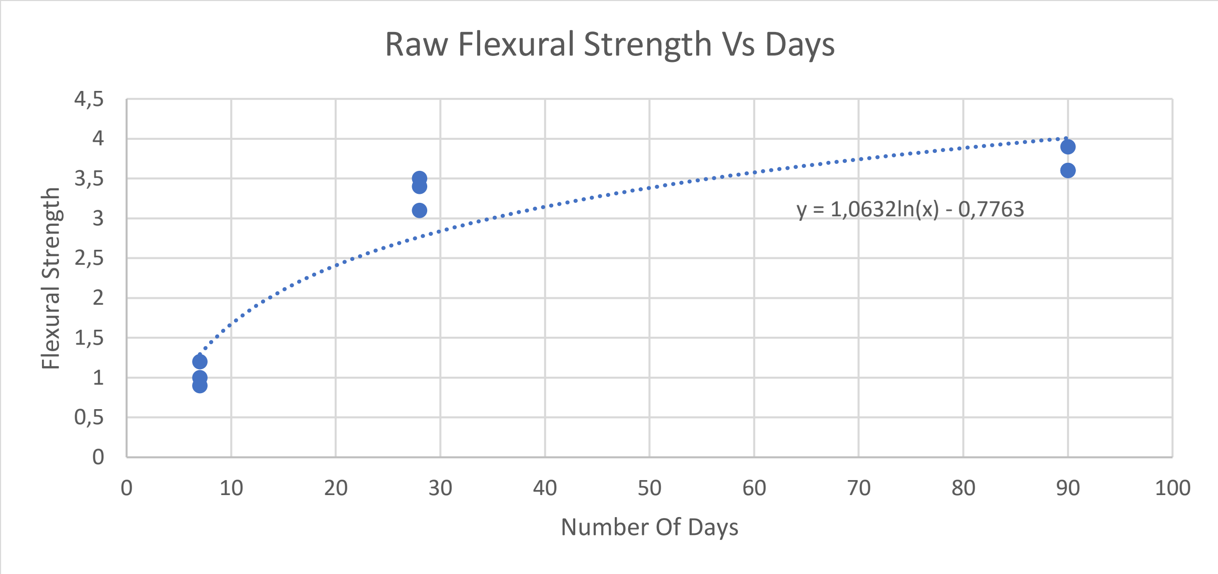


Figure 4.52: Scatter plot of the flexural strength of mix 2 over the 90 day period.

The logarithmic regression model of mix 2 for flexural strength over 90 days can be represented by:

$$y = 1{,}0632\ln(x) - 0{,}7763 \qquad (4.5)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of flexural strength over days for mix 2. There is a high positive logarithmic correlation between flexural strength and curing days of 78% and 85% of the variability observed in the target variable is explained by the regression model.

4.13.1.3 Modelling of concrete mix including EPS mixed using river water

The proportions of the concrete mix that incorporated EPS for mix 3 are shown in Table 4.66. The quantities for mix 3 do not differ from mix 2 since the objective of mix 3 was to test through experimentation how the same mix as mix 2 would perform when mixed using river water instead of potable water.

Table 4.66: Mix proportions of mix 3.

Material	**Quantity made for 1 m^3**
Cement (kg)	150
Sand (kg)	310
Stone (kg)	420
Expanded Polystyrene (kg)	50
Water (l)	70

The compressive strength test results obtained for mix 3 are shown in Table 4.67.

Table 4.67: Compressive strength test results for mix 3.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Compressive strength)	0	8.4	7.9	7.5	20	20.2	19.1	24.9	29.1	26.2

In order to develop an estimative model for the compressive strength of mix 3, the data from Table 4.67 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\,a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula = CompressiveStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-2.42118 -0.92845 -0.02845 1.31630 1.77882

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -5.9666 1.6330 -3.654 0.00814 **

log(Days) 7.3976 0.4772 15.504 1.12e-06 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.494 on 7 degrees of freedom

Multiple R-squared: 0.9717, Adjusted R-squared: 0.9677

F-statistic: 240.4 on 1 and 7 DF, p-value: 1.122e-06

Output:

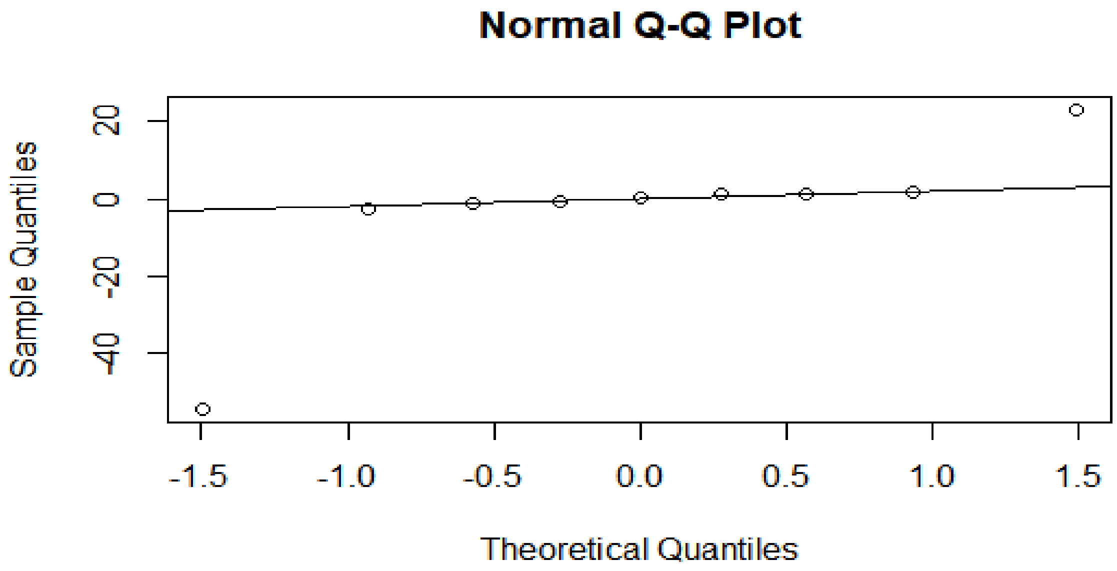


Figure 4.53: Q-Q plot of the compressive strength of mix 3.

The points on the Normal Q-Q plot in Figure 4.53 approximate a diagonal line except for two outliers implying that the data follows a normal distribution with minimal skewness. In order to visually depict the relationship between the compressive strength of mix 3 over the 90 day period, a scatter plot was drawn as shown in Figure 4.54.

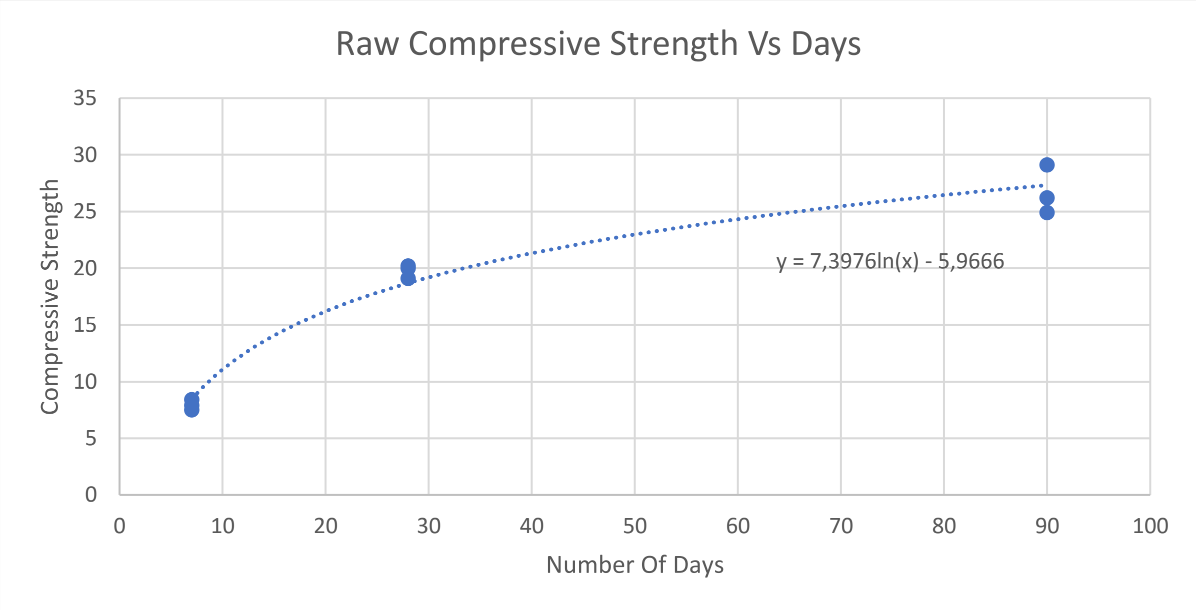


Figure 4.54: Scatter plot of the compressive strength of mix 3 over the 90 day period.

The logarithmic regression model of mix 3 for compressive strength over 90 days can be represented by:

$$y = 7{,}3976\ln(x) - 5{,}9666 \qquad (4.6)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of compressive strength over 90 days for mix 3. There is a high positive logarithmic correlation between compressive strength and curing days of 90% and 97% of the variability observed in the target variable is explained by the regression model.

The flexural strength test results obtained for mix 3 are show in Table 4.68.

Table 4.68: Flexural strength test results for mix 3.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Flexural strength)	0	1.4	1.3	1.3	2.8	3	3.2	2.7	3.8	3.7

In order to develop an estimative model for the flexural strength of mix 3, the data from Table 4.68 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm (formula = FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-0.8967 -0.1990 0.1033 0.2033 0.5624

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -0.09932 0.49202 -0.202 0.845770

log(Days) 0.82137 0.14377 5.713 0.000725 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4502 on 7 degrees of freedom

Multiple R-squared: 0.8234, Adjusted R-squared: 0.7982

F-statistic: 32.64 on 1 and 7 DF, p-value: 0.0007253

Output:

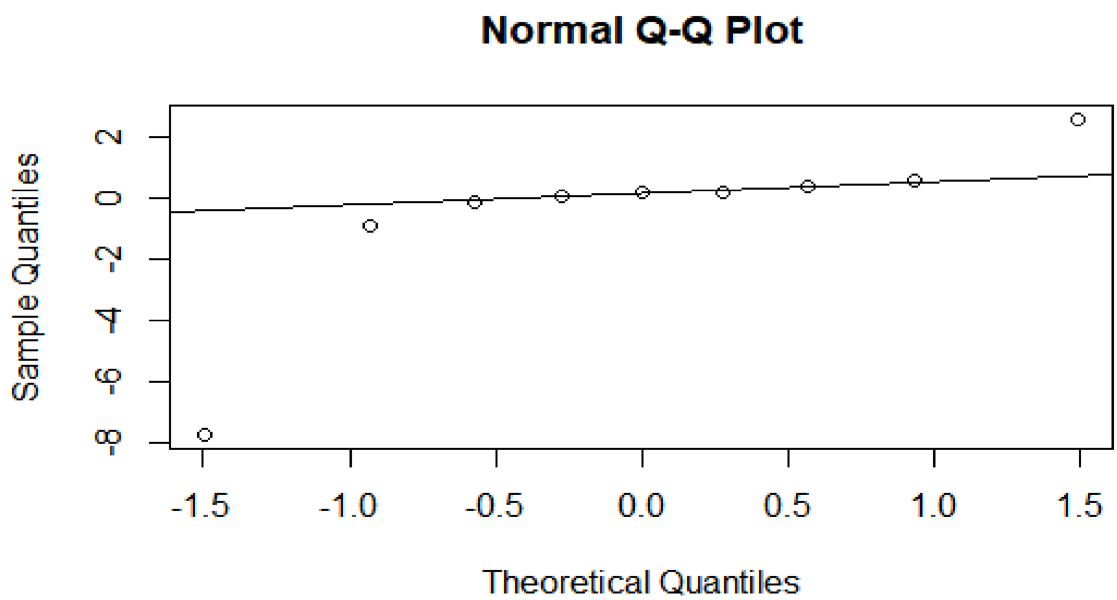


Figure 4.55: Q-Q plot of the flexural strength of mix 3.

The points on the Normal Q-Q plot in Figure 4.55 approximate a diagonal line except for two outliers implying that the data follows a normal distribution with minimal skewness. In order to visually depict the relationship between the flexural strength of mix 3 over the 90 day period, a scatter plot was drawn as shown in Figure 4.56.

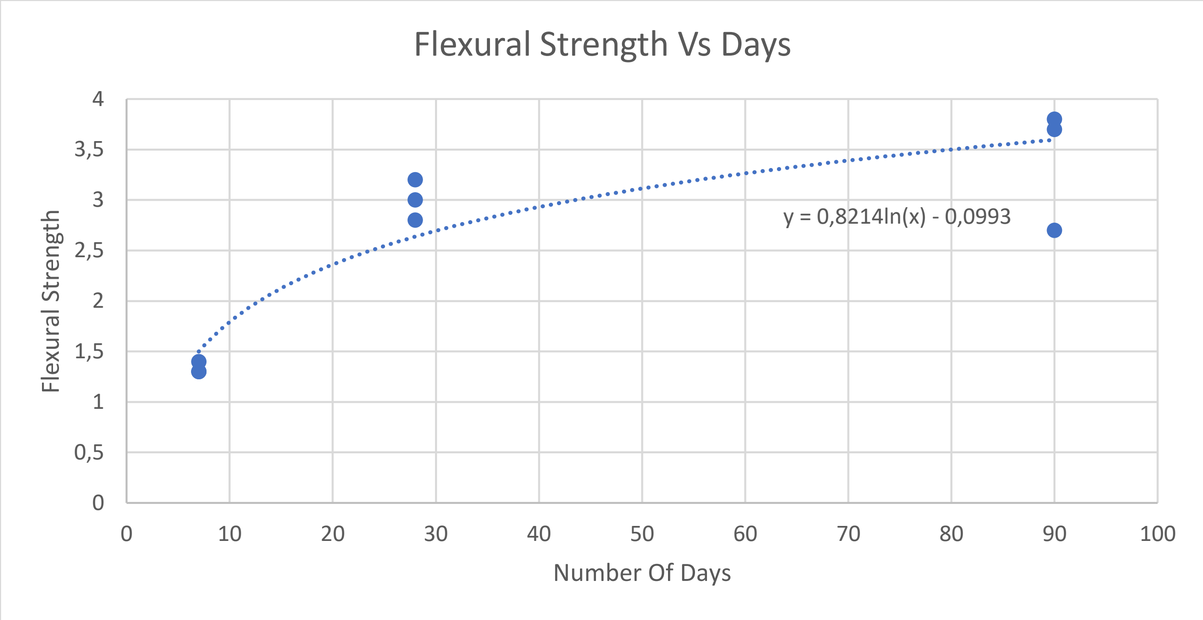


Figure 4.56: Scatter plot of the flexural strength of mix 3 over the 90 day period.

The logarithmic regression model of mix 3 for flexural strength over 90 days can be represented by:

$$y = 0{,}8214\ln(x) - 0{,}09993 \qquad (4.7)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of flexural strength over 90 days for mix 3. There is a high positive logarithmic correlation between flexural strength and curing days of 77% and 80% of the variability observed in the target variable is explained by the regression model.

4.13.1.4 Modelling of concrete mix including EPS and eggshell powder mixed using river water

The proportions of the concrete mix that incorporated EPS and eggshell powder and were mixed using river water, are shown in Table 4.69.

Table 4.69: Mix proportions of mix 4.

Material	**Quantity made for 1m^3**
Cement (kg)	146
Sand (kg)	307
Stone (kg)	438
Expanded Polystyrene (kg)	24
Water (l)	77
Eggshell powder (kg)	8

The compressive strength test results obtained for mix 4 are shown in Table 4.70.

Table 4.70: Compressive strength test results for mix 4.

$\boldsymbol{x}$ (no. of days)	0	7	7	7	28	28	28	90	90	90

y (Compressive strength)	0	12.4	12.7	13.2	23.2	23.8	25.6	31.4	29.7	33.2

In order to develop a estimative model for the compressive strength of mix 4, the data from Table 4.70 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula = FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-2.2029 -0.5029 -0.1349 0.4651 2.2651

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -1.1171 1.4864 -0.752 0.477

log(Days) 7.3381 0.4343 16.896 6.23e-07 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.36 on 7 degrees of freedom

Multiple R-squared: 0.9761, Adjusted R-squared: 0.9726

F-statistic: 285.5 on 1 and 7 DF, p-value: 6.23e-07

Output:

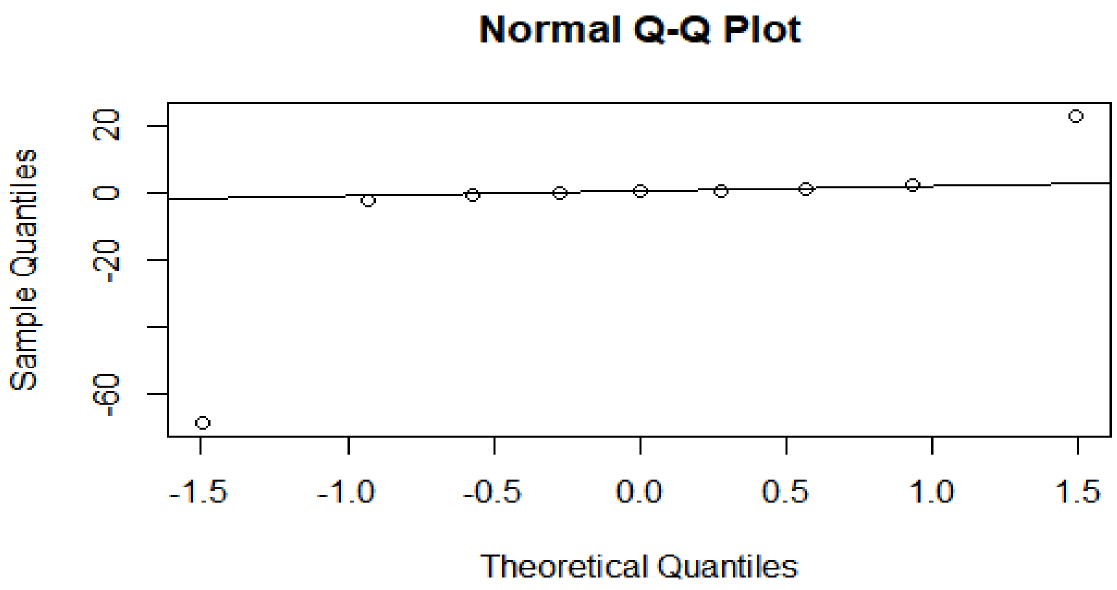


Figure 4.57: Q-Q plot of the compressive strength of mix 4.

The points on the Normal Q-Q plot in Figure 4.57 approximate a diagonal line except for two outliers implying that the data follows a normal distribution. In order to visually depict the relationship between the compressive strength of mix 4 over the 90 day period, a scatter plot was drawn as shown in Figure 4.58.

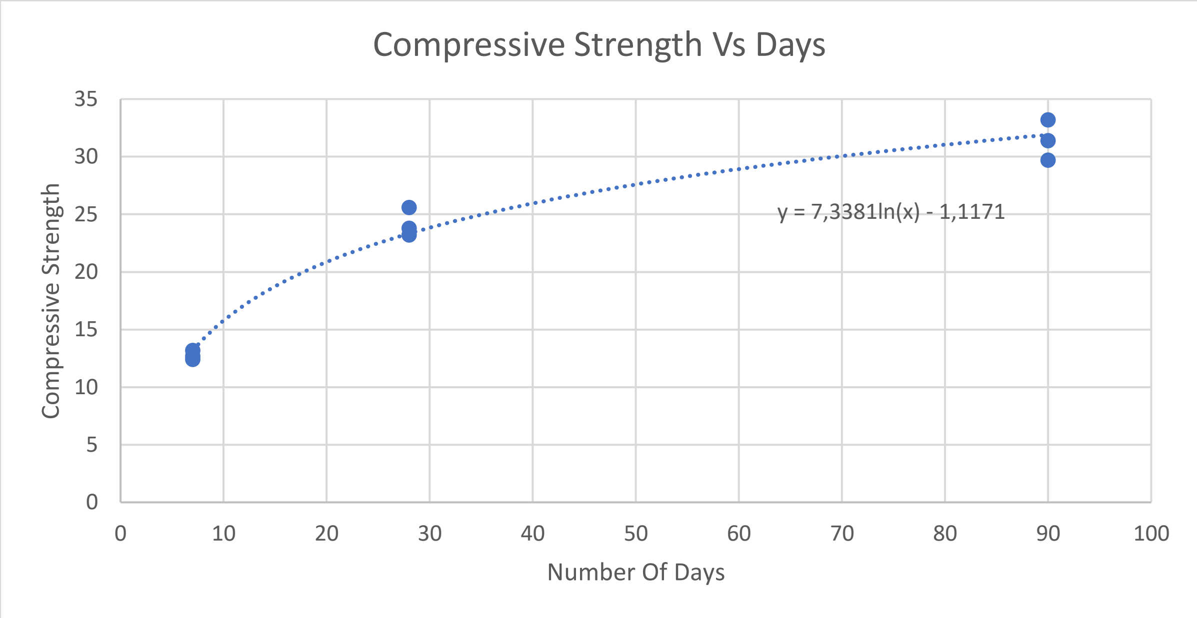


Figure 4.58: Scatter plot of the compressive strength of mix 4 over the 90 day period.

The logarithmic regression model of mix 4 for compressive strength over 90 days can be represented by:

$$y = 7{,}3381\ln(x) - 1{,}1171 \qquad (4.8)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of compressive strength over 90 days for mix 4. There is a high positive logarithmic correlation between compressive strength and curing days of 91% and 97% of the variability observed in the target variable is explained by the regression model.

The flexural strength test results obtained for mix 4 are shown in Table 4.71.

Table 4.71: Flexural strength test results for mix 4.

x (no. of days)	0	7	7	7	28	28	28	90	90	90
y (Flexural strength)	0	1.4	1.3	1.5	3	2.5	3.5	4.2	4.2	4

In order to develop an estimative model for the flexural strength of mix 4, the data from Table 4.71 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula = FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-0.42265 -0.13536 0.02468 0.06464 0.57735

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -0.65231 0.31284 -2.085 0.0755

log(Days) 1.07285 0.09141 11.737 7.38e-06 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2863 on 7 degrees of freedom

Multiple R-squared: 0.9516, Adjusted R-squared: 0.9447

F-statistic: 137.7 on 1 and 7 DF, p-value: 7.378e-06

Output:

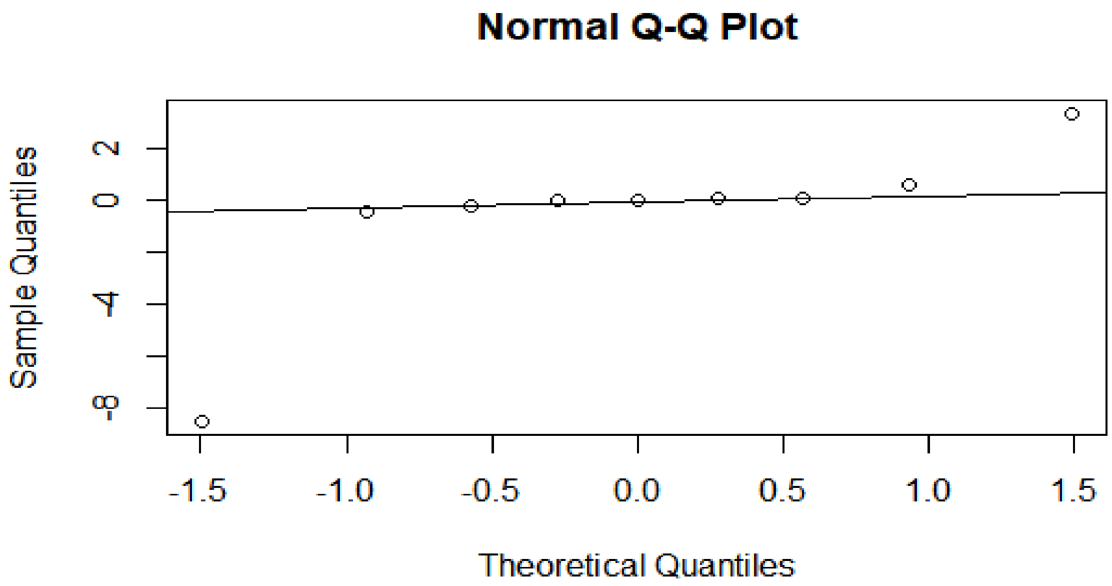


Figure 4.59: Q-Q plot of the flexural strength of mix 4.

The points on the Normal Q-Q plot in Figure 4.59 approximate a diagonal line except for two outliers implying that the data follows a normal distribution. In order to visually depict the relationship between the flexural strength of mix 4 over the 90 day period, a scatter plot was drawn as shown in Figure 4.60.

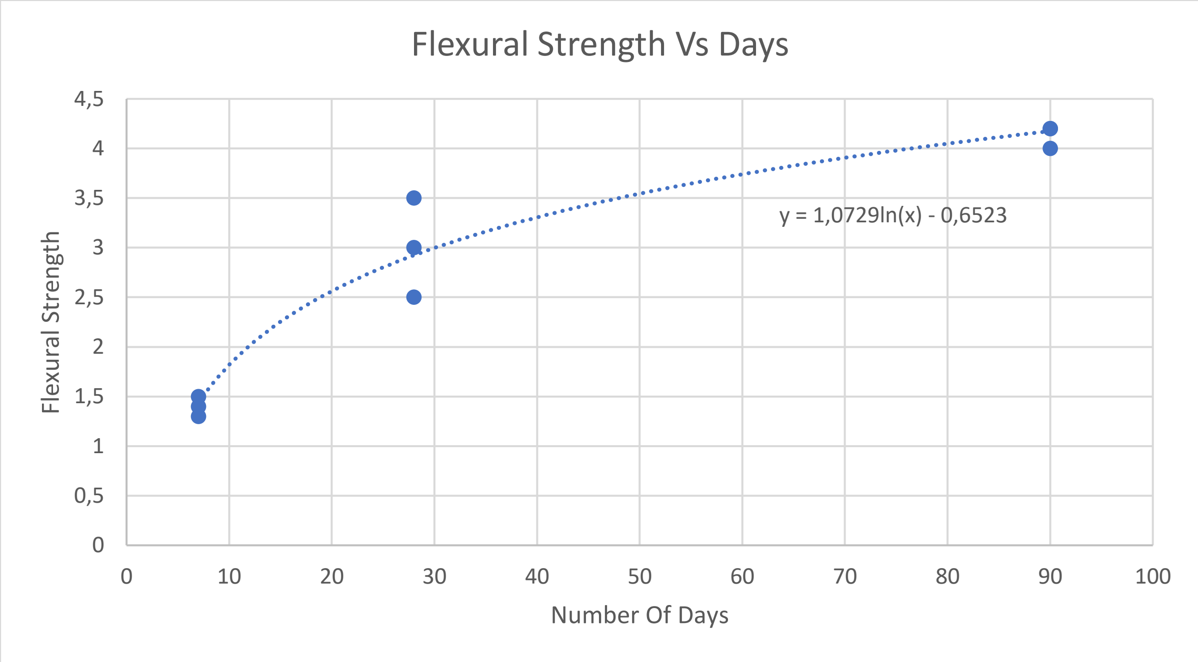


Figure 4.60: Scatter plot of the flexural strength of mix 4 over the 90 day period.

The logarithmic regression model of mix 4 for flexural strength over 90 days can be represented by:

$$y = 1{,}0729\ln(x) - 0{,}6523 \quad (4.9)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of flexural strength over 90 days for mix 4. There is a high positive logarithmic correlation between flexural strength and curing days of 91% and 97% of the variability observed in the target variable is explained by the regression model.

4.13.1.5 Modelling of concrete mix including eggshell powder mixed using river water

The proportions of the concrete mix that incorporated eggshell powder mixed using river water are shown in Table 4.72.

Table 4.72: Mix proportions of mix 5.

Material	**Quantity made for 1 m^3**
Cement (kg)	138
Sand (kg)	308
Stone (kg)	462
Water (l)	77
Eggshell powder (kg)	15

The compressive strength test results obtained for mix 5 are shown in Table 4.73.

Table 4.73: Compressive strength test results for mix 5.

x (no. of days)	0	7	7	7	28	28	28	90	90	90

y (Compressive strength)	0	3.8	3.7	4	10.8	10	9.6	14.6	13.7	16.8

In order to develop an estimative model for the compressive strength of mix 5, the data from Table 4.73 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula = FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-1.41292 -0.38671 -0.10037 0.09963 1.68708

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -4.6429 1.0098 -4.598 0.00249 **

log(Days) 4.3904 0.2951 14.880 1.48e-06 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Residual standard error: 0.924 on 7 degrees of freedom

Multiple R-squared: 0.9694, Adjusted R-squared: 0.965

F-statistic: 221.4 on 1 and 7 DF, p-value: 1.485e-06

Output:

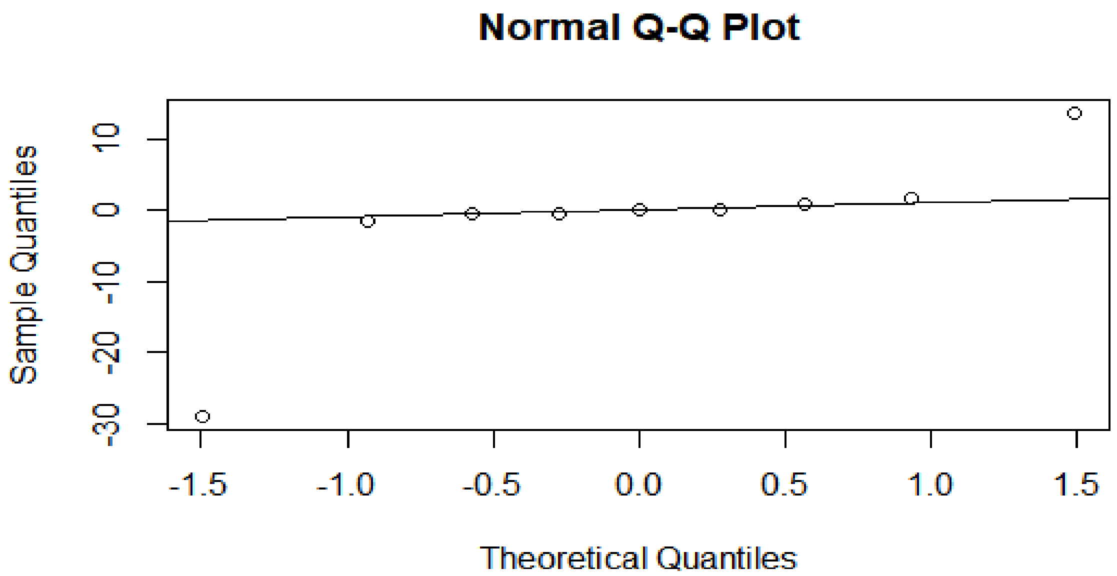


Figure 4.61: Q-Q plot of the compressive strength of mix 5.

The points on the Normal Q-Q plot in Figure 4.61 approximate a diagonal line except for two outliers implying that the data follows a normal distribution. In order to visually depict the relationship between the compressive strength of mix 5 over the 90 day period, a scatter plot was drawn as shown in Figure 4.62.

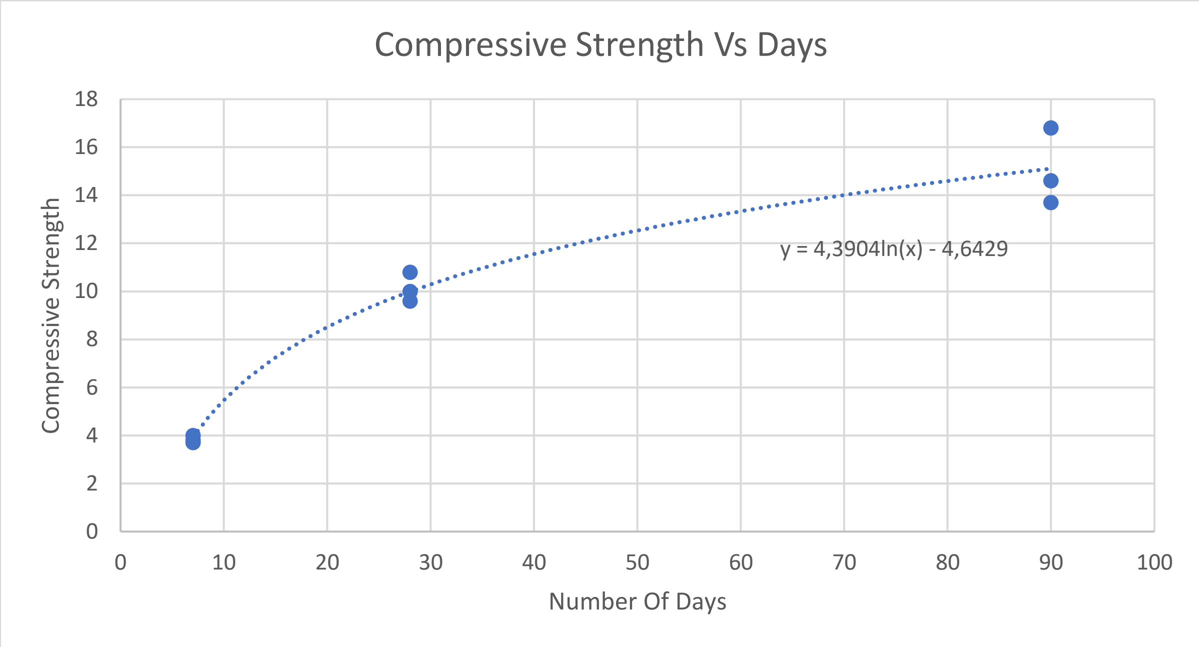


Figure 4.62: Scatter plot of the compressive strength of mix 5 over the 90 day period.

The logarithmic regression model of mix 5 for compressive strength over 90 days can be represented by:

$$y = 4{,}3904\ln(x) - 4{,}6429 \qquad (4.10)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of compressive strength over 90 days for mix 5. There is a high positive logarithmic correlation between compressive strength and curing days of 93% and 97% of the variability observed in the target variable is explained by the regression model.

The flexural strength test results obtained for mix 5 are shown in Table 4.74.

Table 4.74: Flexural strength test results for mix 5.

$\boldsymbol{x}$ (no. of days)	0	7	7	7	28	28	28	90	90	90
$\boldsymbol{y}$ (Flexural strength)	0	1.2	1.1	1.2	2.8	3.3	3.2	3.8	3.8	4.5

In order to develop an estimative model for the flexural strength of mix 5, the data from Table 4.74 was used. The estimative model was developed using logarithmic regression in the form of:

$$y = \ln(x)\, a + b$$

In order to test the normality assumption, a Q-Q plot was used. By using this method, the observed value and expected value were plotted on a graph.

Call:

lm(formula = FlexuralStrength ~ log(Days))

Residuals:

Min 1Q Median 3Q Max

-0.36952 -0.18137 -0.08137 0.33048 0.45090

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -0.9192 0.3594 -2.557 0.0377 *

log(FlexuralStrength$Days) 1.1309 0.1050 10.767 1.31e-05 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3289 on 7 degrees of freedom

Multiple R-squared: 0.9431, Adjusted R-squared: 0.9349

F-statistic: 115.9 on 1 and 7 DF, p-value: 1.311e-05

Output:

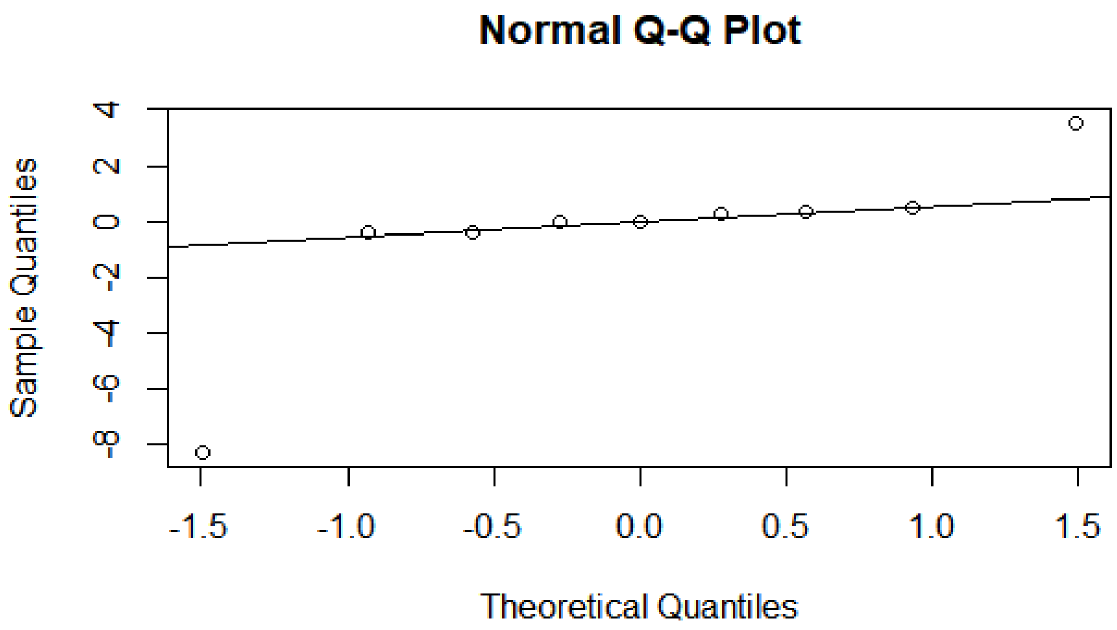


Figure 4.63: Q-Q plot of the flexural strength of mix 5.

The points on the Normal Q-Q plot in Figure 4.63 approximate a diagonal line except for two outliers implying that the data follows a normal distribution. In order to visually depict the relationship between the flexural strength of mix 5 over the 90 day period, a scatter plot was drawn as shown in Figure 4.64.

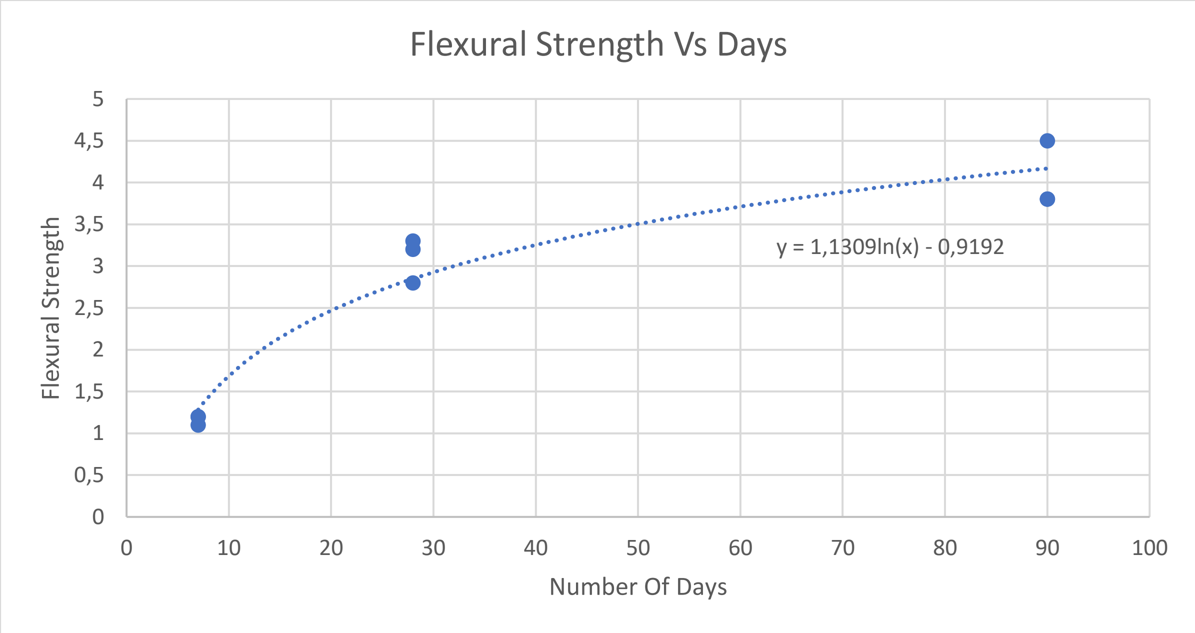


Figure 4.64: Scatter plot of the flexural strength of mix 5 over the 90 day period.

The logarithmic regression model of mix 5 for flexural strength over 90 days can be represented by:

$$y = 1{,}1309\ln(x) - 0{,}9192 \quad (4.11)$$

The points on the scatter plot are nonlinear and do not fit a linear model hence logarithmic regression was suitable for the regression analysis of flexural strength over 90 days for mix 5. There is a high positive logarithmic correlation between flexural strength and curing days of 87% and 97% of the variability observed in the target variable is explained by the regression model.

4.13.2 Trend analysis of compressive and flexural strength of considered mixes using regression models

The period from when the 28 day compressive and flexural strength tests were conducted to the point when the 90 day tests were conducted is lengthy when compared to the time between the 7 day and 28 day tests. For this reason, regression models were used to further understand the strength development trends of each considered mix at increments of 14 days between the 28 day and 90 day testing occasions. The approximate strength at each incremental age for both compression and flexure are shown in Table 4.75 and Table 4.76 respectively.

Table 4.75: Approximate compressive strength results for the various mixes at each incremental age.

Mix	**Regression model**	**42 days**	**56 days**	**70 days**	**84 days**
Control mix	$y = 8{,}5426\ln(x) - 4{,}2097$	27,71	30,18	32,08	33,64
Mix 2	$y = 8{,}0486\ln(x) - 7{,}4328$	22,65	24,97	26,76	28,23
Mix 3	$y = 7{,}3976\ln(x) - 5{,}9666$	21,68	23,81	25,46	26,81

Mix 4	$y = 7{,}3381\ln(x) - 1{,}1171$	26,31	28,42	30,06	31,40
Mix 5	$y = 4{,}3904\ln(x) - 4{,}6429$	11,77	13,03	14,01	14,81

Table 4.76: Approximate flexural strength results for the various mixes at each incremental age.

Mix	Regression model	42 days	56 days	70 days	84 days
Control mix	$y = 0{,}9427\ln(x) + 0{,}3942$	3,92	4,19	4,40	4,57
Mix 2	$y = 1{,}0632\ln(x) - 0{,}7763$	3,20	3,50	3,74	3,93
Mix 3	$y = 0{,}8214\ln(x) - 0{,}09993$	2,97	3,21	3,39	3,54
Mix 4	$y = 1{,}0729\ln(x) - 0{,}6523$	3,36	3,67	3,91	4,10
Mix 5	$y = 1{,}1309\ln(x) - 0{,}9192$	3,31	3,63	3,89	4,09

Graphical representations of the data obtained in Table 4.75 and 4.76 are shown in Figure 4.65 and Figure 4.66.

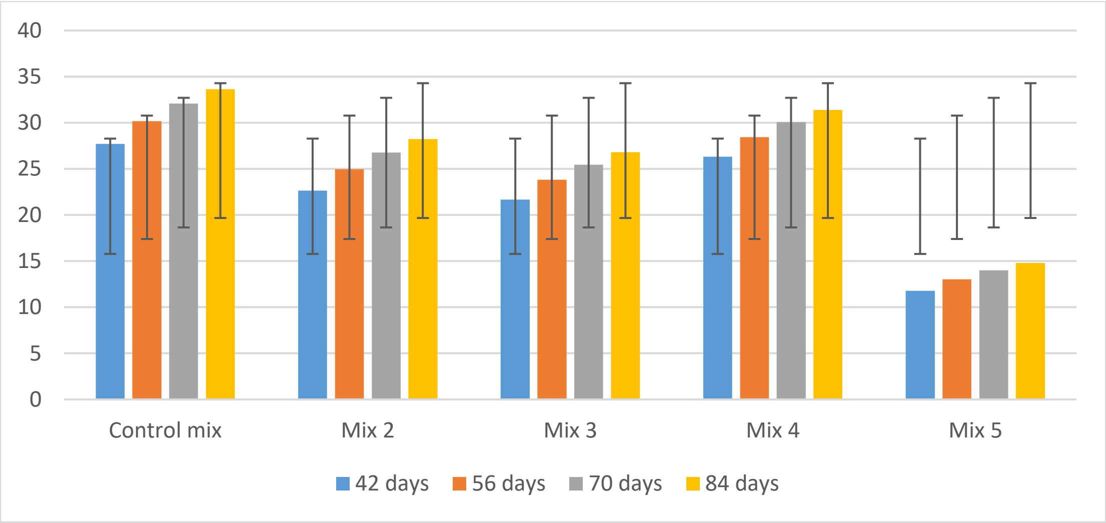


Figure 4.65: Compressive strength of various mixes at different ages using regression models.

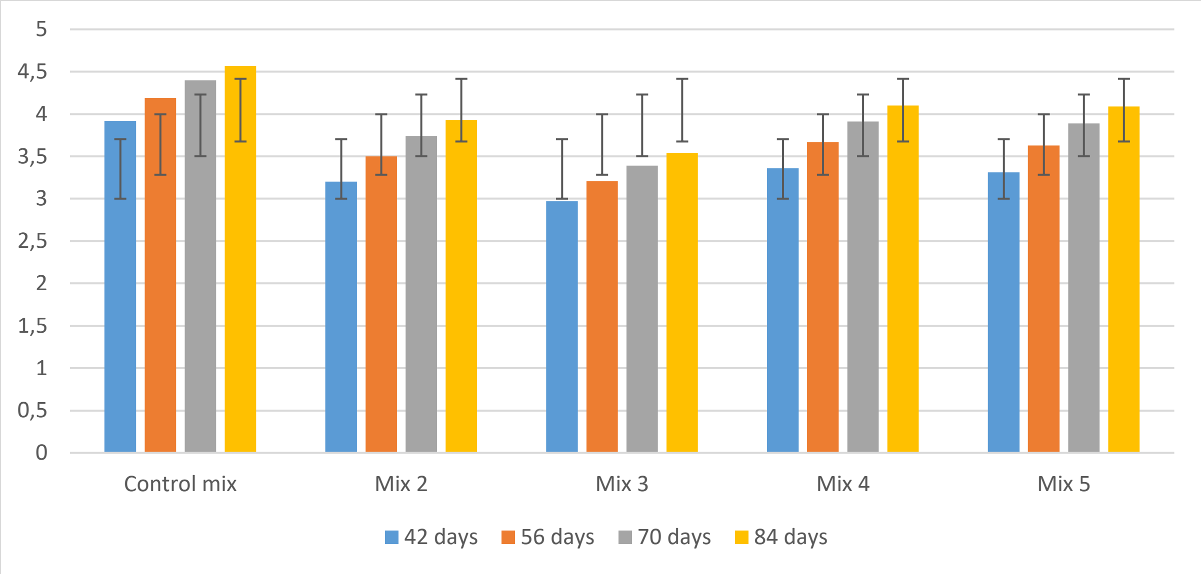


Figure 4.66: Flexural strength of various mixes at different ages using regression models.

The figures obtained for each mix from mix 2 to mix 5 at each incremental age show that between the 42 day and 84 day period in increments of 14 days there was a consistent increase in the development of both the compressive and flexural strength within each mix. However, it is also evident from the graphical representation of data obtained using the regression models that the greatest compressive strength development from the considered ages when comparing each mix from mix 2 to 5 occurred in the following order: mix 2, mix 4, mix 3 and lastly mix 5. This trend differed when observing the flexural strength development since the greatest flexural strength development was found to be in the following order: mix 5, mix 4, mix 2 and lastly mix 3. In terms of compressive strength development when considering the regression models obtained, the finding was that mix 2 is the most comparable mix to the control mix, and in terms of flexural strength development, mix 5 is the most comparable mix to the control mix.

4.14 Discussion

The objective of the four varying mix scenarios was to investigate through experimentation the following questions:

- Is the sole substitution of stone by EPS at a percentage of 10 % in any way comparable in strength qualities to the same mix ratio when the only difference between the two is the type of water used to mix the individual mixes?
- Can eggshell powder be used as a partial substitute for cement at a percentage of 5 % when incorporated into a mix similar to that of both mix 2 and mix 3, where the only difference would be the substitution of EPS at a reduced percentage of 5 %? Does this mix yield results that are comparable in strength qualities to mix 2 and mix 3?

- Can a mix that contains more than one substitute of concretes' conventional materials compare in any way to the control mix?
- Is the sole substitution of cement with eggshell powder at a percentage of 10 % in any way comparable to the strength qualities of a mix such as mix 2 that only contains EPS as a substitute also at a percentage of 10 %?
- Do any of the substitution percentage scenarios of the different mixes compare favourably to the control mix?

From the above evidence, it has been shown that:

- The substitution of stone by EPS at a percentage of 10 % when mixed with river water is comparable to the substitution of stone by EPS at a percentage of 10 % when mixed with potable water. The results show that there was a difference of not more than 1.4 MPa and 0.3 MPa in compressive and flexural strength respectively amongst the averages obtained at each age tested.
- A mix such as mix 4 that contains eggshell powder showed that it is possible to use eggshell powder as a partial substitute for cement at a percentage of 5 % when incorporated into a mix similar to that of mix 2 and mix 3 where the only difference would be the substitution of EPS at a reduced percentage of 5 %. The results obtained for mix 4 were found to be comparable to those of mix 2 and mix 3, since the strength qualities of mix 4 in terms of compressive and flexural strength surpassed those of mix 2 and mix 3. The results obtained for mix 4 were also similar to the results of the control mix, however, as expressed in section 2.2 of the literature review, it is important to highlight that there are pertinent elements in conventional cement such as alumina, magnesia, iron oxide and sulfur trioxide which are not present in eggshell powder. During the microscopic analysis that was conducted on the cement used in this study, a variety of these elemental constituents were identified and can be seen visually in Figure 4.67.

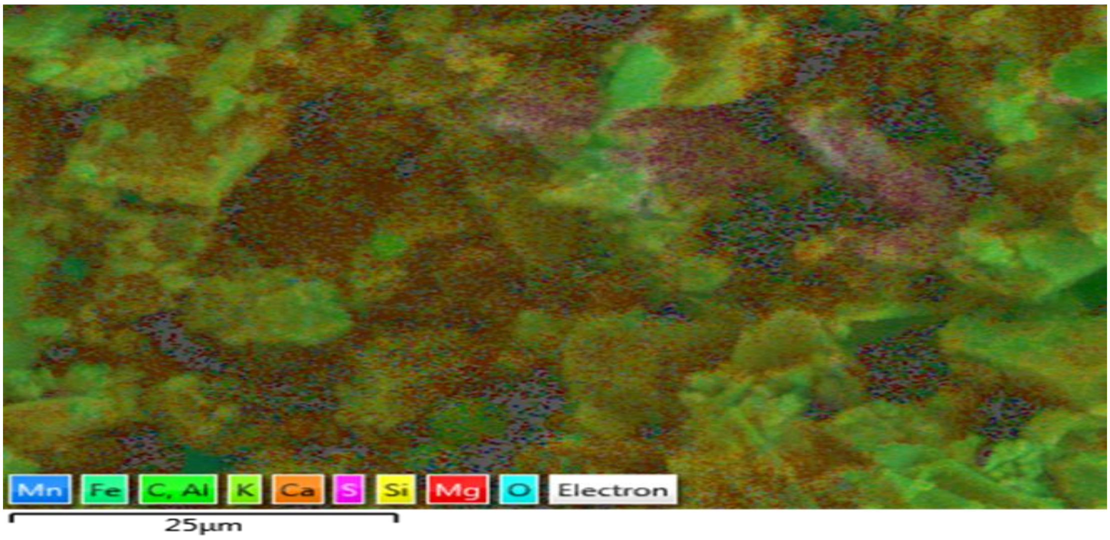


Figure 4.67: Layered image of NPC Original Blue CEM III/A 32.5N cement.

Figure 4.68 shows the element calcium as observed at a point in the cement specimen. When calcium is singled out from the rest of the elements in the specimen, it is evident that it is present in large quantities, but this does not invalidate the importance of all the other less dominant elemental constituents in cement since they all have a specific purpose in the process of concrete production.

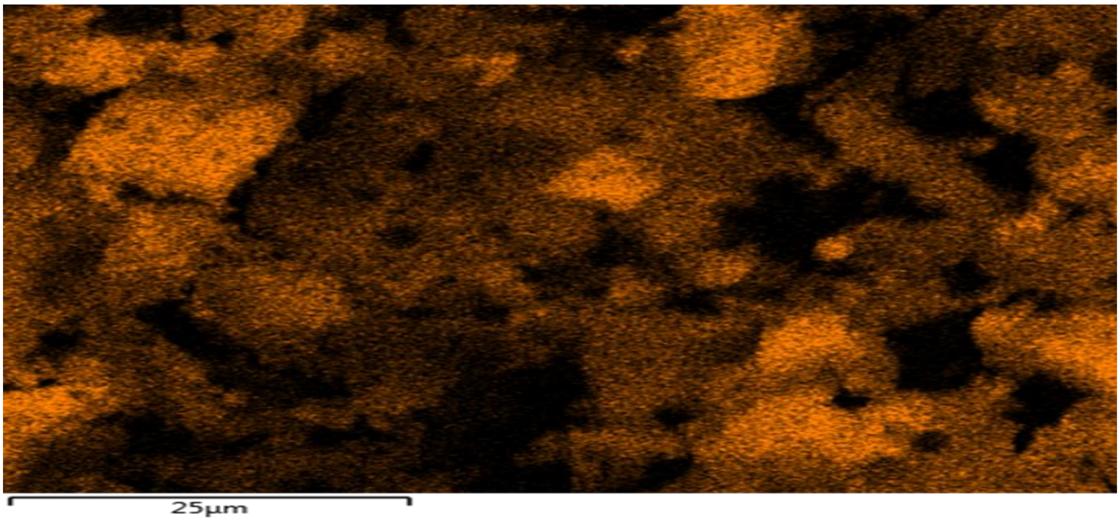


Figure 4.68: Image showing the dominant presence of calcium in NPC Original Blue CEM III/A 32.5N cement.

Although the compressive and flexural strength results obtained for mix 4 were similar to that of the control mix, it is highly probable that the lack of some of the elemental constituents that are present in conventional cement (that are not present within eggshell powder) are the cause of why the overall strength outcomes of the control mix were slightly higher than that of mix 4.

- A mix that contains more than one substitute of concretes' conventional materials compares favourably to the control mix since the results show that the compressive strength of mix 4 surpassed the results of the control mix at 7 days. Furthermore, the results obtained for mix 4 at 28 days and 90 days in compression as well as those obtained at 7 days, 28 days and 90 days for flexure, were all similar to the results obtained for the control mix.
- The sole substitution of cement with eggshell powder at a percentage of 10 % was not comparable in terms of strength qualities with a mix such as mix 2 which also contained EPS as a substitute at a percentage of 10 %.
- Regarding the different substitution percentage scenarios, the scenario that compared most favourably to the control mix is that of mix 4.

Considering the four experimental mixes, this research study found that the preferred mix in terms of the best substitution scenario would be mix 4 where eggshell powder was used as a substitute for cement, and where EPS was used as a substitute for stone, and river water was substituted for potable water, since this mix compared favourably to the control mix. The equation for forecasting the compressive strength of the preferred mix was therefore:

$$y = 7{,}3381 \ln(x) - 1{,}1171 \qquad (4.8)$$

The equation for forecasting the flexural strength of the preferred mix was therefore:

$$y = 1{,}0729 \ln(x) - 0{,}6523 \qquad (4.9)$$

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Concluding discussion

The research conducted was a case study and therefore the findings from the research are case-specific. This study analysed the substitution of cement with eggshell powder and stone by EPS. The research also went further to assess how non-potable water (collected from the Msunduzi River), when used in different substitution scenarios for various mixes, alters the compressive and flexural strength of the different mixes, and how these mixes compare to each other as well as to the control mix. The research was undertaken out of a concern for the following:

- Although concrete is known to be the number one building material globally, it is not easily accessible to poor communities since they do not possess the financial ability to procure the conventional raw materials for it.
- Although conventionally produced concrete has excellent strength qualities, the continued extraction of the earth's natural materials such as coarse aggregate (stone) is not sustainable and poses a great risk to the environment.
- Waste build-up globally is advancing at a rapid rate due to increased levels of urbanisation. A closer look is therefore required into how waste products can be used to improve existing products. This research study utilised a common waste material that can be found throughout the world in both upper- and lower-income countries, namely, eggshells, in the production of concrete. Finding a use for such an abundant waste material could possibly significantly reduce the volume of eggshells that are found in landfills globally.
- Clean drinking water is a scarce commodity in many low-to middle-income countries, and will become increasingly so as the need for housing and commercial building projects rise. Provision of adequate housing requires vast quantities of concrete and in order for such quantities to be produced with conventional concrete, adequate quantities of potable water are required. This research study therefore not only looked at a way to save natural resources such as coarse aggregate, but also at the viability of non-potable water being used to produce concrete from streams and rivers such as the Msunduzi River. In this way, potable water can be preserved for human consumption, which is the main reason so much money is invested in the purification process.

The main objectives of this research were to:

a) Determine the morphology of cement compared to eggshell powder.

b) Determine the elemental composition of cement, eggshell powder, potable water, river water, fine aggregate and coarse aggregate.

c) Determine the mechanical properties of eggshell powder/expanded polystyrene/river water concrete when used as substitute materials in concrete production.

d) Determine which mix out of the set of the four experimental mixes investigated displayed an optimal mix in terms of strength output for the concrete produced through substitutionary trials of cement and fine aggregate with the use of river water in place of potable water.

e) Develop regression models for estimating the compressive and flexural strength of eggshell powder/expanded polystyrene/river water concrete within various scenarios of substitution.

In conclusion:

a) When the micro-structure of CEM III/A 32.5N cement was compared to the micro-structure of eggshell powder, it was found that eggshell powder has a higher void potential than CEM III/A 32.5N. It is highly probable that this was a contributing factor for the slightly higher compressive and flexural strength test results that were achieved by the control mix when compared to mixes tested that contained eggshell powder.

b) The elemental composition of CEM III/A 32.5N cement showed that calcium is one of the dominant elements in its composition. This is the commonality that CEM III/A 32.5N cement and eggshell powder share since eggshell powder is mainly composed of calcium. However, the results of compressive and flexural strength tests for mixes which contained eggshell powder showed that the control mix achieved slightly higher strength outcomes than all the considered mixes where eggshell powder was used as a substitute for cement. This could be due to the fact that CEM III/A 32.5N cement has certain elemental constituents that eggshell powder does not have. The elemental composition of water considered for this research from the Msunduzi River was largely comparable to the elemental composition of potable water, although of concern were the bacteriological contaminants in the river water which are known to vary from location to location as well as from season to season.

c) Results from the various substitutions from mix 2 to mix 5 show that there is a difference in the bulk density of the concrete of the different mixes when compared to the control mix. The average bulk densities of mix 2 to mix 5 were found to be generally lower than that of the control mix. This signals that the concrete mixes produced through substitutionary experimentation are lighter in weight than conventional concrete. The results showed a higher 7 day compressive strength outcome when non-potable water was used in a mix that only contained the substitution of coarse aggregate by EPS such as in mix 3 when compared to mix 2 which contained potable water. This was also observed for the 7 day flexural strength outcome since the flexural strength of mix 3 was higher at 7 days than that of mix 2. However, the 28 day and 90 day compressive and flexural strength results of mix 2 were higher than that of mix

3. This signifies that a concrete mix such as mix 3 has faster initial strength gain over a concrete mix such as mix 2.

d) The results showed that a higher 7 day compressive strength result was obtained when cement was substituted by eggshell powder at a percentage of 5 % and coarse aggregate was also substituted by EPS at a percentage of 5 % (mix 4) when compared to the control mix. However, the 28 day and 90 day compressive strength results of the control mix were higher than that of mix 4. This trend was not observed with the flexural strength outcomes, since the flexural strength results of the control mix were higher at all the test ages when compared to that of mix 4. This signifies that a concrete mix such as mix 4 that has cement substituted by eggshell powder at a percentage of 5 % and coarse aggregate substituted by EPS at a percentage of 5 % mixed with non-potable water has faster initial compressive strength gain than conventional concrete. Substituting cement and coarse aggregate simultaneously with eggshell powder and EPS was more advantageous in terms of compressive strength since the compressive strength of mix 4 was higher at 7 days than any other considered mix including that of the control mix. The overall compressive strength obtained for mix 4 was higher than that obtained by fellow researchers such as Tayal et al. (2018), even though mix 4 contained an additional substitution which was eggshell powder for a portion of cement. This indicates that there is merit in the simultaneous substitution of more than one of concrete’s conventional materials because in this study a higher strength outcome was achieved for one of the ages tested. In practical usage, a mix such as mix 4 will not only yield savings in terms of mined coarse aggregate, but will also save scarce purified and cleansed water that is meant to be used as drinking water, since a lot of resources and effort go into cleansing a single drop of water to a drinkable standard. Furthermore, it can potentially save up to 5% of the total volume of cement required by replacing it with eggshell powder. This research has also shown that although there exists a commonly accepted substitution percentage of 5 % to 10 % when substituting coarse aggregate by EPS in EPS concrete mixed with potable water, it is also possible to achieve comparable strength results when non-potable water is used as the mixing agent instead of potable water. The results obtained for mix 5 when compared to the results of all the other mixes as well as that of the control mix showed that a substitution of up to 10 % for cement by eggshell powder is not suitable. This indicates that a suitable range of acceptance for the use of eggshell powder should be 5 % or less.

e) Regression models for estimating the compressive and flexural strength of eggshell powder/ expanded polystyrene/river water concrete within various scenarios of substitution were developed. Trend analysis using the developed regression models found that the greatest compressive strength development of the considered ages when comparing each mix from mix 2 to mix 5 occurred in the following order; mix 2, mix 4, mix 3 and lastly mix 5. This trend differed when observing the flexural strength development since the greatest flexural strength development was found to be in the following order: mix 5, mix 4, mix 2 and lastly mix 3.

5.2 Recommendations for further research

The experimental approach undertaken in this study has proved to be a viable tool for investigating environmentally friendly solutions in the domain of concrete. Further studies along these lines are warranted.

Recommendations for further studies are therefore as follows:

- This study only looked at one type of eggshell whereas there are various types of eggshells from different animals across the world. Future research can therefore investigate the contributions or improvements that can be brought about by different types of eggshells from different types of species.
- Since glass powder as indicated by Vijayakumar et al. (2013) increases the flexural strength of concrete when used as a partial substitute for cement, further research should consider the incorporation of glass powder with eggshell powder and EPS as simultaneous substitutes in concrete in an effort to improve the flexural capabilities of mixes such as mix 4.
- There are various types of waste products that have not yet been adequately explored as inclusion materials in concrete production, for example, recycled bamboo. These should be explored.
- Additional mathematical models should be explored in order to interrogate the durability of both eggshell powder and EPS in concrete.
- The effects of different pollutants in non-potable water on the properties of concrete should be studied further in order to determine their overall impact on the compressive and flexural strength of concrete.

REFERENCES

Adeala, A.J. and Soyemi, O.B. (2020) 'Structural Use of Expanded Polystyrene Concrete', International Journal of Innovative Science and Research Technology, volume 5, issue 6, pg. 1131-1138

Adogla, F. Yalley, P.P.K. and Arkoh, M. (2016) 'Improving Compressed Laterite Bricks using Powdered Eggshells', The International Journal of Engineering and Science, volume 5, issue 4, pg. 65-70

Ahmad, S., Malik, I., Wani, M.B. and Ahmad, R. (2013) 'Study of Concrete Involving Use of Waste Paper Sludge Ash as Partial Replacement of Cement', Journal of Engineering, volume 3, issue 11, pg. 6-15

Al-ghusain, I and Terro, M.J. (2003) 'Use of Treated Wastewater for Concrete mixing in Kuwait', Kuwait Journal of Science & Engineering, volume 30, issue 1, pg. 213-228

Ali, A. and Ansari, A.A. (2013) 'Polymer Concrete as Innovative Material for Development of Sustainable Architecture', Available: https://www.researchgate.net/publication/269701774_Polymer_Concrete_as_Innovative_Material_for_Development_of_Sustainable_Architecture (Accessed 17 June 2021)

Ali, B., Kurda, R., De Brito, J. and Alyousef, R. (2021) 'A Review on the Performance of Concrete Containing Non-Potable Water', Applied Sciences, volume 11, issue 15, pg. 1-22

Aliabo, A.A., Elmoaty, A.E and Aboshama, A.Y. (2016) 'Utilization of Waste Glass Powder in the Production of Cement and Concrete', Construction and Building Materials, volume 124, issue 1, pg. 866-877

Al-Jabri, K.S., Al-Saidy, A.H., Taha, R. and Al-Kemyani, A.J. (2011) 'Effect of using Wastewater on the Properties of High Strength Concrete', Procedia Engineering, volume 14, issue 1, pg. 370-376

American Public Health Association (1998) Standard Methods for the Examination of Water and Wastewater, American Public Health Association. Inc., Washington, DC.

American Society for Testing and Materials (2016) ASTM C33 Standard Specification for Concrete Aggregates, American Society for Testing and Materials, West Conshohocken, PA

Amu, O.O., Fajobi, A.B. and Oke, B.O. (2005) 'Effect of Eggshell Powder on the Stabilizing Potential of Lime on an Expansive Clay Soil', Research Journal of Agriculture and Biological Sciences, volume 1, issue 1, pg. 80-84

Assaad, J.J. and Mir, A.E. (2020) 'Durability of polymer-modified lightweight flowable concrete made using expanded polystyrene', Construction and Building Materials, volume 249, issue 1, pg. 1-15

Association of Cementitious Material Producers (2016) Cement Manufacturing Process, Available: https://www.acmp.co.za/about-cement/cement-manufacturing-process/ (Accessed 6 May 2021)

Babor, D.T., Plian, D. and Judele, L. (2009) Environmental Impact of Concrete, Available: https://www.researchgate.net/publication/40497595_Environmental_Impact_of_Concrete (Accessed 2 August 2021)

Babu, G. R. and Ramana, N.V. (2018) 'Feasibility of Wastewater as Mixing Water in Cement', Materials Today: Proceedings, volume 5, issue 1, pg. 1607-1614

Bedeković, G., Grčić, I., Vučinić, A.A. and Premur, V. (2019) 'Recovery of Waste Expanded Polystyrene in Lightweight Concrete Production', Mining-Geological-Petroleum Engineering Bulletin, volume 34, issue 3, pg. 73-80

Bedi, R., Chandra, R. and Singh, S.P. (2013) 'Mechanical Properties of Polymer Concrete', Journal of Composites, volume 1, issue 1, pg. 1-12

Bicer, A. (2019) 'Influence of Tragacanth Resin on the Thermal and Mechanical Properties of Fly Ash-Cement Composites', Journal of Adhesion Science and Technology, volume 33, issue 10, pg. 1019-1032

Brandon, C.J., Hohlfelder, R.L., Jackson, M.D. and Oleson, J.P. (2014) Building for Eternity: The History and Technology of Roman Concrete Engineering in the Sea, United Kingdom: Oxbow Books

British Standard Institution (1983) BS 1881, Method for Making Test Cubes from Fresh Concrete, London: British Standard Institution

Butcher, G.D. and Miles, R. (2019) Concepts of Eggshell Quality, Available: https://edis.ifas.ufl.edu/publication/VM013 (Accessed 4 January 2020)

Cement & Concrete Institute (2021) Quantities for Ordering Building Materials, Available: http://afrisam-rebuild.promisedev.co.za/uploads/documents/Quantities_for_ordering_building_materials.pdf (Accessed 29 September 2021)

Cement & Concrete South Africa (2022) Concrete Hardened, Available: https://cemcon-sa.org.za/faq/concrete-hardend/ (Accessed 20 August 2021)

Chandwani, V., Agrawal, V. and Nagar, R. (2015) 'Modeling Slump of Ready Mix Concrete Using Genetic Algorithms Assisted Training of Artificial Neural Networks', Expert Systems with Applications, volume 42, issue 2, pg. 885-893

Chatveera, B., Lertwattanaruk, P. and Makul, N. (2006) ‘Effect of Sludge Water from Ready-Mixed Concrete Plant on Properties and Durability of Concrete’, Cement and Concrete Composites, volume 28, issue 5, pg. 441-450

Chen, B. and Liu, J. (2004) ‘Properties of Lightweight Expanded Polystyrene Concrete Reinforced with Steel Fibre’, Cement and Concrete Research, volume 34, issue 7, pg. 1259-1263

Cheng, Y., Zhang, Y., Jiao, Y. and Yang, J. (2016) ‘Quantitative Analysis of Concrete Property Under Effects of Crack, Freeze-Thaw and Carbonation’, Construction and Building Materials, volume 129, issue 1, pg. 106-115

Civil Engineering (2021a) Advantages and Disadvantages of Concrete, Available: https://civiltoday.com/civil-engineering-materials/concrete/15-advantages-and-disadvantages-of-concrete (Accessed 29 January 2021)

Civil Engineering (2021b) Concrete Slump Test, Available: https://civiltoday.com/civil-engineering-materials/concrete/79-concrete-slump-test-standard-equipment-procedures-cautions (Accessed 05 January 2021)

Civil Engineering (2022) 8 Main Cement Ingredients & Their Functions, Available: https://civiltoday.com/civil-engineering-materials/cement/10-cement-ingredients-with-functions (Accessed 1 April 2021)

Cook, D.J. (1972) Expanded Polystyrene Beads as Lightweight Aggregate for Concrete, Available: https://catalogue.nla.gov.au/Record/2465481 (Accessed 30 July 2021)

Cronin, D.S. and Ouellet, S. (2016) ‘Low Density Polyethylene, Expanded Polystyrene and Expanded Polypropylene: Strain Rate and Size Effects on Mechanical Properties’, Polymer Testing, volume 53, issue 1, pg. 40-50

Dauda, O.A., Akinmusuru, J.O., Dauda, A.M., Fayomi, O.S.I. and Durotoye, T.O. (2018) ‘Effect of Curing Water Qualities on Compressive Strength of Concrete’, Covenant Journal of Engineering Technology, volume 1, issue 2, pg. 28-40

Davis, K. (1955) ‘The Origin and Growth of Urbanization in the World’, American Journal of Sociology, volume 60, issue 5, pg. 429-437

Duarte, N.C., Amaral, A.E., Gomes, B.G., Siqueira, G.H. and Tonetti, A.L. (2019) ‘Water Reuse in the Production of Non-Reinforced Concrete Elements: An Alternative for Decentralized Wastewater Management’, Water, Sanitation & Hygiene for Development, volume 9, issue 3, pg. 596-600

Durastanti, C. and Moretti, L. (2020) ‘Environmental Impacts of Cement Production: A Statistical Analysis’, Applied Sciences, volume 10, issue 1, pg. 1-25

Ede, A.N., Olofinnade, O.M., Bamigboye, G.O. and Shittu, K.K. (2017) ‘Prediction of Fresh and Hardened Properties of Normal Concrete via Choice of Aggregate Sizes, Concrete Mix-Ratios and Cement’, International Journal of Civil Engineering and Technology, volume 8, issue 10, pg. 288-301

EduRev (2021) Low Workability of Concrete, Availability: https://edurev.in/question/2769603/Low-workability-of-concrete-conforms-to-slump-of-a (Accessed 20 November 2021)

Elchalakani, M. and Elgaali, E. (2012), ‘Sustainable Concrete made of Construction and Demolition Wastes using Recycled Wastewater in the UAE’, Journal of Advanced Concrete Technology, volume 10, issue 3, pg. 110-125

Envirocrete (2021) Why is Concrete Work so Expensive? Available: https://www.envirocrete.ca/post/why-is-concrete-so-expensive (Accessed 27 April 2020)

European Standards (2006), EN 206 Part 1. Specification, performance, production conformity

Expanded Polystyrene Association of Southern Africa (2018) Introducing Expanded Polystyrene, Available: http://epsasa.co.za/wp-content/uploads/2018/07/Selection_Guide_Introducing_EPS.pdf (Accessed 2 January 2021)

Federal Highway Administration (2016) Chapter 5, Jefferson County, Available: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/02086/chapt5.cfm (Accessed 18 January 2020)

Fischetti, D.C. (2009) Tabby: Engineering Characteristics of a Vernacular Construction Material, in Structural Investigation of Historic Buildings: A Case Study Guide to Preservation Technology for Buildings, Bridges, Towers, and Mills, John Wiley & Sons Inc, Hoboken, NJ

Gadzama, E.W., Ekele, O.J., Anametemfiok, V.E. and Abubakar, A.U. (2015) ‘Effects of Sugar Factory Wastewater as Mixing Water on the Properties of Normal Strength Concrete’, International Journal of Science, Environment, volume 4, issue 3, pg. 813-825

Gameiro, F., de-Brito, J. and da-Silva, D.C. (2014) ‘Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry’, Engineering Structures, volume 59, issue 1, pg. 654-662

Gangola, P.S. (2020) ‘Urbanization: Boon or Bane with Reference to Rudrapur City’, Indian Journal Social & Political Science, volume 7, issue 2, pg. 81-86

Gardner, M., Comber, S., Scrimshaw, M.D., Cartmell, E., Lester, J. and Ellor, B. (2012) ‘The Significance of Hazardous Chemicals in Wastewater Treatment Works Effluents’, Science of the Total Environment, volume 437, issue 1, pg. 363-372

Get Cracking (2021) White & Brown Eggs, Available: https://www.eggs.ca/yourquestions/question/21/are-white-and-brown-eggs-different (Accessed 24 July 2020)

Ghais, A., Ahmed, D., Siddig, E., Elsadig, I. and Albager, S. (2014) 'Performance of Concrete with Fly Ash and Kaolin Inclusion', International Journal of Geosciences, volume 5, issue 12, pg. 1-6

Ghrair, A.M., Al-Mashaqbeh, O.A., Sarireh, M.K., Al-Kouz, N., Farfoura, M. and Megdal, S.B. (2018) 'Influence of Grey Water on Physical and Mechanical Properties of Mortar and Concrete Mixes', Ain Shams Engineering Journal, volume 9, issue 4, pg. 1519-1525

Giatec Scientific (2017) The History of Concrete, Available: https://www.giatecscientific.com/education/the-history-of-concrete/ (Accessed 6 February 2021)

Glaeser, E.L. (2014) 'A World of Cities: The Causes and Consequences of Urbanization in Poorer Countries', Journal of the European Economic Association, volume 12, issue 5, pg. 1154-1199

Goffin, B., Banthia, N. and Yonemitsu, N. (2020) 'Use of Infrared Thermal Imaging to Detect Corrosion of Epoxy Coated and Uncoated Rebar in Concrete', Construction and Building Materials, volume 263, issue 1, pg. 1-12

Gulve, B.D., Bothe, R.S., Dange, P.B., Gite, P.E., Jondhale, S.S., Landge, A.S. and Nagpure, A.S. (2018) 'Effect of Treated Waste Water (TWW) on Mechanical Properties of Concrete', International Journal of Advance Research and Innovative Ideas in Education, volume 4, issue 3, pg. 1390-1396

Hernandez-Zaragoza, J.B., Lopez-lara, T., Horta-Rangel, J., Lopez-Cajun, C., Rojas-Gonzalez, E., Garcia-Rodriguez, F.J. and Adue, J. (2013) 'Cellular Concrete Bricks with Recycled Expanded Polystyrene Aggregate', Advances in Materials Science and Engineering, pg. 1-5

Hincke, M.T., Nys, Y., Gautron, J., Mann, K., Rodriguez-Navarro, A.B. and McKee, M.D. (2012) 'The Eggshell: Structure, Composition and Mineralization', Frontiers in Bioscience, volume 17, issue 1, pg. 1266-1280

Hu, J. and Wang, K. (2011) 'Effect of Coarse Aggregate Characteristics on Concrete Rheology', Construction and Building Materials, volume 25, issue 3, pg. 1196-1204

Huang, C., Lin, S., Chang, C. and Chen, H. (2013) 'Mix Proportions and Mechanical Properties of Concrete Containing Very High-Volume of Class F fly ash', Construction and Building Materials, volume 46, issue 1, pg. 71-78

Hussein, M.N. (2015) 'Properties of Concrete Containing New and Used Engines Oil', International Journal of Science and Research, volume 4, issue 12, pg. 268-272

Iffat, S. (2015) ‘Relation Between Density and Compressive Strength of Hardened Concrete’, Concrete Research Letters, volume 6, issue 4, pg. 182-189

Independent (2013) What would Happen if Oxygen Disappeared for Five Seconds? Available: https://www.independent.co.uk/news/science/what-would-happen-if-oxygen-disappeared-for-five-seconds-8925756.html (Accessed 24 August 2021)

International Association of Certified Home Inspectors (2021) The History of Concrete, Available: https://www.nachi.org/history-of-concrete.htm (Accessed 10 December 2020)

Islam, R., Nazifa, T.H., Yuniarto, A., Shanawaz-Uddin, A.S.M, Salmiati, S. and Shahid, S. (2019) ‘An Empirical Study of construction and Demolition Waste Generation and Implication of Recycling’, Waste Management, volume 95, issue 1, pg. 10-21

Ismail, Z.Z and Al-Hashmi, E.A. (2008) ‘Use of Waste Plastic in Concrete Mixture as Aggregate Replacement’, Waste Management, volume 28, issue 11, pg. 2041-2047

Isover (2021) Typical Values of Expanded Polystyrene, Available: https://www.isover.co.za/sites/isover.za/files/assets/documents/eps_data_sheet_2017_low_res.pdf (Accessed 2 December 2020)

Jahren, P. and Sui, T. (2017) History of Concrete: A Very Old and Modern Material, Singapore: World Scientific Publishing Company Pte Limited

Kaboosi, K. and Emami, K. (2019) ‘Interaction of Treated Industrial Wastewater and Zeolite on Compressive Strength of Plain Concrete in Different Cement Contents and Curing Ages’, Case Studies in Construction Materials, volume 11, issue 1, pg. 1-17

Kanitha, M., Ramya, P., Revathi, V. and Bhuvanya, S. (2014) ‘Potential Utilisation of Untreated/Treated Textile Effluent in Concrete’, International Journal of Research in Engineering and Technology, volume 3, issue 7, pg. 518-522

Karthick, M.D., Ramya, S.B., Bharathi, R. and Mullainathan, R. (2018) ‘Experimental Study on Strength Behaviour of Concrete Block with Partial Replacement of Expanded Polystyrene Beads, International Journal of Engineering Research & Technology, volume 6, issue 10, pg. 1-5

Kaya, A. and Kar, F. (2016) ‘Properties of Concrete Containing Waste Expanded Polystyrene and Natural Resin’, Construction and Building Materials, volume 105, issue 1, pg. 572-578

Khaleel, O.R., Razak, H.A., Mammen, R. and Dawood, M.H. (2018) ‘Powder Materials and Their Effect on the Behaviour of Self-Compacting Concrete in Malaysia’, Materials Science and Engineering, volume 1, issue 1, pg. 1-9

Kumar, A. and Kober, B. (2012) ‘Urbanization, Human Capital, and Cross-Country Productivity Differences’, Economics Letters, volume 117, issue 1, pg. 14-17

Lakhiar, M.T., Mohamad, N. and Shaikh, M.A.B. (2018) ‘Effect of River Indus Sand on Concrete Tensile Strength’, Engineering, Technology & Applied Science Research, volume 8, issue 2, pg. 2796-2798

Lauren, B. (1999), Sickels-Taves, the Lost Art of Tabby: Preserving Oglethorpes Architectural Legacy, Architectural Conservation Press, Southfield, MI

Liu, S., Kong, Y. and Wang, L. (2014) ‘A Comparison of Hydration Properties of Cement–Low Quality Fly Ash Binder and Cement–Limestone Powder Binder’, Journal of Thermal Analysis and Calorimetry, volume 1, issue 116, pg. 937-943

Lollini, F., Redaelli, E. and Bertolini, L. (2014) ‘Effects of Portland Cement Replacement with Limestone on the Properties of Hardened Concrete’, Cement and Concrete Composites, volume 46, issue 1, pg. 32-40

Mahasneh, B. (2014) Assessment of Replacing Wastewater and Treated Water with Tap Water in Making Concrete Mix, Available: https://www.ijaiem.org/pabstract2.php?pid=IJAIEM-2017-03-03-2 (Accessed 5 September 2020)

Mahasneh, B.Z. (2014) Assessment of Replacing Wastewater and Treated Water with Tap Water in Making Concrete Mix, Available: https://www.researchgate.net/publication/268508115_Assessment_of_Replacing_Wastewater_and_treated_water_with_Tap_water_in_making_Concrete_Mix (Accessed 04 May 2021)

Malesev, M., Radonjanin, V. and Marinkovic, S. (2010) ‘Recycled Concrete as Aggregate for Structural Concrete Production’, Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering, volume 2, issue 5, pg. 1204-1225

McDonald, J. F. and McMillen, D. P. (2008) Urban Economics and Real Estate, Oxford: Blackwell Publishing

McDonald, R.I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P.A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G. and Montgomery, M. (2014) ‘Water on an Urban Planet: Urbanization and the Reach of Urban Water Infrastructure’, Global Environmental Change, volume 27, issue 1, pg. 96-105

Mehr, A.D. and Ghatte, H.F. (2019) Treated Wastewater for Concrete Mixing; a Comparative Study Between ASTM and Turkish Standards, Available: https://www.researchgate.net/profile/Ali-Danandeh-

Mehr/publication/335992389_TREATED_WASTEWATER_FOR_CONCRETE_MIXING_A_COMPARITIVE_STUDY_BETWEEN_ASTM_AND_TURKISH_STANDARDS/links/5d89e9ff92851ceb793ad793/TREATED-WASTEWATER-FOR-CONCRETE-MIXING-A-COMPARITIVE-STUDY-BETWEEN-ASTM-AND-TURKISH-STANDARDS.pdf (Accessed 1 August 2021)

Midmar Group. (2020) Concrete Stone & Aggregates, Available: https://midmarbuildingsupplies.co.za/concrete-stone-and-aggregates/ (Accessed 11 November 2020)

Mir, F.Q. and Sagu, V.S. (2019) 'Effect of Lime Stone Waste as Partial Sand Replacement and Fly Ash as Partial Cement Replacement on Concrete', International Journal of Scientific Development and Research, volume 4, issue 5, pg. 165-168

Mohammed, A. and Abdullah, A. (2018) Scanning Electron Microscopy (SEM): a Review, Available: https://fluidas.ro/hervex/proceedings2018/77-85.pdf (Accessed 20 October 2021)

Morandin-Ahuerma, I., Contreras-Hernandez, A., Ayala-Ortiz, D.A. and Perez-Maqueo, O. (2019) 'Socio–Ecosystemic Sustainability', Sustainability, volume 11, issue 12, pg. 1-26

Mortazavi, M. (2011) 'From Ancient to Modern Urbanization: Intermediary Function of an Urban Society', International Journal of Historical Archaeology, volume 15, issue 1, pg. 126-137

Murakami, F.S., Rodrigues, P.O., Campos, C.M.T. and Silva, M.A.S. (2007) 'Physicochemical Study of CaCO3 from Eggshells', Food Science and Technology, volume 27, issue 3, pg. 658-662

Murugesan, A., Rizwan, S., Mariasusai, M, Karpagavalli, S., Saravanan, V.P., Sivakumar, K. and Marimuthu, A. (2015) 'Experimental Investigation on Partial Replacement of Coarse Aggregate with Polystyrene', International Journal of Engineering and Management Research, volume 5, issue 5, pg. 348-352

Naceri, A. and Hamina, M.C. (2009) 'Use of Waste Brick as a Partial Replacement of Cement in Mortar', Waste Management, volume 29, issue 8, pg. 2378-2384

Okeke, V.U. and Ahaotu, E.O. (2021) 'Linking Urbanization to Urban Poverty: a Marxist Interpretation', International Journal of Environmental Design & Construction Management, volume 21, issue 4, pg. 391-407

Olarewaju, A.J., Balogun, M.O. and Akinlolu, S.O. (2011) Suitability of Eggshell Stabilized Lateritic Soil as Subgrade Material for Road Construction, Available: https://www.researchgate.net/publication/266464520_Suitability_of_Eggshell_Stabilized_Lateritic_Soil_as_Subgrade_Material_for_Road_Construction#:~:text=Eggshell%20powder%20was%20also%20used,the%20subgrade%20soil%20%5B11%5D%20. (Accessed 20 February 2020)

Olugbenga, A.T.A. (2014) ‘Effects of Different Sources of Water on Concrete Strength: A Case Study of Ile-Ife’, Civil and Environmental Research, volume 6, issue 3, pg. 39-43

Onwubu, S.C., Vahed, A., Singh, S. and Kanny, K.M. (2017) ‘Physicochemical Characterization of a Dental Eggshell Powder Abrasive Material’, Journal of Applied Biomaterials & Functional Materials, volume 15, issue 4, pg. 341-346

Perry, S.H., Bischoff, P.H. and Yamura, K. (1991) ‘Mix Details and Material Behaviour of Polystyrene Aggregate Concrete’, Magazine of Concrete Research, volume 43, issue 154, pg. 71-76

Punurai, S., Punurai, W. and Thomas-Hsu, C. (2007) ‘A Very Early Strength Concrete for Highway Construction’, Journal of Testing and Evaluation, volume 35, issue 6, pg. 1-9

Radic, J., Kindij, A. and Ivankovic, A.M. (2008) History of Concrete Application in Development of Concrete and Hybrid Arch Bridges, Available: https://www.researchgate.net/publication/273455117_HISTORY_OF_CONCRETE_APPLICATION_IN_DEVELOPMENT_OF_CONCRETE_AND_HYBRID_ARCH_BRIDGES (Accessed 6 March 2020)

Ragheb, A.F. (2011) Towards Environmental Profiling for Office Buildings Using Life Cycle Assessment, Available at: https://deepblue.lib.umich.edu/bitstream/handle/2027.42/86391/aragheb_1.pdf?sequence=1 (Accessed 10 May 2018)

Rahman, N.A., Jaini, Z.M., Rahim, N.A.A. and Razak, S.A.A. (2015) ‘An Experimental Study on the Fracture Energy of Foamed Concrete Using V-Notched Beams’, Proceedings of the International Civil and Infrastructure Engineering Conference, volume 1, issue 1, pg. 97-108

Raza, A., Rafique, U. and Haq, F. (2021) ‘Mechanical and Durability Behavior of Recycled Aggregate Concrete Made with Different Kinds of Wastewater’, Journal of Building Engineering, volume 34, pg. 1-10

Regal, X. and Hanus, J.L. (2017) ‘Experimental Study of the Dynamic Flexural Strength of Concrete’, Experimental Mechanics, volume 57, issue 1, pg. 427-442

Remoundou, K. and Koundouri, P. (2009) ‘Environmental Effects on Public Health: An Economic Perspective’, International Journal of Environ Res Public Health, volume 6, issue 8, pg. 2160-2178

Rheosense (2021) Viscosity of Newtonian and Non-Newtonian Fluids, Available: https://www.rheosense.com/applications/viscosity/newtonian-non-newtonian (Accessed 17 May 2021)

Richardson, A.E. and Fuller, T. (2013) ‘Sea Shells Used as Partial Aggregate Replacement in Concrete’, Structural Survey, volume 31, issue 5, pg. 347-354

Rojas-Carbonell, S., Artyushkova, K., Serov, A., Santoro, C., Matanovic, I. and Atanassov, P. (2018) 'Effect of pH on the Activity of Platinum Group Metal-Free Catalysts in Oxygen Reduction Reaction', American Chemical Society, volume 8, issue 4, pg. 3041-3053

Safiuddin, M., Kaish, A.B.M., Woon, C. and Raman, S. (2018) 'Early-Age Cracking in Concrete: Causes, Consequences, Remedial Measures, and Recommendations', Applied Sciences, volume 8, issue 10, pg. 1-25

Saidani, M., Saraireh, D. and Gerges, M. (2016) 'Behaviour of Different Types of Fibre Reinforced Concrete Without Admixture', Engineering Structures, volume 113, issue 1, pg. 328-334

Saxena, S. and Tembhurkar, A.R. (2018) 'Impact of Use of Steel Slag as Coarse Aggregate and Wastewater on Fresh and Hardened Properties of Concrete', Construction and Building Materials, volume 165, pg. 126-137

Sayadi, A.A., Tapia, J.V., Neitzert, T.R. and Clifton, G.C. (2016) 'Effects of expanded Polystyrene (EPS) Particles on Fire Resistance, Thermal Conductivity and Compressive Strength of Foamed Concrete', Construction and Building Materials, volume 112, pg. 716-724

Schneider, M., Romer, M., Tschudin, M. and Bolio, H. (2011) 'Sustainable Cement Production—Present and Future', Cement and Concrete Research, volume 41, issue 7, pg. 642-650

Seifan, M., Samani, A. and Berenjian, A. (2016) 'Bio Concrete: Next Generation of Self-Healing Concrete', Applied Microbiology and Biotechnology, volume 100, issue 1, pg. 2591-2602

Shahidan, S., Senin, M.S., Kadir, A.B.A., Yee, L.H. and Ali, N. (2017) 'Properties of Concrete Mixes with Carwash Wastewater', MATEC Web of Conferences, volume 87, issue 1, pg. 1-6

Shraddha, D., Hitali, F., Pradeep, D. and Varpe, S. (2014) 'Sustainable Concrete by Partially Replacing Coarse Aggregate Using Coconut Shell', Journal on Today's Ideas – Tomorrow's Technologies, volume 2, issue 1, pg. 41-54

Silva, R.V., Brito, J. and Dhir, R.K. (2015) 'Tensile Strength Behaviour of Recycled Aggregate Concrete', Construction and Building Materials, volume 83, issue 1, pg. 108-118

Singh, M., Srivastava, A. and Bhunia, D. (2017) 'An Investigation on Effect of Partial Replacement of Cement by Waste Marble Slurry', Construction and Building Materials, volume 134, pg. 471-488

Singh, R.L. and Singh, P.K. (2016) Global Environmental Problems, Available: https://link.springer.com/chapter/10.1007/978-981-10-1866-4_2 (Accessed 21 November 2020)

Soria, M.A., Bueno, D.J. and Bernigaud, I.I.C. (2013) 'Comparison of Quality Parameters in Hens' Eggs According to Eggshell Color', International Journal of Poultry Science, volume 12, issue 4, pg. 224-234

South African National Standards. (2006a) SANS 5845, Bulk Densities and Voids Content of Aggregates, SANS, Pretoria, South Africa

South African National Standards. (2006b) SANS 5861-1, Concrete Tests - Mixing Fresh Concrete in the Laboratory, Pretoria, South Africa

South African National Standards. (2006c) SANS 5862-1, Concrete Tests - Consistence of freshly Mixed Concrete - Slump test, Pretoria, South Africa

South African National Standards. (2006d) SANS 5863, Concrete Tests - Compressive Strength of Hardened Concrete, Pretoria, South Africa

South African National Standards. (2006e) SANS 5864, Concrete tests – Flexural Strength of Hardened Concrete, Pretoria, South Africa

South African National Standards. (2010) SANS 3001-GR20, Civil Engineering Test Methods Part GR20: Determination of the Moisture Content by Oven-Drying, Pretoria, South Africa

South African National Standards. (2012) SANS 878, South African National Standard, Ready-Mixed Concrete, Pretoria, South Africa

South African National Standards. (2013) SANS 50197-1, South African National Standard, Composition, Specifications and Conformity Criteria for Common Cements, Pretoria, South Africa

South African National Standards. (2014a) SANS 3001-AG1, Civil Engineering Test Methods Part AG1: Particle Size Analysis of Aggregates by Sieving, Pretoria, South Africa

South African National Standards. (2014b) SANS 3001-AG23, Civil Engineering Test Methods Part AG23: Particle and Relative Densities of Aggregates, Pretoria, South Africa

South African National Standards. (2015) SANS 241-1, Drinking Water Part 1: Microbiological, Physical, Aesthetic and Chemical Determinants, Pretoria, South Africa

South African National Standards. (2018) SANS 1083, Aggregates from Natural Sources - Aggregates for Concrete, Pretoria, South Africa

Stanton, J.M. (2001) 'Galton, Pearson, and the Peas: A Brief History of Logarithmic regression for Statistics Instructors', Journal of Statistics Education, volume 9, issue 3, pg. 1-13

Sultana, I. and Sadiqul Islam, M.G. (2018) Applicability of Treated Industrial Wastewater in Concrete Industry, Available: https://www.southern.edu.bd/conference/upload/conferencproceding/seee/77.pdf (Accessed 28 August 2020)

Supe, J.D. and Gupta, M.K. (2014) 'Flexural Strength – A Measure to Control Quality of Rigid Concrete Pavements', International Journal of Scientific & Engineering Research, volume 5, issue 11, pg. 46-57

Tamut, T., Prabhu, R., Venkataramana, K. and Yaragal, S.C. (2014) 'Partial Replacement of Coarse Aggregates by Expanded Polystyrene Beads in Concrete', volume 3, issue 2, pg. 238-241

Tang, S.W., Yao, Y., Andrade, C. and Li, Z.J. (2015) 'Recent Durability Studies on Concrete Structure', Cement and Concrete Research, volume 78, issue 1, pg. 143-154

Tayal, A., Gupta, G., Choudhary, P., Tomar, T., Kumar, N. and Mittal, S. (2018) 'Lightweight Concrete Using Recycled Expanded Polystyrene Beads', International Research Journal of Engineering and Technology, volume 5, issue 5, pg. 91-93

Thanh, L.D., Jougnot, D., Van-do, P. and Van-nghia, N. (2019) 'A Physically Based Model for the Electrical Conductivity of Water-Saturated Porous Media', Geophysical Journal International, volume 219, issue 2, pg. 866-876

The Constructor (2020) Hand Mixing of Concrete- Procedure and Precautions, Available: https://theconstructor.org/concrete/hand-mixing-concrete-procedure-precautions/18488/ (Accessed 14 July 2020)

Ujin, F., Ali, K.S. and Harith, Z.Y.H. (2017) 'The Effect of Eggshells Ash on the Compressive Strength of Concrete', Key Engineering Materials, volume 728, issue 1, pg. 402-407

United Nations (2018) Department of Economic and Social Affairs, Available: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (Accessed 10 April 2021)

United States Geological Survey (2019) pH and Water, Available: https://www.usgs.gov/special-topics/water-science-school/science/ph-and-water (Accessed 2 February 2020)

Utsev, J.T. and Taku, J.K. (2012) 'Coconut Shell Ash As Partial Replacement of Ordinary Portland Cement In Concrete Production', International Journal of Scientific & Technology Research, volume 1, issue 8, pg. 86-89

Venkatraman, S. and Ramasamy, V. (2017) 'Effect of Glass Powder on Performance of Concrete Subjected to Sulphate Attack', International Journal of Pure and Applied Mathematics, volume 116, issue 13, pg. 585-590

Verma, R. and Jain, N. (2020) 'Partial Replacement Coarse Aggregate by EPS', Journal of Mechanical and Civil Engineering, volume 17, issue 4, pg. 42-52

Vijayakumar, G., Vishaliny, H. and Govindarajulu, D. (2013) 'Studies on Glass Powder as Partial Replacement of Cement in Concrete Production', International Journal of Emerging Technology and Advanced Engineering, volume 3, issue 2, pg. 153-157

Vu, C., Ple, O., Weiss, J. and Amitrano, D. (2020) 'Revisiting the Concept of Characteristic Compressive Strength of Concrete', Construction and Building Materials, volume 263, issue 1, pg. 1-21

Walton, J.H. (1995) 'The Mesopotamian Background of the Tower of Babel Account and Its Implications', Bulletin for Biblical Research, volume 5, issue 1, pg. 155-175

Wang, F. (2013) 'The Birth and Use of Concrete and Reinforced Concrete', Advanced Materials Research, volume 712, issue 1, pg. 955-960

Wankhede, P.R. and Fulari, V.A. (2014) 'Effect of Fly Ash on Properties of Concrete', International Journal of Emerging Technology and Advanced Engineering, volume 4, issue 7, pg. 1-6

Water & Water Digest. (2020) What is Wastewater? Available: https://www.wwdmag.com/wastewater-treatment/what-wastewater (Accessed 22 November 2020)

World Bank (2016) Housing Consumption and Urbanization, Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2524675 (Accessed 2 September 2021)

World Health Organization (2022) Preventing Diarrhoea Through Better Water, Sanitation and Hygiene, Available: https://apps.who.int/iris/bitstream/handle/10665/150112/9789241564823_eng.pdf (Accessed 21 April 2021)

World History (2014) Urbanization, Available: https://www.worldhistory.org/urbanization/ (Accessed 2 April 2020)

Xi, X. and Yang, S. (2017) 'Time to Surface Cracking and Crack Width of Reinforced Concrete Structures under Corrosion of Multiple Rebar's, Construction and Building Materials, volume 155, issue 1, pg. 114-125

Yan, P., Chen, B., Afgan, S., Haque, M.A., Wu, M. and Han, J. (2021) 'Experimental Research on Ductility Enhancement of Ultra-High Performance Concrete Incorporation with Basalt Fibre, Polypropylene Fibre and Glass Fibre', Construction and Building Materials, volume 279, issue 1, pg. 1-15

Yang, L., An, X. and Du, S. (2021) 'Estimating Workability of Concrete with Different Strength Grades Based on Deep Learning', Measurement, volume 186, issue 1, pg. 1-17

Yeheyis, M., Hewage, K., Alam, M.S., Eskicioglu, C. and Sadiq, R. (2013) 'An Overview of Construction and Demolition Waste Management in Canada: A Lifecycle Analysis Approach to Sustainability', Clean Technologies and Environmental Policy, volume 15, issue 1, pg. 81-91

Yerramala, A. (2014) 'Properties of Concrete with Eggshell Powder as Cement Replacement', The Indian Concrete Journal, volume 1, issue 1, pg. 94-102

Yoon, G.L., Kim, B.T., Kim, B.O. and Han, S.H. (2003) 'Chemical-Mechanical Characteristics of Crushed Oyster-Shell', Waste Management, volume 23, issue 9, pg. 825-883

Zhang, J., Ling, X. and Guan, Z. (2017) 'Finite Element Modeling of Concrete Cover Crack Propagation due to Non-Uniform Corrosion of Reinforcement', Construction and Building Materials, volume 132, issue 1, pg. 487-499

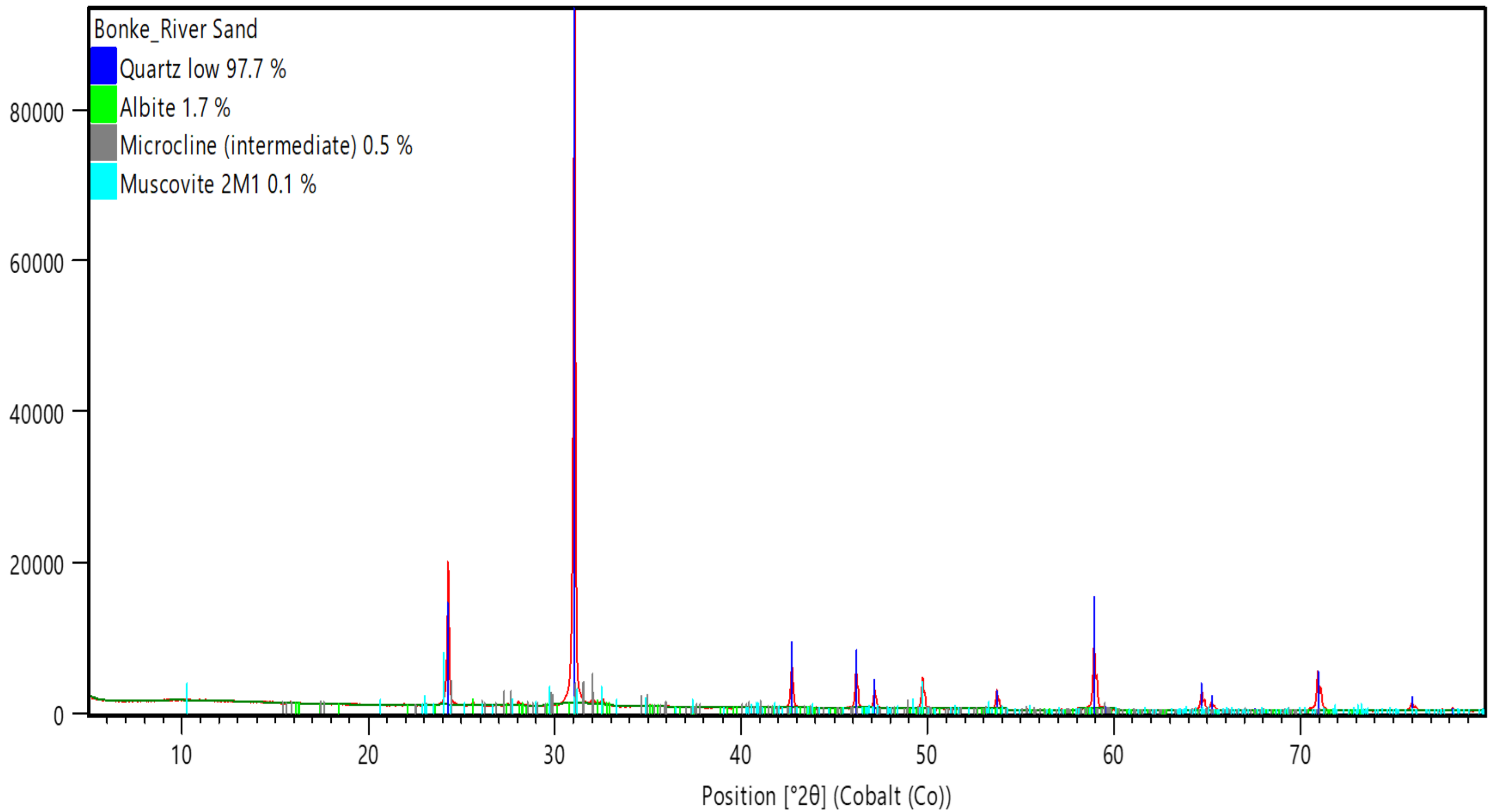
Zhang, S., Pei, J., Li, R., Zhou, J., Xue, B. and Hu, D. (2019) 'Effect of Coarse Aggregate Composition on Physical and Mechanical Properties', Journal of Materials in Civil Engineering, volume 31, issue 10, pg. 1-8

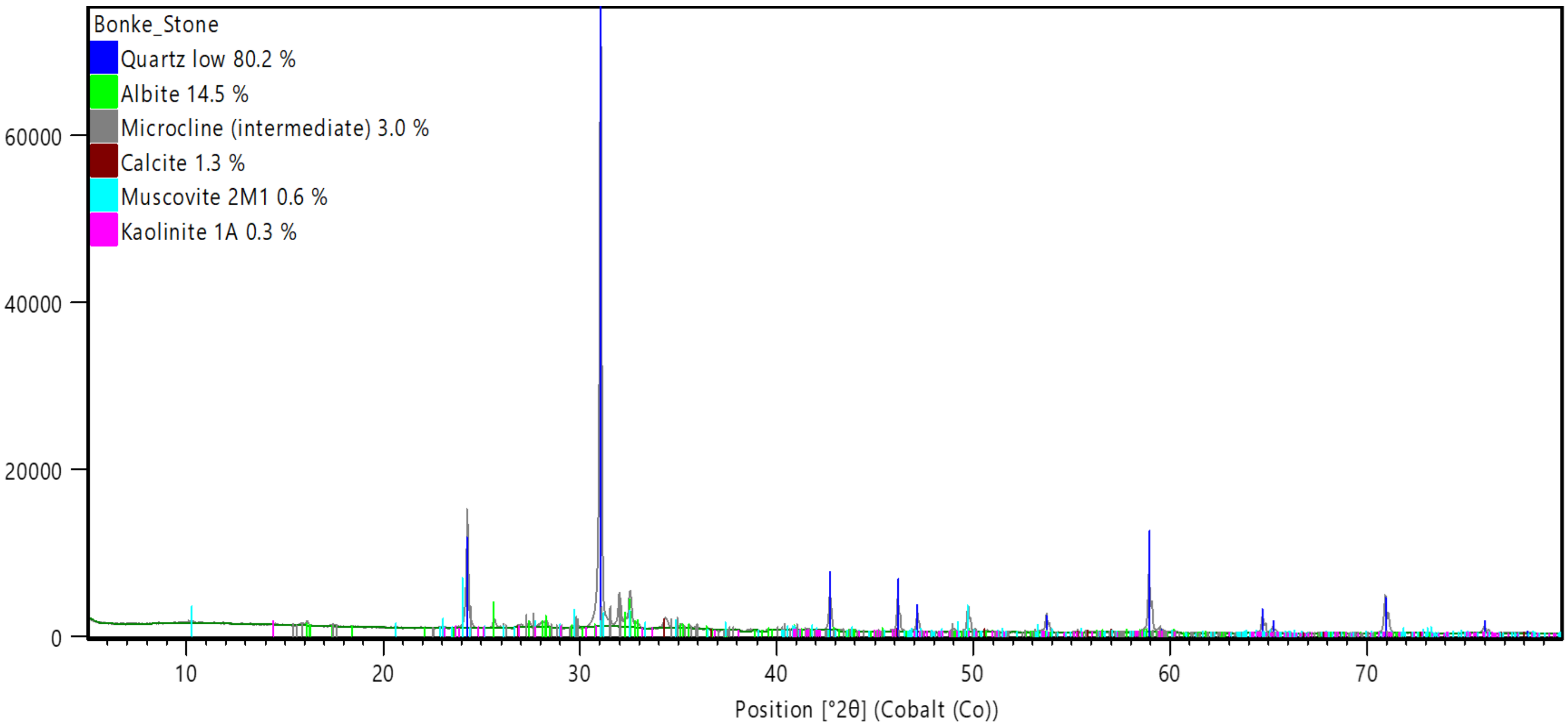
ANNEXURES

Annexure A: List of publications

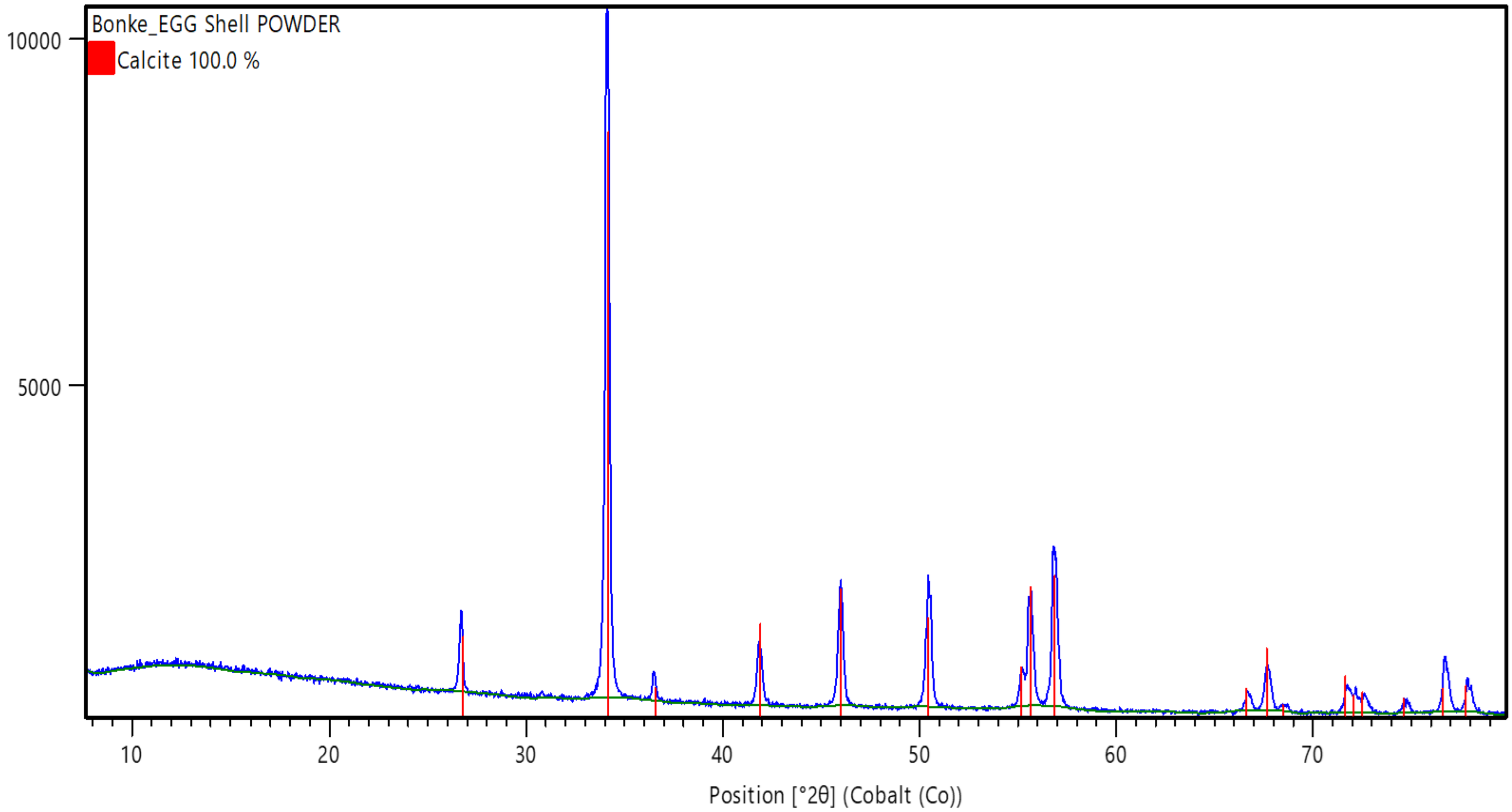
- Mncwango, B. and Allopi, D. (2021) ‘A comparative review of eggshell powders for use in concrete production’, International journal of advanced research in engineering and technology, volume 12, issue 4, pg. 280-287, ISSN: 0976-6499
- Mncwango, B. and Allopi, D. (2021) ‘The viability of eggshell powder as a substitute in concrete’, Institute of municipal engineering of Southern Africa, volume 46, issue 11, pg. 48–49, ISSN: 0257-1978
- Mncwango, B. and Allopi, D. (2020) ‘Urban poverty- A complex resulting from the inability of goverments to keep up with urbanization’, Environmental Research Journal, volume 15, issue 21, pg. 3599-3604, ISSN: 1816-949x
- Mncwango, B., Pududu, B. and Allopi, D. (2020) ‘A review of the role and contributions of microorganisms in exacerbating the covid-19 pandemic from an infrastructure perspective’, International Journal of Civil Engineering and Technology, volume 12, issue 2, pg. 683-692, ISSN: 0976-6499

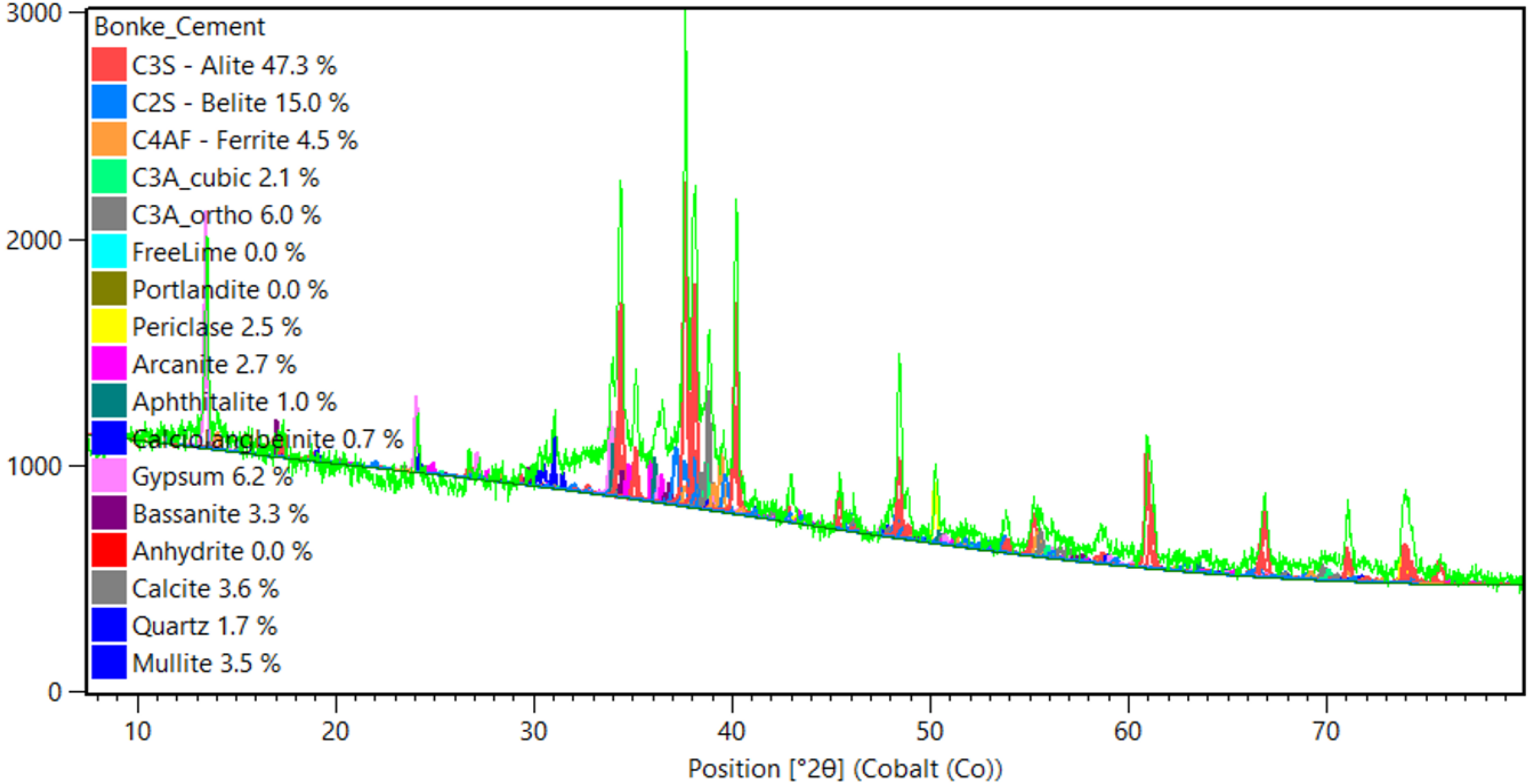
Annexure B: XDR results – river sand, stone, egg shell powder, cement





Bonke_Stone
Quartz low 80.2 %
Albite 14.5 %
Microcline (intermediate) 3.0 %
Calcite 1.3 %
Muscovite 2M1 0.6 %
Kaolinite 1A 0.3 %
60000
40000
20000
0
10
20
30
40
50
60
70
Position [°2θ] (Cobalt (Co))


Bonke_EGG Shell POWDER
Calcite 100.0 %
10000
5000
10
20
30
40
50
60
70
Position [°2θ] (Cobalt (Co))



Bonke_Cement
C3S - Alite 47.3 %
C2S - Belite 15.0 %
C4AF - Ferrite 4.5 %
C3A_cubic 2.1 %
C3A_ortho 6.0 %
FreeLime 0.0 %
Portlandite 0.0 %
Periclase 2.5 %
Arcanite 2.7 %
Aphthitalite 1.0 %
Calciolangbeinite 0.7 %
Gypsum 6.2 %
Bassanite 3.3 %
Anhydrite 0.0 %
Calcite 3.6 %
Quartz 1.7 %
Mullite 3.5 %
3000
2000
1000
0
10
20
30
40
50
60
70
Position [°2θ] (Cobalt (Co))

Annexure C: Editing certificate

DR RICHARD STEELE
BA HDE MTech(Hom)
HOMEOPATH
Registration No. A07309 HM
Practice No. 0807524
Freelance academic editor
Associate member: Professional Editors' Guild, South Africa

154 Magenta Place
Morgan Bay
5292
Eastern Cape

082-928-6208
rsteele@vodamail.co.za

EDITING CERTIFICATE

Re: **Bonke Mncwango**
PhD thesis (DUT): **CHARACTERIZATION OF CONCRETE WITH EXPANDED POLYSTYRENE, EGGSHELL POWDER AND NON-POTABLE WATER**

I confirm that I have edited this thesis and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

Dr Richard Steele
06 October 2022
per email