THE EFFECT OF BIOCHAR AS A PARTIAL REPLACEMENT OF CEMENT IN CEMENT MORTAR MIXTURE AND ITS MECHANICAL PROPERTIES

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ABSTRACT

Carbon Dioxide (CO_2) pollution is one of the leading causes of present day environmental issues. The construction industry, having a huge cement production contributes to these issues such as global warming and climate change. According to Mota-Panizio et al., (2023), the third largest CO_2 emission contributor is cement production. Several research has been done on agricultural waste solutions which includes the use of rice husk, sugarcane bagasse, and biochar as a partial replacement to cement mortar and concrete. This study will focus on the use and benefits of biochar as a partial replacement to cement, not only results in a decrease in usage of cement, lessening CO_2 but as this study will show, it will also help in improving the mechanical properties of cement mortar. The biochar used in this study is a Pinus Radiata Sawdust Biochar, a commercial biochar made in New Zealand. This study finds that 2-3% of biochar as a partial replacement to cement in cement mortar is the optimum percentage with a D50, 0.0172mm particle size and with an 818m2/kg specific area, in which the mechanical properties would prove to be better than that of a pure cement mixture. To determine the internal curing ability of biochar, it is observed in the 3rd batch , a mix with 2% of biochar water cured for 3 days has the same 28-day compressive strength as the control mix was cured for 7 days. It is also found in this experimental study 1-3% of biochar replacement with cement mortar gave increased compressive strength compared to plain cement mortar in all days of curing.

While biochar can be produced from agricultural wastes, it can also be derived from forest waste. Not only does it help in eliminating CO_2 emission, it also adds commercial value to forestry waste providing an opportunity to use rather than discard it. One consequence of climate change is an increase in the number of extreme weather events such as Cyclone Gabrielle in 2023. The effects of this were made worse in some parts of the country due to accumulated forestry waste which blocked waterways making the flooding worse and damaging essential infrastructure.

The main questions this study asks are: How does Biochar influence the mechanical properties of cement mortar such as flexural strength, flowability, and compressive strength? How is the incorporation of Biochar to cement mortar significant

in lessening the increase of CO2 emission? And In which ways can the use of Biochar help improve forest waste management most especially in New Zealand? To answer these questions, conducted tests of flowability, compressive strength, flexural strength, TGA, and SEM Analysis that would determine which percentage best depicts the effect of biochar to cement mortar and analyze the mechanical properties of cement mortar when combined with Biochar.

ACKNOWLEDGEMENT

The work presented would have not been made possible without several entities that have helped me all throughout this journey.

First, I would like to give my special appreciation to my school, University of Waikato, School of Engineering for giving me the opportunity to conduct and publish this dissertation titled: The Effect of Biochar as A Partial Replacement of Cement in Cement Mortar Mixture and its Mechanical Properties.

I offer my sincerest gratitude to my thesis supervisor, Ray Hudd, who supported me throughout my thesis with his enlightenment, expertise, and patience. Without his invaluable guidance, this thesis would not be written nor completed.

Lastly, I thank my dearest parents, who endlessly encouraged and motivated me to keep extending my reach and for the unrelenting emotional support during this trying time. With their patience and help, undying and unconditional support, we are able to complete this research study.

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LIST OF ACRONYMS

DTG	Differentiated Thermogravimetry
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
XRD	X-ray Diffraction Analysis
XRF	X-ray Fluorescence Analysis

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CHAPTER I: INTRODUCTION

BACKGROUND OF THE STUDY

Population Growth and Effects on The Environment

There are currently 8 billion people in the world, and the United Nations estimates that by 2080, that number is predicted to increase to approximately 10 billion (United Nations, n.d.). Some effects of population increase include production of wastes and increase in the rate of CO2 emissions. It is reported that global CO2 emissions have climbed to approximately 32 billion tons annually, which is more than fifty percent of what it was thirty years ago (Nwakaire et al., 2020). This has led to destructive impacts on ecology and thus climate change.

Greenhouse Gas Emissions and CO2 From Construction Industry

The building and construction industry alone is estimated to be responsible for over two-fifth of the energy-related carbon dioxide emissions, based on the Global Alliance construction index (Nasir et al., 2017). Therefore, concrete, which is the most widely used material globally in construction, contributes over one-third of CO2 emissions from construction, and cement, which is ranked eighth of emissions contributing nearly 5% of total human greenhouse gas emissions (Nasir et al., 2017). Therefore, when speaking about global carbon reduction, it will be necessary to invest an impressive amount of work into the creation and popularization of carbon-neutral or even carbon-negative construction materials by utilizing an innovative design and other methods.

Properties and Environmental Impact of Concrete

Concrete is the most familiar material that relates cement to itself being a composite material that plays a critical role in construction. Concrete is created through the mixture of cement, water, sand, and gravel and is prized for its great strength, endurance and flexibility (Shanks et al., 2019). This at the same time improves the cost of construction and at the same time also the toughness and longevity of buildings (The QMJ Group Ltd, 2017). Cement mortar is a durable building material that requires little maintenance and is resistant to fire, rust, and erosion. It strengthens the construction and lengthens a building's lifespan. Just in cement production, there is enough carbon footprint that is generated in relation to construction materials. Therefore, the reduction of cement content in concrete is a prerequisite to cut down CO2 emission from construction business.

Alternative Materials to Cement

As discussed by Professor Herbert Pollman (2021), Portland Cement, over the years, is made by using raw materials such as limestone, which then forms a so-called “clinker” when burned. Over recent years, researchers have considered various alternatives to cement such as ground granulated blast-furnace slag (GGBS), fly ash, and biochar. While the use of GGBS cement in concrete as compared to the use of the regular mix of Portland cement sets slower, over time, it also gains strength, improving concrete’s durability and life expectancy (Concrete: Cement Substitutes - GGBS, PFA and More, n.d.). Although a few of the disadvantages are longer setting and drying time, cold climates causing delays in setting, and low strength in cold climates, fly ash also helps prevent cracks or expansions, as well as reduces concrete’s permeability. (Dale, 2023). Fly ash is most commonly used as partial replacement to cement with 40%-60% (Truscott, 2024). Biochar is defined as a black material that includes ashes and carbonized matter. Biochar has also played a big role in enhancing the quality of soil by raising its pH as well as the development of soil moisture.

Waste Management In The Forestry Industry of New Zealand

Given the existing status on the management of forestry waste in New Zealand, it could be seen that the concept of adding biochar to cement mortar mix has not been unfamiliar to researchers (Zhou et al., 2023). Biochar is usually produced from different biomass feedstock such as forestry residues and agri-residuals. Subsequently, the application of biochar into the materials regularly used mean that unnecessary forest and agricultural waste can be put to good use.

Biochar As A Carbon Sequester

Biochar is defined as a black material that includes ashes and carbonized matter. Biochar has also played a big role in enhancing the quality of soil by raising its pH as well as the development of soil moisture. However, the steady application of biochar also fosters the decrease of overall concentration which concerns greenhouse gas emissions mostly at low level. As suggested by Senadheera et al. (2023), the use of biochar instead of cement assists in the enhancement of an excellent construction of a building that conserves the environment alongside the reduction in CO2 emission. This can be regarded as a porous carbon when the application of high temperature is feasible concerning the obtainable sustainable applicability. Also, it contributes to the reduction of cement used in construction which is beneficial to the environment and may minimize instances of climate change. It can cause more influence in construction, optimizes the quality of the soil and the flexibility and versatility of the soil in construction applicability.

OBJECTIVES OF THE RESEARCH

This experimental study aims to:

- Analyze the effects of Biochar to Cement Mortar by studying the mixtures' mechanical properties;
- Identify the gaps in relation to current research papers in terms of the difference of mechanical properties with different biochar used;
- Analyze and compare the effects of Biochar to Cement Mortar by using different percentages in mixes with 7 up to 56 days curing periods; and
- Determine the optimum percentage of Biochar in cement mixture that retains or increases the quality.

SCOPE AND LIMITATION

This research mainly focuses on the benefits of Biochar incorporated in Portland Cement- based Mortars. While there are various sources of Biochar, the Biochar used in this experiment is a commercial New Zealand Pine Biochar. The researcher understands that when using different kinds of Biochar, different results may also be obtained, depending on manufacturing processes and the kinds of raw materials. The results have also been obtained from conducting curing periods between 7 to 56 days only under New Zealand weather conditions.

Given that the curing periods used to obtain the results of this study ranges between 7 to 56 days, the researcher considers a change in the results if they are respectively cured for a longer period. It is also understood that using different equipment may also affect mixtures, therefore altering the results of the experiments. While conducting this research, secondary data was gathered to support the results obtained from the experiments but does not claim to be accurately correlational due to the different types of Biochar available.

CHAPTHER II: REVIEW OF RELATED LITERATURE

2.1 Anthropogenic Conditions of The Use of Cement

According to Xi et al. (2016), between 1930 and 2013, China accounted for one-third of the world's cement production emissions, with the United States and Europe following closely behind. Currently, 43% of emissions remain sequestered, leaving 56% in the air. Overall, 68% of the total emissions generated from concrete and 27% from cement mortars and at present, 43% of them are sequestrated, while 56% remains in the atmosphere. The US, China, the European Union, and the rest of the globe accounted for 7%, 33%, 25%, and 35% of the emissions of carbon dioxide from cement manufacturing between 1930 as well as 2013 (Region). 68% of the emissions come from concrete, 27% through mortar, 2% from lost cement during the building phase, and 3% from the creation of cement-know-how (CKD) materials. 89% of the emissions are related to service life cement, 5% to destroyed cement, and 6% to landfills and recovery (current life cycle) of demolished cement.

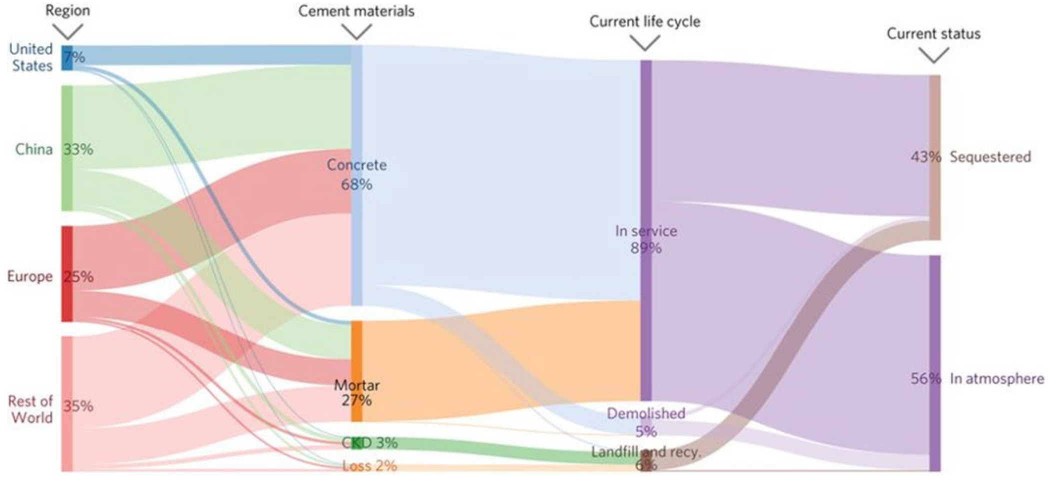

Figure 1: Global emission data from the cementing procedure (1930-2013)
Xi et al., (2016)

2.1.1 Reducing Emissions from Concrete

The study of Chandar & Santhosh (2022) presents an overview of a prior study that included "cementitious materials such as fly ash (FA), ground-granulated slag from blast furnaces (GGBS), fly ash (FA), metakaolin (MK), silica fume (SF), rice husk ash (RHA), and so forth". A certain quantity of mortar cement using such cement-like substances has had positive outcomes in regard to strength. Though it reached the desired target strength at another point in time, the concrete prepared with these components demonstrated less mechanical strength than ordinary concrete. A portion of the cement used in the manufacturing of concrete has been replaced with mineral admixtures such as FA, MK, SF, which is RHA, GGBS, Alccofine, and so forth (Chandar & Santhosh, 2022). Mineral admixtures readily react with cement because of their metallic nature, which imparts strength. In the process of producing high-strength concrete Potential partial substitutes include fly ash along with eggshell powder, as per Mohamad et al. (2016), neither of which has shown good strength performance. Concrete with outstanding strength may benefit greatly from the best possible utilization of 30% and 40% fly ash as well as 5% powdered eggshells.

2.2 Cementitious Materials as Cement Replacement

Several researches have been made, studying different cementitious materials used as cement replacement.

Fly ash: The application of Fly ash has the potential to improve the partial cement replacement process in concrete mixtures. The application has created an energy-intensive production that has improved the scope of workability. This material has also increased the durability of the cement and helps in mitigating the emission of CO2 or greenhouse gases. Fly ash can also reduce the demand for water in construction and create the flowability of cement concrete. In accordance with the research of Kalombe et al. (2020), the illustration is that fly ash particles fill voids in the concrete mixture of cement. The process has also improved effective building construction. The mentioned component has reduced the harmful impact of cement mixtures. This involves substantial evidence to assess the proper way of waste management. The creation of structural growth can be sustained to create an effective building construction. Finally, it has also improved environmental upgradation.

Rice Husk Ash (RHA): It is an agricultural byproduct derived from the burning of rice husks. The material has gained attention in the construction industry due to the property as a pozzolanic material that can enhance the property of cement mortar and concrete. Rice is the main source of food and has a major consumption for billions of people which is approximately 1% of the land on earth (Xu et al., 2012). Rice husk ash is one of the main residues from the agriculture waste and has a high reactive amorphous silica 85 to 95%. After the controlled combustion of rice husk it is converted to rice husk ash which has a highest pozzolanic behavior as compared to other plant residues productions (Cordeiro et al., 2008b). The usage of rice husk ash as a construction material improved the mechanical properties and durability of concrete in harsh environments (Alex et al., 2016). So many researchers have incorporated rice husk ash in mortars and concluded that it enhances the compressive strength in the long run and also suggested the optimum level of replacement which has positive effects were limited to 20% by weight of cement (Jamil et al., 2016; De Souza Rodrigues et al., 2010; Chao-Lung et al., 2011; Antiohos et al., 2014). Rice husk ash (RHA) blended mortars provides significant improvement in opposition to chloride ions penetration with higher dosage replacement as compared to compressive strength which shows rice husk biochar improves the durability of mortars (Anwar et al., 2000; Chindaprasirt & Rukzon, 2014).

Sugarcane Bagasse Ash (SBA): Sugarcane bagasse ash (SBA) is derived from the combustion of sugarcane bagasse, which is a byproduct of sugar production. SBA is a high pozzolanic substance because it has a high amount of reactive amorphous silica with appropriate chemical composition to be utilized as a pozzolan. The SBA addition as a cementitious material improves the compressive strength, reduces permeability and enhances chemical resistance. By making use of agricultural waste it promotes sustainable building construction. In a study by Batool et al. 2020 observed increase in compressive strength of concrete when replaced cement with sugarcane bagasse ash (SBA), showed that the pozzolanic reaction of SBA contributes to the strength improvement (Batool et al., 2020).

Volcano Ash: Volcanic ashes is a natural occurring pozzolan, which is obtained from the rapid cooling and fragmentation of the volcanic glass during eruptions. Due to high silica content it contributes to the pozzolanic reaction. When used in concrete and cement mortar it improves the mechanical properties of cement based mixtures. It is being used back in ancient times one of the examples is Roman Pantheon and aqueducts, where it was used for the longevity and durability of the building. Based on an experimental study by Abdulazeez et al. (2020) replaced cement with volcanic ash from 5% to 20% and found that after 38 days of curing concrete samples with 7.5% and 10% showed significant increase in compressive strength as compared to plain and other concrete mixes.

Metakaolin: It is manufactured from the calcination of Kaolin clay. Kaolin is a white color fine mineral which is being used traditionally to produce porcelain. Metakaolin is neither a by-product nor wholly natural. It is derived from the mineral and manufactured for cementing application. The process of heating a kaolin clay is involved at a temperature 650 to 800 degree Celsius, transforming it into a highly reactive aluminosilicate. Based on the study by Malagavelli et al. (2018) observed increase in compressive strength by 7% and 16.5% when metakaolin is added by 5% and 10% respectively. In this study it is found that all metakaolin blended mixture showed increased compressive strength as compared to plain concrete.

Silica Fume: A byproduct of the manufacture of silicon and ferrosilicon alloys is silica fume, also known as micro silica. It is made up of very fine amorphous silica particles that play a part in the pozzolanic process in concrete. Concrete that has silica fume improves the durability, compressive strength and resistance to chemical attack. Silica fume has a high specific surface area and fine particles resulting in denser and cohesive concrete mixture. In the study made by Tak et al. (2023) incorporated silica fume into concrete in 5%, 8%, 11% and 15%, found that 11% silica fume substitution gives increase in all mechanical properties determined as compressive strength, flexural strength and split tensile strength when compared to plain concrete.

Ground Granulated Blast Furnace Slag (GGBFS): It is a byproduct of iron and steel manufacturing process, ground granulated blast furnace slag is created by rapidly quenching molten slag from the blast furnace with water or steam, forming glassy grains, granular substance that is subsequently dried and crushed into a fine powder. GGBFS is finer than the Portland cement which is resulting in the significant improvement in the workability of fresh concrete and makes it easier to place and finish. In a study by Dom et al. (2022) observed that 30% GGBS replacement improves the compressive strength after 28 days as compared to plain concrete, also observed replacement from 30% to 60% result in higher strength at a later stages of curing (Dom et al., 2022).

Alccofine: Improving concrete by its particle packing, this is an essential material which is known to be a slag-based micro-fine admixture (BLN Srinath, S. et al., 2022). A new generation, Alccofine 1203 is described to be as an ultra-fine with low calcium silicate product manufactured in India, processed from Ground Granulated Blast-furnace Slag (GGBS), a waste material which is often produced by iron ore. According to BLN Srinath S. (2022), in a study done to compare cement and alccofine regarding their suitability towards concrete, given its properties that includes silica and alumina, it is beneficial to providing better strength towards the mixture. In the same research, the researcher concluded that having 15% of Alccofine is the optimal dosage in terms of gaining hydration and strength values.

2.3 Forest Waste Management in New Zealand

New Zealand, with both the forestry and farming industry being essential contributors to its economy, throughout the years, have been going back and forth in terms of contention for land. According to Clark (2019), It is expected for forestry to continuously expand in the next coming years as it is known to have less carbon footprint in comparison with the farming industry due to the farming of sheep and cattle and the continuous need for timber not only locally but as well as internationally. Although the forestry industry takes up fewer carbon footprint, this opens up New Zealand to the risk of damage possibly due to forest wastes washed away by flood water.

In the past few years, the country has been experiencing severe floods due to severe weather conditions (Sadler, 2023). In the year 2023, A severe tropical storm, Cyclone Gabrielle hit the North Island of New Zealand with it's eye mainly along the east coast. (Manaaki Whenua – Landcare Research et al., 2023) According to McMillan, A et al. (2023), some of the possible factors that contributed to this event in Hawke's Bay and Gisborne poor forestry management in terms of non-thinning, various forestry rotations, and thin layer of soils that was caused by past erosions.

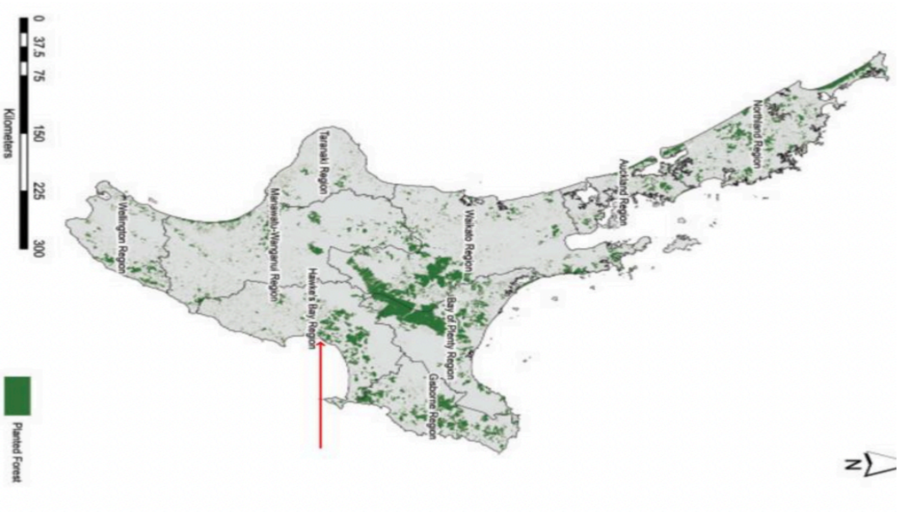

Figure 2: Planted Forests Across North Island of New Zealand
Source: Yao (2013)

The Figure above shows the space of North Island occupied with planted forests (Pinus Radiata). The red arrow is where Esk Valley is found, the forestry surrounding this area was a big factor that contributed to the magnified effect of Cyclone Gabrielle all throughout the region of North Island. Although one of the main reasons why trees are planted is to balance the absorption and flow of water during the rain, strong or severe weather conditions can also cause the same trees to be broken into pieces and be washed away by water which then results in its debris being unmanageable or put to waste. During Cyclone Gabrielle, a big chunk of forest waste such as rock, soil, and slash from Esk Valley was washed into the ocean which then resulted in various drainage systems being blocked, causing a massive flood.

2.3.1 Practices to Combat Forest Waste

Through the years, there have been different researches conducted to come up with various solutions in aiding the management of forestry waste. A lot of it would include chipping, mulching, or burning in order to dispose of the growing amount of forestry slash (Azwood, 2023). Forestry waste can be converted into bioenergy, used to manage soil erosion. converting forest waste into compost can also be considered for soil fertility, thereby recycling nutrients back to the ecosystem.

Over the years, researchers have been exploring a new partial alternative to cement. This material can be derived from various sources such as agricultural wastes, forest wastes, sewage waste, etc. which in turn helps in lessening carbon emissions from concrete. Biochar, which piqued the interest of the researcher will be further talked about during this experimental study.

Biochar: The material of biochar has the properties of thermal insulation that regulates the temperature of the construction building. The use of Biochar develops as a fundamental building material that involves a unique property that is associated with the building of effective construction. It has a high level of porosity and a low level of thermal conductivity. Moreover, as the building material, biochar has played a contributory role in mitigating carbon emissions. It also controls the moisture of soil and regulates the humidity level of the cement mixture which provides indoor comfort. It provides a strong structural support that helps to resist fire in the building by the application of biochar in the cement concrete mixture.

2.4 Biochar

Biochar is a waste by-product derived from the thermochemical conversion of organic waste/biomass either in the absence or under limited oxygen.

2.4.1 Types of Biochar

Biochar can be differentiated by the process of its production of different pyrolysis processes. As per Ambaye, Vaccari, van Hullebusch, Amrane, & Rtimi, (2021), biochar has highlighted the following types.

Figure 3: Biochar Types
Ambaye, Vaccari, van Hullebusch, Amrane, & Rtimi, 2021)

Agricultural Biochar: The development of agricultural waste can create the process of making agricultural biomass that helps to create this biochar. This has comparatively more nutrients and mineral content that improves the quality of soil. It creates a beneficial improvement to the environment to mitigate agricultural waste.

Manure Biochar: It has been produced from animal manure and develops as a specialized biochar that contains more nutrients and is developed by organic matter. It improves the soil health and its fertility. It has mitigated odors and improved as a material of construction.

Green Waste Biochar: It develops from the green waste that is associated with grass clipping, leaves, yard trimming and so on. It creates an improvement of soil that helps to develop the strength in the construction (Ippolito et al. 2020). It helps to create green building development that involves a diverse range of organic materials. It helps to maintain biodiversity and microbial activity to create sustainable construction.

Shell Biochar: It is created through the biomass of shells that have increased the carbon removal credit and developed environmental sustainability in the construction process. It has reduced the atmospheric concentration and reduced the CO2 gas emission to create a sustainable environment.

Wood Biochar: It can be developed from wood biomass and can be identified as the most available type of biochar. It has a high level of carbon content and develops through wood chips, forestry residue, sawdust and so on. It increases stability which involves a strong porous structure and creates fertile soil production.

2.4.2 Biochar Production

Different types of chemical reactions owing to biochar production can be evaluated with respect to the reaction conditions, yield, and energy efficiency in the following manner.

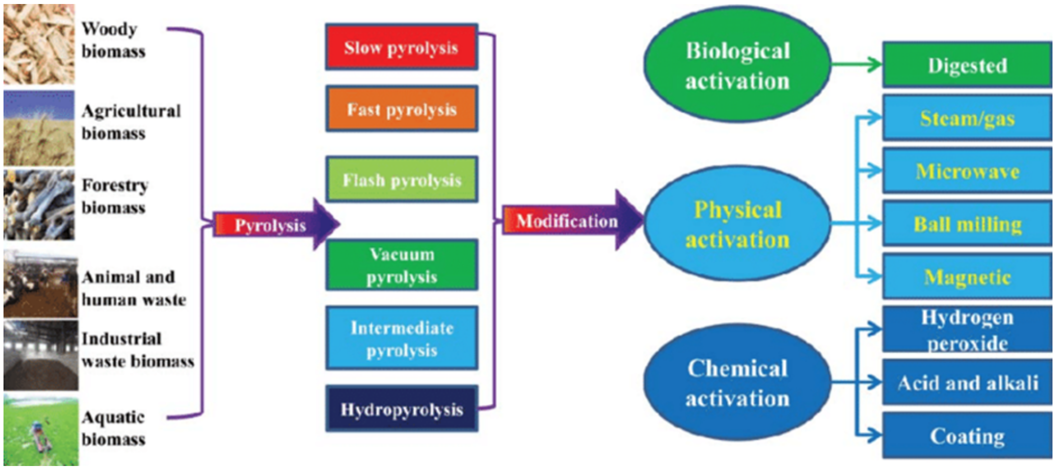

Figure 4: Different kinds of biochar production process
Wang et al. (2017)

Pyrolysis

Pyrolysis involves heating and decomposing organic materials in the absence of oxygen (Lewandowski et al. 2020). 250 to 900 degrees Celsius temperature is required to obtain the reaction condition to convert waste biomass into value-added products and biochar can be regarded as one of the significant value-added products among them. This process to produce biochar is associated with the substrates of waste biomass consisting of cellulose, hemicellulose, and lignin (Adeoye et al. 2023). A series of chemical reactions are involved in the process in a stepwise manner integrating the reactions of depolymerization, and fragmentation, followed by cross-linking, leading to the generation of a mixture of bio-oil and char. The liberation of CO2, H2, CO, and a mixture of H2 and CO are also assisted in this reaction. It is essential to mention the importance of optimal temperature for the reaction efficiency of the biochar formulation which was represented considerably by Yaashikaa et al (2020).

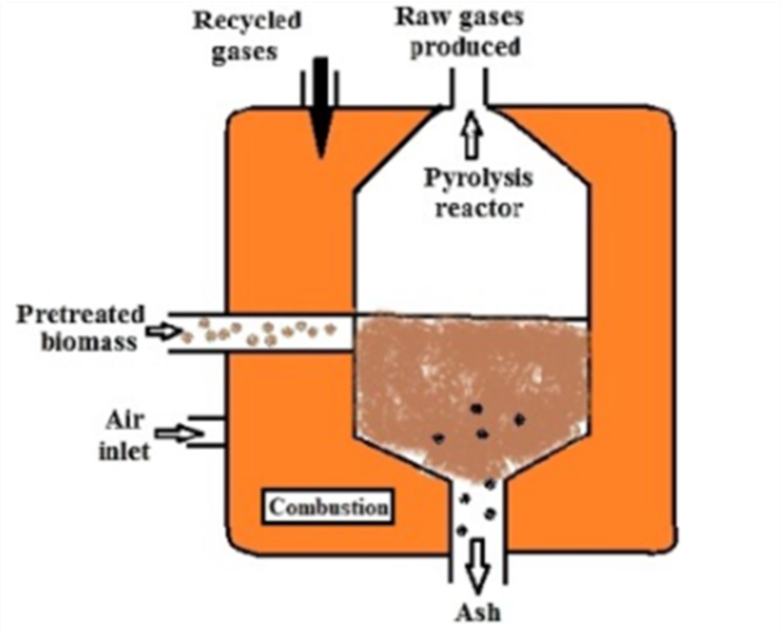

Figure 5: Biogas production in pyrolysis reactor
Yaashikaa et al. (2020)

Pyrolysis is a complicated process using heat. Without oxygen, it takes place at 400–800 °C in temperature. According to Lombardi et al. (2015), the primary factors affecting the amount produced and overall quality of decomposition gas, oil, as well as char are the rate of heating, process temperatures, residence, period of time waste content, as well as waste particle size. At a lower temperature (500–550 °C), the most common byproducts include pyrolysis oil, waxy substance, and tar; at greater temperatures (>700 °C), the main result is pyrolysis fumes. A certain type of waste must be used as feedstock for high-quality products from pyrolysis (material, the city of tyre electronics, electric garbage, woody waste) As per Prurapark et al. (2020), Pyrolysis involves a method of breaking down different substances or materials by heat at temperatures between 400 and 800 degrees Celsius in an atmosphere without oxygen or with not much oxygen present. In most cases, multiple types of products can be separated from the process of pyrolysis based on the conditions. Gas, liquid (which resembles oil), as well as char are the main products that can be obtained. The proportion of goods obtained is contingent upon the parameters of the manufacturing, including temperature and heat rate. Fluid or oil-based products are the most popular.

Hydrothermal carbonization

In this process, hydrochar is produced which has a greater percentage of carbon in terms of composition. This chemical ratio represents the coalification of crude biomass to form hydrochar (Lucian et al. 2017). In this reaction, a wide range of waste materials including organic wastes, agricultural wastes, animal manure, and sludge are thermally decomposed to produce hydrochar at 180-250℃ under an extremely pressurised condition. Like the previous method (pyrolysis), optimal reaction temperature is required in this process as well to ensure the reaction efficiency (Sharma et al. 2020). Rather than the organic wastes and sludge, lignin and hemicellulose can also be used in this reaction.

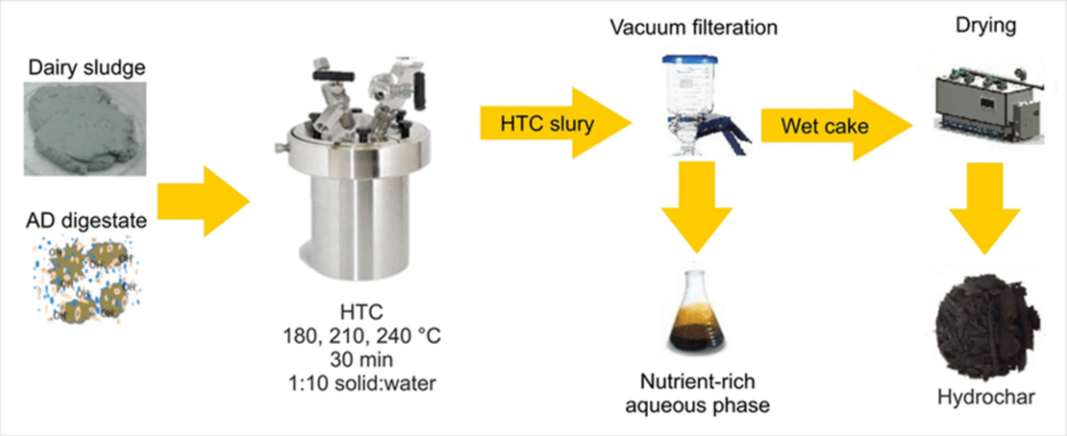

Figure 6: Hydrothermal carbonization
Al Ramahi et al. (2021)

Gasification

This thermochemical reaction can be used to produce biochar along with the production of syngas as a side product and this reaction has not been found to be highly effective in terms of biochar production due to reduced product yield as compared to other reactions of biochar formulation (Yao et al. 2018). An optimal temperature is also required in this reaction (>500℃) under a choking condition. This gasification process has also been found to be more sustainable as compared to other processes (You et al. 2018).

However, as opined by Amalina et al. (2022), current days, a wide range of biomass and waste materials are available to produce biochar from the gasification reaction including municipal wastes, crop residue, and animal manure, leading to the possibility of including fine-tune gasification biochar. In terms of energy efficiency, the researchers found the gasification method of biochar production somewhat more advantageous as compared to the chemical methods as this method leads to associate high concession efficiency of carbonaceous substrates along with self-sustaining energy support due to the auto thermal nature of the reaction (Ofori-Boateng et al. 2013).

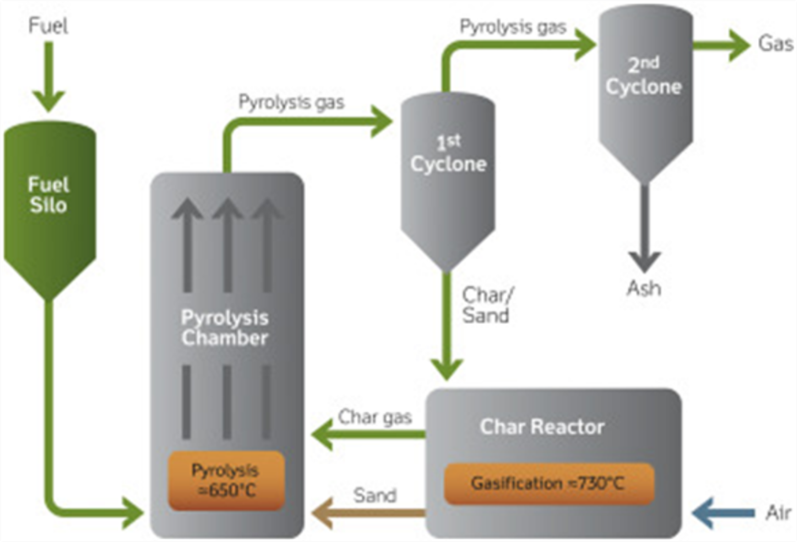

Figure 7: Production of biochar as a valuable byproduct of gasification reaction
Hansen et al. (2015)

Flash carbonization- It is another efficient thermochemical process to convert biomass quickly into biochar by the ignition of a flash fire at the bottom of a packed biomass bed at 300 to 600 degrees Celsius under 2 MPa pressure. This method is efficient for its faster biochar generation efficiency with a residence time of fewer than 30 minutes (Wade et al. 2006). Muthu Kumar & Varunkumar (2023) focused on the devolatilization process in this context for biochar production as a source of ultra-rich carbonization procedure by using lignin-associated compounds to produce biochar. The research found that the yield of biochar in such reactions is almost 33%, 2 times greater than the conventional gasification process, with a fuel consumption rate of greater than 200 g/m2s.

2.4.3 Properties of Biochar

Regarding biotic or abiotic processes, one of the most important variables in reducing greenhouse gas emissions into the environment is the age of biochar. Consequently, the characteristics of biochar dictate its efficiency in mitigating greenhouse gas emissions from the atmosphere. The distinctive characteristics of biochar, including its highly porous structure, ability to buffer acids, and its ability to store water and retain vitamins and minerals, might be connected to and surely used as a beneficial technique for mitigating greenhouse gas emissions in fertilizer.

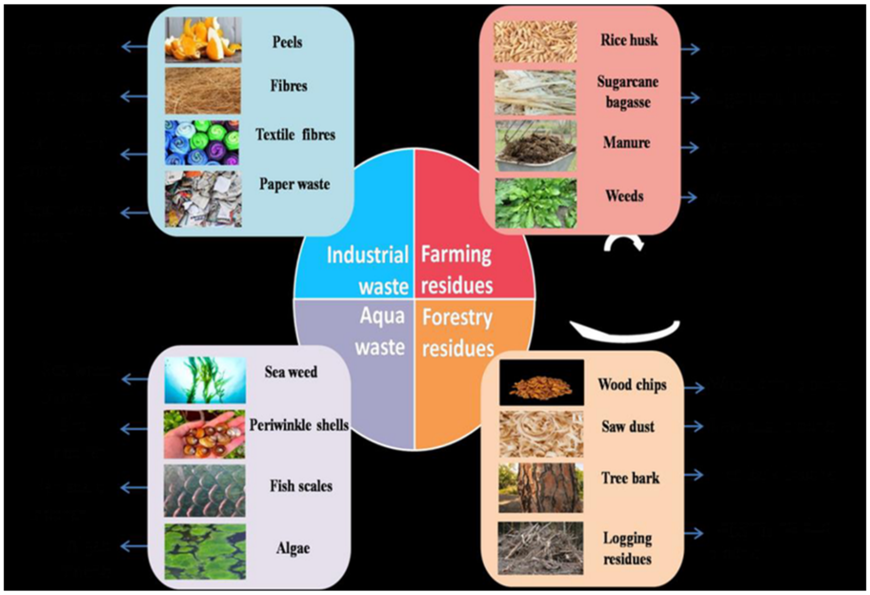

Figure 8: Biochar
Jha et al., (2023)

Porosity: Biochar is considered a high level of porosity that improves the production process and plays a beneficial role in soil improvement as well as water filtration.

Surface area: Biochar contains a high surface area that involves organic compounds and improves the environment of a construction project.

Density: Biochar consists of lower density that impacts the lower volatility of the cement concrete and improves the mixture quality.

Hydrophobicity: It involves the hydrophobic properties that improve the control of moisture in the concrete mixes and develop more effective and durability of cement *mortar.*

Chemical Composition*:* This influences the mechanical aspects that consist of the practice of high carbon content and impact stability and persistence that mitigates degradation of the cement.

2.4.4 Evolution of Biochar Through the Years

According to Punnoose (2015), the Origins of Biochar serve as "Ancient Soil Amendment Charcoal" made from superheated biomass known as biochar. As vegetation blazes, it occurs naturally in soils all throughout the planet. In the South American Amazon Basin, biochar was produced and utilized by humans for over 2,500 years in conventional farming methods. In areas that used to have poor and sometimes hazardous soils, productive farms were supported by dark, charcoal-rich soil, also called terra preta as well as black earth. Dutch soil researcher Wim Sombroek made the discovery of Terra preta in the Amazon jungle in the year 1950. 10% of the total Amazonian Basin is still covered by Terra preta (Clement, 2021). South American countries such as Peru, Ecuador, Benin, as well as Liberia, have all produced similar locations. Conventional Methods of Production— Traditionally, charcoal was made by simply piling and covering wood and letting it burn slowly with little air. This process, which is still in use in underdeveloped nations today, produces half of the CO2 that is produced from the initial biomass and produces a significant amount of smoke. Although the output is charcoal, which may be applied to soil, the process of producing it is unhealthy for both humans and the environment and wastes the entire heat (energy).

2.4.5 Biochar as A Carbon Sequester

According to Rahman et al. (2017), the utility of biochar’s use as a carbon sequester has been shown by different authors which is due to the capability of biochar to capture biomass carbon into soil. Zhang et al. (2023) opined that biochar has the unity of the provision of environmental sustainability by sinking 1 gigaton of carbon dioxide annually (Maniarasu et al. 2023). Furthermore, in the experimental study it is observed that 4wt% of biochar incorporation into cementitious products can improve carbon-capturing up to 12% (Gupta et al., 2021a). However, as compared to other solid adsorbents, biochar can be regarded as the most eco-friendly substance as it can be generated from waste materials, demonstrating the efficacy of sustainable development, by reducing the concentration of wastes. Further, as opined by Shoudho et al. (2024), it has an aromatic carbon structure with a high level of thermal stability which leads to increased carbon sequestration possibilities, preventing the possibility of further release of CO2 in the atmosphere. In the experimental study by Chen et al. (2022) added biochar derived from corn straw processed at 500°C pyrolysis utilized to test the carbon capture capacity of biochar concrete. The author (Cher et al., 2022) replaced cement by 5 wt%, suggesting 32.4 kg/m3 CO2 emissions can be stopped by considering the replacement of cement. It is evident that the use of biochar provides an extra 15.8kg/m3 reduction in greenhouse gas emissions (GHGE) (Chen et al., 2022). It can be calculated that a total decrease in GHGS could be reached to 14.7%.

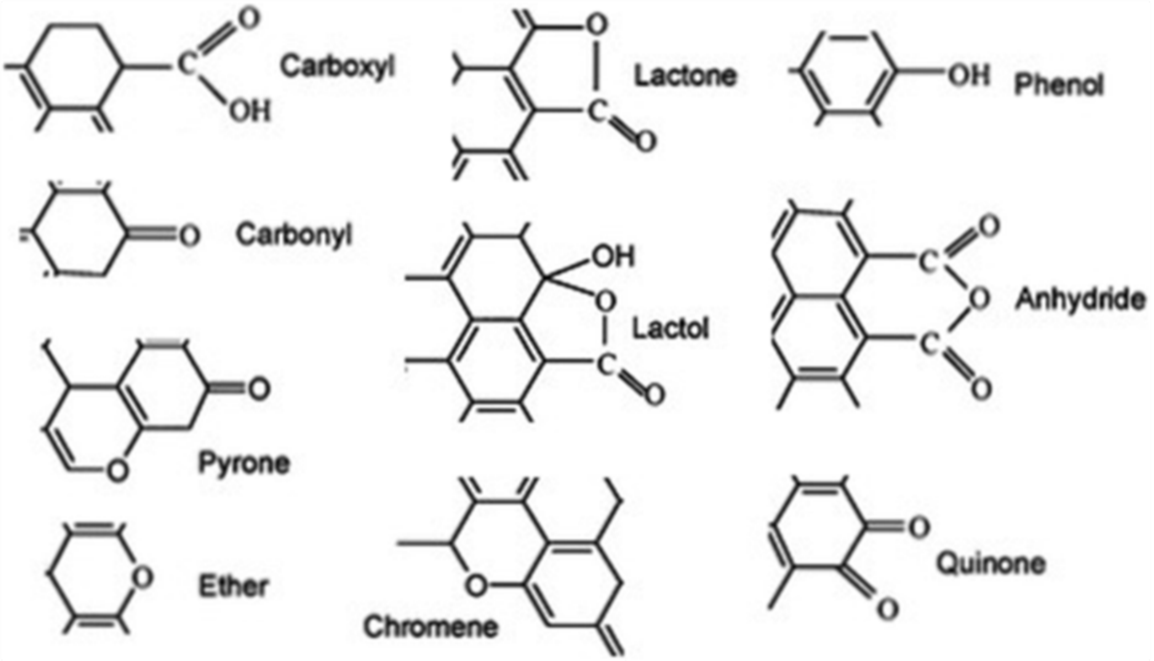

Figure 9 : Aromatic functional groups present on the surface of biochar owing to the carbon-capturing capacity
Tomczyk et al. (2020)

To be precisely stated, biochar acts as a carbon sink for the environment as the production of biochar is capable of reducing atmospheric carbon dioxide through the transformation of decaying organic biomass in a carbon-neutral process, owing to the carbon-negative attribute to the environment (Mulabagal et al. 2015). This way of stabilizing decaying organic matter in the soil can improve the stability of those organic matters in the soil for a long time which not only helps to potentially prevent the leakage of CO2 in the atmosphere from those decaying organic substances but also improves the fertility of the soil by enriching its nutrient value with an optional level of pH and soil acidity. As opined by Mukherjee & Lal (2013), the enhancement of carbon concentration in the soil not only improves its nutrient quality but also enriches its water retention ability, owing to the reduction of the acidity of the soil. It helps in increased crop production facilities by improving the soil's chemical nature as well as making the soil an effective environment for the growth of beneficial microorganisms.

Figure 10: Improved chemical and thermal stability of biochar endorsing the carbon sequestration process
Xu et al. (2021)

As per the study by Elkhlifi et al. (2023), it has also been supported that the properties of biochar concerning carbon sequestration are essential for the amendment of soil quality by endorsing the organic carbon content of the soil as well as improvement in the soil fertility but the capacity of biochar to improve the soil quality is dependent on the process of biochar production and the raw materials of the feedstock used. The carbon sinking capability of biochar has also been regarded as an essential element in regulating the soil pH along with the aggregation and accumulation of heavy metals in the soil. Focusing on this capability of biochar, a wide range of engineered biochar has also been found to be generated with the desired composition and carbon sequestration rate. They are prepared by controlling the conditions of the pyrolysis reaction, biomass used for the biochar preparation, as well as reaction conditions. The engineered BC is prepared with a modified protocol to get the desired rate and quality of the carbon sequestration process; it can be stated that it is far better as compared to the conventional BC in terms of carbon sequestration (Wang et al. 2017). With the increasing surface area of sinking substances, the rate of carbon sequestration increases, and thus, the engineered biochar is associated with high adsorption strength of atmospheric carbon dioxide, reactivity, and higher surface area, to upregulate the rate of capturing atmospheric CO_2 and also used as effective soil composites.

2.4.5.1 Biochar as an Aggregate Filler

According to Piccolo, Andreola, Barbieri & Lancellotti, (2021), The combination of biochar ameliorates the performance of the construction and possesses the properties of thermal insulation. It creates an effective porous structure and develops a low level of thermal conductivity. It improves the performance of the thermal plan. Biochar improves insulation to regulate the internal temperature by reducing energy consumption.

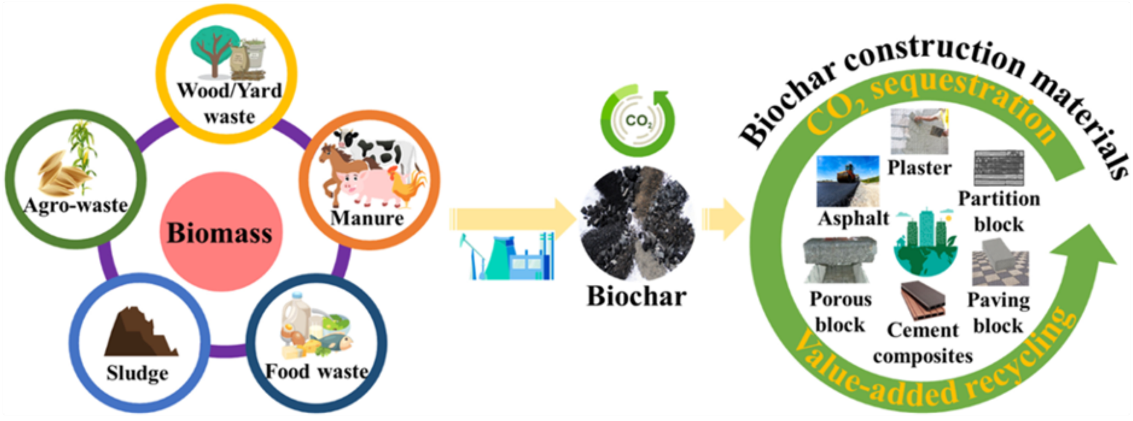

Figure 11: Biochar as a construction material
Zhang et al. 2022)

The above figure highlights the development of biomass by considering food waste, agro-waste, wood waste, manure, sludge and so on that create the formation of biochar and improve environmental sustainability. It can create a reduction of carbon footprint in the cement mix and be used as the construction material. It has created value-added services in the recycling process in the building development. It has been determined as an additive to create insulation processes such as plaster, partition block, cement composite, paving block, porous block and so on. The material enhances occupant comfort which creates a proper way of moisture management and maintains the indoor air quality. Biochar develops carbon sequestration that involves a stable form of carbon and helps to mitigate greenhouse gas emissions. It controls climate change and global warming in the environment by constructing an effective way of building development. As per Akinyemi & Adesina, (2020), it can be evidenced that the geotechnical application of biochar creates a soil stabilizer that improves the quality of soil and controls erosion in the construction process. Moreover, biochar has played a responsible action in generating a green building certificate and developing the maintenance of the attributes of sustainability. It creates an efficiency in building design that involves societal and environmental benefits.

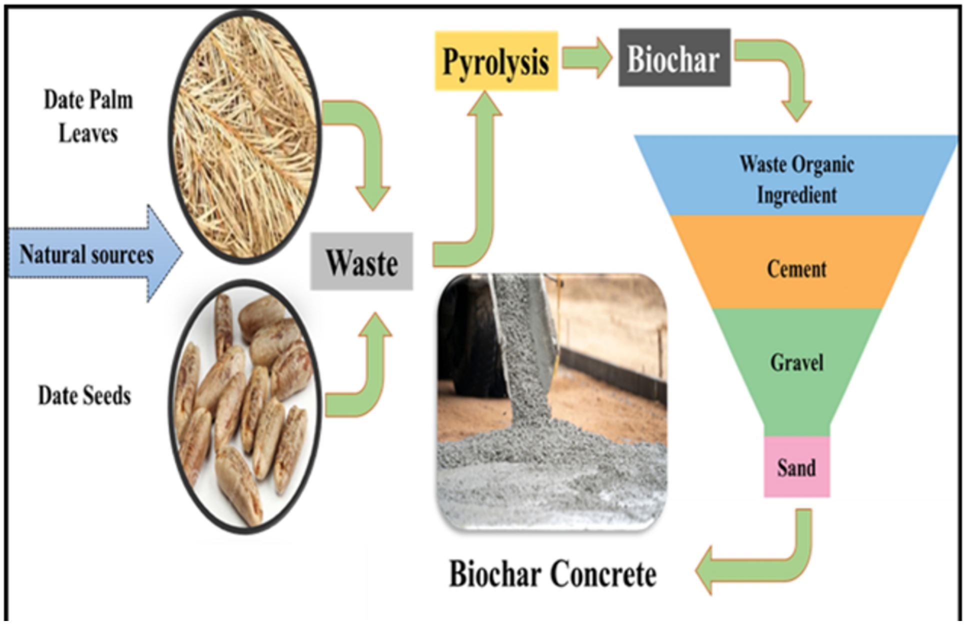

Figure 12: Application of Biochar in Cement Mortar
researchgate.net (2023)

According to Restuccia et al. (2020), it can be stated that biochar-base applies as a cement mortar for creating sustainable buildings. It combines a mixture of traditional cement and biochar to maintain green building construction. It has also contained a high level of porosity that impacts soil fertility, carbon sequestration as well as water retention. The development of cement mortar with biochar focuses on carbon sequestration that helps to mitigate the issue of climate change and global warming due to cement usage in construction. It reduces the carbon footprint and develops sustainable building construction. It has also illustrated the way of improving the process of insulation that develops the porous structure of biochar and reduces thermal conductivity. It creates a potential lower consumption of energy and improves the efficiency of the cement mortar. It improves the flowability and workability of cement mortar which enhances the strength of the building material. It has also increased durability by improving the mechanical properties of the cement mortar. It develops a potential lead in the long-lasting structure and improves the building construction. This has also highlighted the reduction of environmental impact that creates green building development and regulates the moisture in the cement mixture. Besides, biochar improves the sustainability of cement mortar by improving its mechanical characteristics, decreasing the process of shrinkage and preventing cracks.

2.4.5.2 Biochar as a construction material

The researchers started to get interested in biochar and its manufacture less than two decades ago. Biochar is gaining attention because of its performance and environmental aspects. It is an eco-friendly solution for capturing carbon to mitigate climate change. Adding biochar into a cementitious based mixture showed improvement in compressive strength, flexural strength and improved thermal insulation. Furthermore, the porous nature of biochar and its specific surface area also influence the workability, resulting in optimizing the water content of cement mortar and improving the overall performance. By using forest waste biochar not only manages the waste management but also shows the significant improvement in reducing the carbon footprint from the building construction. In a study made by Gupta et al. (2018) found that biochar blended mortar mixes showed improved hydration. in the same study (Gupta et al., 2018) used saturated and unsaturated biochar and found that unsaturated biochar showed increased strength as compared to saturated biochar after 28 day compressive strength. Another study on biochar as a sand replacement by Praneeth et al. (2021) showed that replacing sand with biochar by 20 % showed an increase in flexural strength by 26% compared to plain cement mortar. These results show that biochar has potential benefits when it comes to utilize it as a construction material.

In general, the incorporation of biochar in the cement mortar improves the mechanical properties on one hand while on the other hand it has environmental advantages like low emission of carbon and enhancement of sustainability. Therefore, the application of biochar in cement mortar enhances the workability and effective operations within the construction structures hence enhancing the growth of sustainable building construction.

2.4.6 Mechanical Properties of Biochar in Cement Mortar and Concrete

In a study conducted by Gupta et al. (2018), they explain that by incorporating 1-2% of biochar can control the water to cement ratio which can increase the mechanical properties of cement mortar by up to 20% and concrete up to 50%.

Workability and Flowability

The application of biochar focuses on the particle size that improves the dispersion and mixing of biochar in cement. It has enhanced the workability to develop the performance of cement mortar. It may increase water demand and develop the strength of the cement. According to Senadheera et al. (2023), it can be stated that biochar consists of optimal moisture that is easier to mix properly and distributed evenly. The high surface area affects the porous structure that increases efficiency through the mix of biochar. It has increased the performance and workability by creating proper adjustments to the water-to-cement ratio. The porous structure of biochar that leads to the absorption of free water from the mix, which can make concrete or mortar hard to handle. To solve these effects, biochar can be pre-treated or pre-soaked to adjust the water absorption resulting in the improvement of workability. Choi et al. (2012) tested the flowability of mortar mixtures incorporating biochar by 5%, 10%, 15% and 20% by weight and found it is impossible to measure the flow at 20% because of extremely low workability. Cuthberston et al. (2019) stated that water required by one kg of biochar is equal to one liter, it was also found in this study that 650 ml of water can be absorbed by one kg of biochar. Studies have shown the influence of biochar as a micro aggregate and influence the water cement ratio, Al-Ajarmeh et al. (2020) found the addition of biochar into the fresh concrete, after 5% replacement of cement with biochar decreases the workability of concrete to 20%, This is related to water absorption by the biochar leaving less free water in the mix (Al-Ajarmeh et al., 2020). Similarly, Javed et al. (2022) used five different types of biochar in the experimental study, and recommended that workability of all biochar blended mortars decreased, due to water retention capacity of biochar.

The research of Navaratnam, Wijaya, Rajeev, Mendis & Nguyen, (2021) has focused on the fact that the flowability of concrete mixes develops by the incorporation of biochar. It is also associated with different properties that develop cement mortar mixes. It creates a change in the degree of porosity that impacts the flowability of mixes. The absorption of moisture also impacts the flow behavior of concrete aggregates. This research has highlighted the impact of biochar which creates an improvement of flowability and improves biochar and cement mixes.

This research highlights that nearly 2% addition of the content of biochar has led to a slight increase in concrete mixes. This has shown potential to improve the flowability of biochar and the cement mixture quality. Chen et al, (2020) observed that after 2% incorporation of sludge based biochar resulting in the reduction of flow this is attributed to the water absorption capacity of biochar. Adding woodchip biochar by wt%, Sirico et al. (2012) significantly reduces the flowability of cement mixture, is attributed to the porous nature of biochar particles that absorb the water, to mitigate superplasticizer used at high percentage. Similar kind of result is found by Yang and Wang, (2021b) when rice husk biochar is added by 5 wt% flowability decreased by 8%, this can be because biochar absorbs water during the mixing.

Compressive Strength

Being the most commonly well-accepted method to measure the strength of concrete, Compressive Strength is used to determine the ability to withstand applied forces to concrete (Lysett, 2022). With cement mixtures being used as building material, the durability of the cement and its ability to hold pressure is one of the most important factors that needs to be considered.

According to Lin, Xi et al. (2023), To enhance the compressive strength (and flexural strength) of concrete, the optimum cement replacement or to be used as a mere filler is 1-2wt% (by weight). An addition of 2wt% of Biochar is advantageous to the durability and strength of cement (Suarez-Riera et al., 2020).

In a research done by Zhao et al. (2024) about Portland cement, he stated that there was an increase in compressive strength after 7 and 28 days curing for biochar doses lower than 2.5wt% in cement. He respectively observed a decrease in compressive strength for the same amount of curing days for dosages above 2.5wt%. He also included that the method (wet or dry) of curing did not affect the results of compressive strength but mentions that Carbonization curing method was the most beneficial in terms of testing the compressive strength of cement.

The study by Javed et al. (2022) incorporated five different types of biochar in different percentages of cement. The author(Javed et al., 2022) found that among all the different percentages 2 wt% of bagasse biochar gave the highest compressive strength of 18% compared to plain cement mortar.

Flexural Strength

Biochar has a property of flexural strength that impacts the strongly concentrated cement mortar and improves the efficiency and sustainability of the building construction. According to Suarez-Riera et al. (2023), it can be suggested that the flexural strength of Biochar depends on different factors that have been involved in the added percentage of biochar in cement, the size of particles of biochar that help to create more strength in the concrete mixes. The incorporation of biochar in cement improves flexural strength and creates a reinforcing effect on the particles. It enhanced the development of specific compositions that are associated with the mixed design of building construction. In the study by Boumaaza et al. (2022) used a biochar derived from desert palm rachis (DBP), where 1% of biochar replacement with cement gave increased flexural strength by 12%, but when increased the substitution by 5 wt% the flexural strength decreased, resulting from the excess voids formed on the tensile zones. Sirico et al. (2020) used wood chip biochar in cement mortar as a filler and reported with 1 wt% of biochar increased flexural strength by 6%, attributed to the finer particles filling the voids (Sirico et al., 2020). It is allocated by Gupta et al. (2020) biochar addition did not significantly influence the flexural strength, biochar 0.50% showed increased flexural strength after 28 days as compared to plain concrete. In a study where sand is replaced with biochar by 20% increased flexural strength by 26% (Praneeth et al., 2021).

Tensile Strength

The study made by Akhtar and Sarmah (2018) incorporated biochar in concrete with poultry litter biochar (PL), rice husk biochar (RH), pulp paper mill sludge biochar (PP) and found that 0.1 wt% of rice husk biochar showed slight increase in tensile strength. Based on a study made by Qin et al. (2021), found a slight increase in tensile strength with the addition of 0.65 wt% of waste biochar as compared to the control sample agreeing to the experimental study of (Akhtar and Sarmah,. 2018). Detailed study performed by Zeidabadi et al. (2018) suggested that 5 wt% is the optimum percentage increasing further replacement resulting in lower tensile strength, due to the excessive porosity in the cementitious structure. Same results have been found in the study made by (Gupta and Kua,. 2018) addition of biochar densify the structure, observed 6% to 7.5% increment in tensile strength incorporating both dry biochar and pre-soaked biochar.

Setting time

Many studies stated that biochar incorporation into cement mixtures influence the initial and final setting time of the biochar cement composites. In a study made by Javed et al. (2022) replaced cement with 2 wt% by coconut husk biochar observed biochar replacement resulting in reduction of initial and final setting time of mortar by 26% and 14.2% respectively. Another study made by Tan et al. (2020) used wood waste as a feedstock for biochar, after replacing cement with 1 wt% of biochar found reduction in initial setting time by 10.4% and reduction in final setting time by 14.6%. With the replacement by 3 wt% of biochar the initial and final setting time is reduced by 11.2% and 16% respectively, this is due to the biochar acting as a nucleation site accelerating the hydration process resulting in reduction of setting time (Gupta & Kashani, 2021). Several other researcher stated that due to finer particles of pulverised biochar reduction can be observed in setting time due to the filler effect of biochar (Maljaee et al,. 2021; Yaashikaa et al,. 2020)

Shrinkage

Biochar influences the shrinkage of cement based mixtures depending upon various factors. Based on the study by Mo et al. (2019) noted by adding 2 wt% of weed tree biochar , resulting in reduction by 16.3% of shrinkage at 180 hours of curing, the author also found 5.5% increment in the internal relative humidity. Same results found by Wei et al . (2018) when added 1-4 wt% of corn straw biochar as a cementitious material observed reduction in the shrinkage, concluded 13.1% of early shrinkage of biochar concrete.

Based on experimental study by Gupta, Krishnan, et al. (2020) found the autogenous reduction by 30% after adding 5 wt% of coconut shell biochar, when compared to wood waste biochar with 5 wt% showed higher shrinkage as compared to 5 wt% coconut shell biochar (Gupta, Krishnan, et al., 2020). Many authors explained higher porosity of the wood waste biochar resulting in less free water in the cement matrix leading to poor performance (Gupta, Krishnan, et al., 2020; Gupta and Kua,. 2019).

Studies prove the fact of using biochar as a partial replacement with 5 wt% in concrete mixture, due to finer biochar particles (< 0.1mm) acting as a filler and densifying the matrix and resist shrinkage deformation (Gupta, Krishnan, et al., 2020b).

2.4.7 Environmental Significance and Economic Analysis of Biochar Addition

The research has analyzed the environmental and economic significance of the use of biochar in cement concrete mixes.

Environmental significance

The carbon-rich properties of biochar have developed through biomass that can improve the functioning of sustainability and develop environmental growth in the construction process. It creates a low carbon footprint in the construction process and improves the potential application of green building that develops the environment of the atmosphere. Moreover, biochar has also helped to create effective waste management that improves the new production of biomass from the residue of agriculture, shell, wood and others. The application of biochar creates a minimization of environmental pollution from the atmosphere and maintains sustainability (Owsianiak et al. 2021). However, biochar has developed the properties of durability, strengthening, thermal insulation and others to the cement concrete mortar. It also has resilience to the structure of concrete and develops the potentiality of the construction process.

Economic impact

The research highlights the initial cost in the practice of incorporation of biochar is high. It has incorporated the cost of production for biochar. However, the analysis highlights in the long term, it provides sustainability and profitability that create growth in the construction building. It has also required a lower cost of investment and the expenses for repairing that focus on a decreased cost of production in building design. It has also developed the properties of insulation that create high carbon credit and develop the economic viability of the use of biochar in cement mortar.

Thus, the application of biochar in cement mix or concrete mix creates efficiency and economic feasibility that improves the cement concentration and improves the construction of buildings more effectively.

2.4.8 Critical comments on biochar addition to cement composites

According to Haque, Khan, Ashraf & Pendse, (2021), it can be stated that the application of biochar in cement composites helps to increase the value of internal relative humidity that has improved the durability of the composite and creates a strong comparative strength of the cement. The presence of biochar helps to influence the parameters of cement composites that impact the concentration and improve the mechanical properties of the building construction. It has also impacted the applicability of thermophysical properties that enhance the micro-pore structure of biochar. It creates an analysis of the string cement composites which develops the property of thermal insulation. It controls humidity through the strong absorption power that impacts the strong cement composites and develops the sustainability of the construction. As per Lin et al. (2023), it can be addressed that biochar improves decarbonization in cement concentration and is associated with an improved practice of thermal conductivity and creates electromagnetic capacity shielding. It has significantly improved the performance of cement mixtures through the use of biochar.

STATEMENT OF THE PROBLEM

This study focuses on the use of Biochar as a partial alternative of cement in cement mortar. Through this research, the researcher will aim to answer a few questions to explain the effects of Biochar in cement mortar.

The main questions that this study asks is:

1. How does Biochar influence the mechanical properties of cement mortar such as flexural strength, workability, flowability, and compressive strength?;
2. What is the percentage of Biochar as a partial replacement to cement that benefits cement mortar the most?; and
3. In which ways can the use of Biochar help improve forest waste management most especially in New Zealand?

CHAPTER III: METHODOLOGY

Materials and Equipment

Cement

Golden Bay EcoSure, a Type GP Cement was used during the entire duration of the experimental study. This cement is known to be free from lumps and was stored in an airtight container. For the particle size distribution range of cement is measured by using a laser diffraction analyzer called Mastersizer 3000. Cement composition was determined by X-Ray Fluorescence (XRF) Spectrometry, a widely known, non-destructive and accurate elemental analysis technique.

Table 1: XRF

Oxides	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	SO_3 (%)
Cement(%)	19.82	3.44	0.313	0.081	3.28407	0.977	64.456	0.268	0.46	0.111	2.36

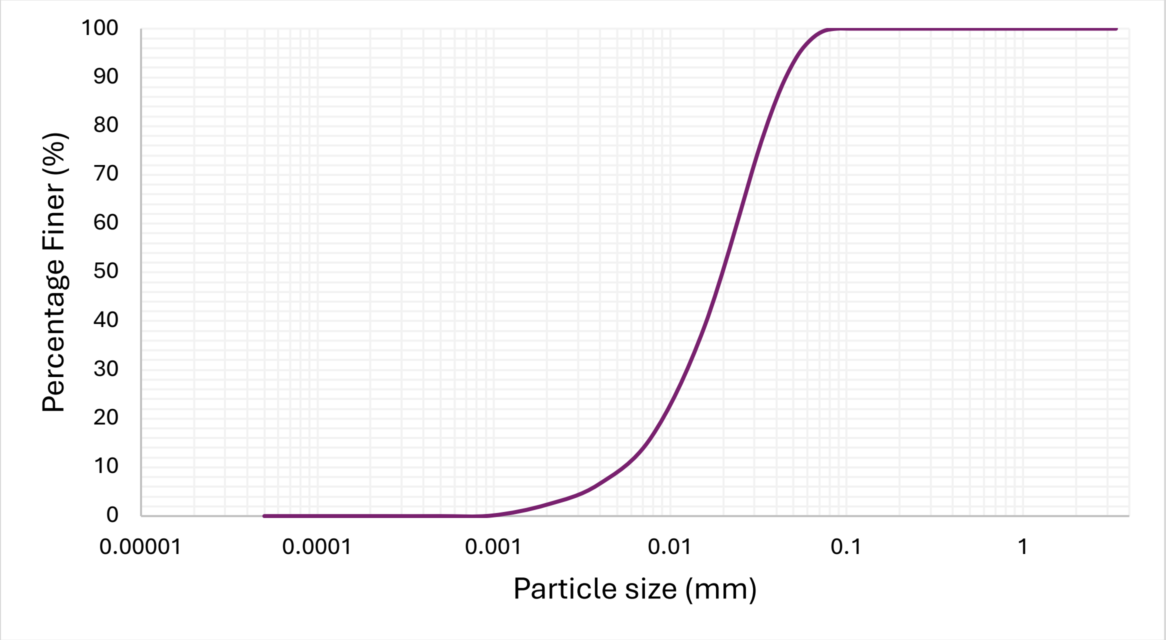

Figure 13: Particle Size Distribution – Cement

The particle size distribution curve is shown in Figure 13.

Sand

The sand used during this experiment was a Builder's Sand mix from Cemix, an ISO 9001 certified company. This mix is composed of wet sand which is normally used in cement mortar. Sand was oven-dried at 105°C prior to use. The particle size distribution range of the sand was measured using a Mastersizer 3000. The particle size distribution curve is shown in Figure 14 below.

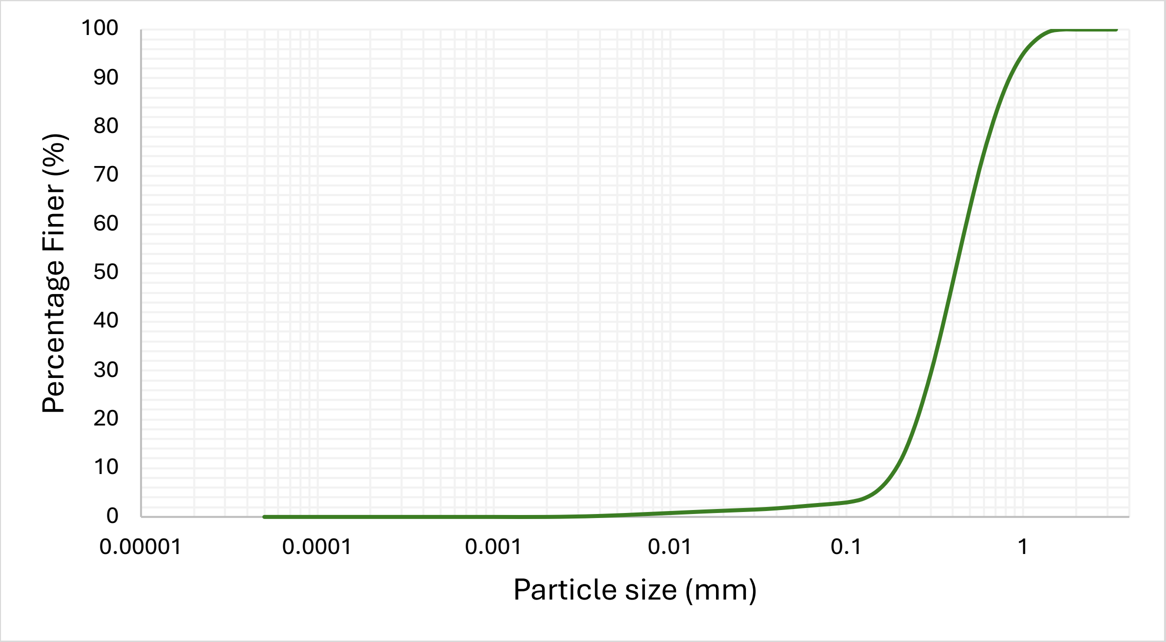

Figure 14: Particle Size Distribution - Sand

Biochar

The Biochar that was used in this experimental study is a commercial biochar purchase from a New Zealand Company called Kiwi Buy. For the duration of the experiments that will be conducted, this biochar will be used as a partial replacement of cement. The original biomass to produce this specific biochar was Pinus Radiata Sawdust. This material has a Brunauer-Emmett-Teller (BET) surface area of approximately 300 meter square per gram, with a carbon content of 98%. This same biochar was initially coarse but was grinded in a mortar pestle which was then stored in an airtight container until the time of test. Mastersizer 3000 was also used to measure the particle size distribution range. The biochar particle size distribution curve for Biochar 1 and 2 is shown in Figure 15 below.

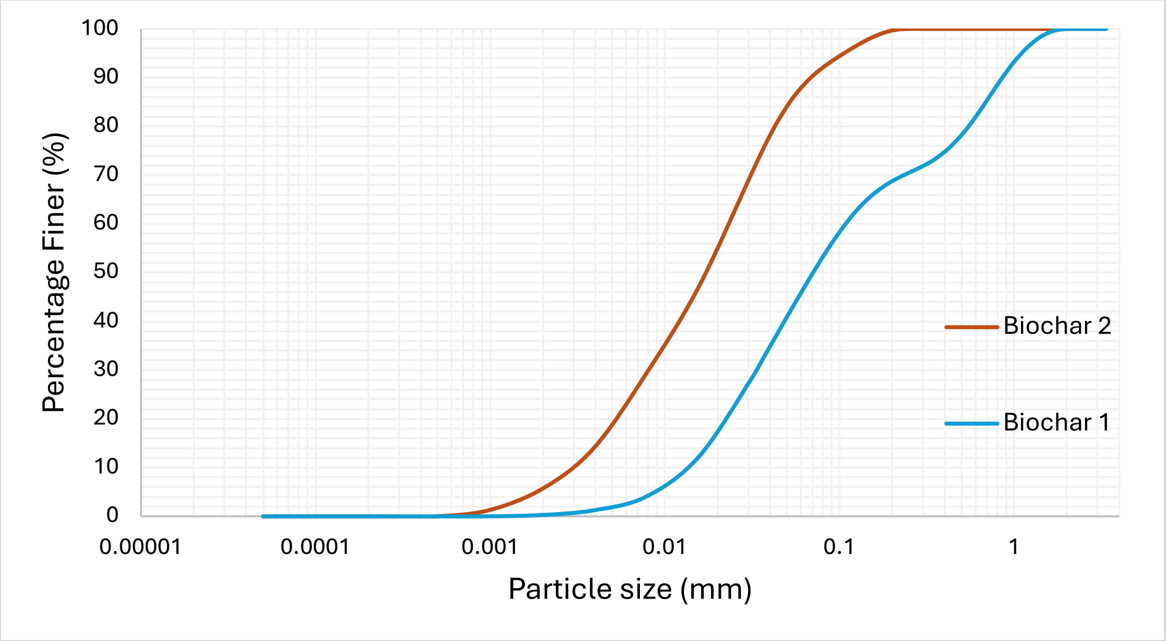

Figure 15: Particle Size Distribution - Biochar

Equipment

- A weighing scale, with an accuracy of 1g was used to measure the ingredients of the cement mortar mixtures used throughout the experiment as well as when measuring the sample cubes.
- The mixer used in this experimental study was a 5-liter capacity Kensington stand mixer.
- A GEO-CON GCL-225 model of oven, having a temperature range from RT+10 to 250/300 was used to dry the sand. Sand was then placed in airtight buckets until it needed to be added to the mixer.
- The Flow Table Test apparatus is used with ASTM C1437-20 (*Standard Test Method for Flow of Hydraulic Cement Mortar*, n.d.-b), a widely recognized method for evaluating the flowability of hydraulic mortars.
- The cube-shaped mold, with the size of 50x50x50mm was used to prepare the cube samples.

- The compressive strength of the cubes are then tested using a Pilot Pro Machine.
- The flexural strength test was done by using an Instron 100 KN machine.

Data Gathering Methods

Mix Design - Control Mix

The mix design that was used in this study was determined through the series of initial tests of mixing trials, with the Flow Table Test being the first. This test is essential, which aims to determine the optimal water to cement ratio, a widely recognized method for evaluating the workability of mortar. This test ensures the accurate water to cement ratio for evaluating the workability of cement mortar.

Prior to the preparation of the mixture, the sand underwent 24 hours of oven drying and 2 hours of air drying to ensure the moisture has been fully eliminated. This was done to standardize the moisture content of sand, ensuring the consistency between the results across the various batches of cement mortar samples. The control mix follows ASTM C109 (ASTM C109 2016) guidelines, which provides a standardized method for preparing and testing hydraulic mortars.

The mix ratio was 1:2.75 in which 1 part of cement is added to 2.75 parts of sand with .485 water. This was then adjusted to the same amount of cement (1) and sand (2.75) with 0.61 water after the initial set of trials, following ASTM C1437-20 (*Standard Test Method for Flow of Hydraulic Cement Mortar*, n.d.-b) guidelines to ensure the flowability of cement mortar, aiming for the targeted flow range between 130 to 210mm. This is indicative of the workability and suitability for practical applications. The water to cement ratio needs to be changed because the sand used in this experimental study does not follow ASTM standards.

This control mix is labeled as CM0 throughout the duration of the experiments. This will act as a reference baseline when comparing the results of other mix proportions.

Properties of Mixes

In the duration of this study, three (3) separate batches of mix proportions were analyzed.

The first batch of mixes were done in six different proportions in which the cement is partially replaced with biochar with 0%, 2%, 4%, 6%, 8%, and 10% by weight, respectively labeled as CM0, CM2, CM4, CM6, CM8, and CM10 showed in Table 2.

Table 2: Batch 1- Mix Proportions of Cement Mortar

Cement Mortar Type	Cement Replacement (g)	Cement (g)	Sand (g)	Biochar (g)	Water (g)
CM0	0%	600	1650	0	366
CM2	2%	588	1650	12	366
CM4	4%	576	1650	24	366
CM6	6%	564	1650	36	366
CM8	8%	552	1650	48	366
CM10	10%	540	1650	60	366

Second batch of tests have been conducted, if reduced biochar replacement levels gave improved strength as reported by other researchers. The second batch of mix came with different biochar replacement proportions. The biochar used in the succeeding test is finer than the biochar used in batch 1 as shown in Figure 15. This was designed in which cement was replaced with biochar with the percentage of 0%, 1%, 2%, 3%, and 4% by weight respectively labeled as CM0, CM1, CM2, CM3, and CM4 as shown in Table 3.

Table 3: Batch v2- Mix Proportions of Cement Mortar

Cement Mortar Type	Cement Replacement (g)	Cement (g)	Sand (g)	Biochar (g)	Water (g)
CM0	0%	600	1650	0	366
CM1	1%	594	1650	6	366
CM2	2%	588	1650	12	366
CM3	3%	582	1650	18	366
CM4	4%	576	1650	24	366

Lastly, the third batch of tests were conducted with the same mixed proportions used in the second test (Table 3). This test was done to analyze the behavior of biochar with the cement mortar when undergoing different conditions.

Mixing Procedure

The entire mixing procedure lasts for at least 7 minutes, ensuring the homogeneity of the mortar being prepared. Initially, the dry ingredients which comprises cement, sand, and biochar were mixed for 2 minutes at normal speed. After the initial mixing of the dry ingredients, half of the quantity of the water required was poured and mixed for another 2 minutes at the same speed applied in dry mixing. The remaining half of the water is then added and mixed for another 2 minutes. The speed of mixing is kept uniform for 6 minutes. Finally, during the final phase of mixing, the speed of the mixer was decreased for 1 minute to ensure that the mortar is cohesive and has reached the desired consistency and workability,

By following the precise and methodological approach, the study aimed to produce a mortar mix that was both uniform and reliable for testing and evaluating.

Casting and Curing

After the Flow Table Test, the mortar mix was then placed in the cube molds with the precision in two layers, ensuring the uniformity in filling and to avoid air voids. To be able to achieve the optimal compaction, the filled molds are then subjected to vibration. The vibrating table is used for compaction, a process that lasts for 120 seconds. This was sufficient enough to eliminate the trapped air voids, ensuring the density and accuracy of the mortar. Once the compaction was completed, the molds were wrapped with a thin transparent sheet and left to harden.

The molds were left to harden and then demoulded after 24 hours. Cubes from Batch 1 and Batch 2 were cured in the tank which was then filled with water, maintaining consistent curing conditions until the time of testing. This method was intended to provide a baseline for comparison by ensuring complete and uninterrupted hydration. In contrast, batch 3 underwent a different curing process in which the specimens were cured in water for different time periods and then exposed to the environment for varying durations. This approach aims to access the internal curing capabilities of biochar blended cement mortar (Gupta et al 2018).

The total number of cubes cast in this experimental study was 144 cubes, of which 54 and 45 cubes were cast for batch 1 and batch 2 respectively and 45 cubes were cast for batch 3.

DATA ANALYSIS METHODS

Flow Table Test

The flow-table test, a standard method for assessing the workability of hydraulic mortars, is conducted in accordance with the ASTM C1437-20 (Standard Test Method for Flow of Hydraulic Cement Mortar, n.d.-b) guidelines. This test is widely recognized for its effectiveness in evaluating the flow characteristics of fresh mortar.

This testing method provides a reliable and consistent assessment of mortar workability, essential for quality control in construction practices. By adhering to the ASTM C1437-20 (Standard Test Method for Flow of Hydraulic Cement Mortar, n.d.-b) guidelines, the test ensures that the mortar meets the required standards for workability, thereby facilitating optimal performance in practical applications.

Compressive Strength

Being the most important parameter used to characterize cement based products, this usually implies a crushing strength of cubes cast in steel molds which is called the compression. The Pilot Pro was used to determine the compressive strength test of cube specimens after 7 days and 28 days. The standard procedure following ASTM C109 (ASTM C109 2016) guidelines were followed in this study.

Throughout the testing procedure a consistent load of 1350N/s was maintained for all samples. For the first and second batch 3 cubes of each mix were tested on the 7, 28 and 56 days respectively, cubes were pulled out from the curing tank 30 minutes prior to the testing. For the third batch 9 cubes were casted, 3 cubes of each mix were pulled out of water on 3, 7, and 14 days respectively, and tested on 28 days from the casting.

Flexural Strength

The flexural strength of the specimen was measured after 7 days and 28 days of curing. To determine the flexural strength were tested on INSTRON 100 KN. These tests were performed according to the ASTM C580-18 (2023)(Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes, n.d.) standard, minimum three specimens were tested for each mix design. The speed of the INSTRON was 0.38mm/min for the flexural strength test.

X-Ray Diffraction (XRD)

In order to determine the phase identification for a variety of crystalline phases of biochar control mix and biochar blended mortar samples. The test performed on the mortar specimen from the compressive strength tests performed after 28 days cured sample was used in this test. The fragments of the best performing sample of each mix were stored in the Isopropyl alcohol to stop for further hydration (Snellings et al. 2018). These samples were subsequently dried in the oven for 24 hours at 105°C to remove any moisture inside the sample. Then all these samples were crushed into a fine powder by using a mortar pestle. The crystalline phase was analyzed by using X-ray diffractometer (Empyrean PANalytical).The X-ray tube current and voltage were fixed at 40 mA and 45 KV, respectively. Spectra were calculated at a range angle (2θ) 10° - 80°at increments of 0.013° and with of cumulative time per step of 8.67s per step.

Thermogravimetric Analysis (TGA)

TGA tests were performed on the mortar mix samples which are prepared the same way while performing the XRD. Thermogravimetric analysis was performed on a thermal analyzer (STA 449 F5 Jupiter). The samples were performed in the presence of Argon as a purge gas at the flow rate of 100 ml/min. Temperature was maintained for 10 min before the start of the experiment. The temperature range of the TGA was from 30°C to 800°C.The uniform heating rate of 10°C/min was kept for all the samples. Approximately weight of 25 mg of each sample was used in this testing procedure.

Microstructural Analysis

SEM analysis was carried out using a Hitachi S-4700 under high vacuum conditions was carried out in this experimental procedure, under 3 KV accelerating voltage. The broken fragments of the mortar mix was then oven dried for 24 hours and then ground into fine powder using a mortar pestle. The ground powder was coated with platinum for better conductivity with the help of a sputter coater.

CHAPTHER IV: RESULTS AND ANALYSIS

Particle Size Distribution

The Particle size distribution for cement, sand, and 2 batches of biochar is shown in Figure 16.

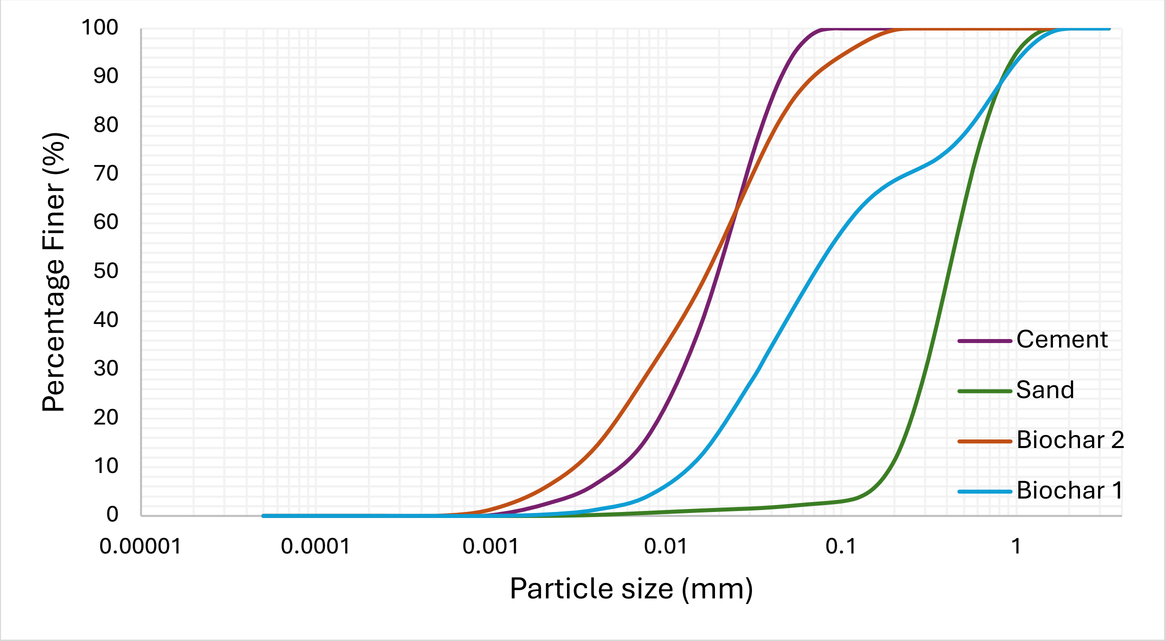

Figure 16: Biochar – Particle Size Distribution

It can be observed through the Particle Size Distribution Curve (Figure 16) that Biochar 2 is finer than Biochar 1 and cement, which can be determined by the mean particle size (D50, 0.0172mm) with a specific surface area of 126.3m2/kg. The particle size distribution of sand was determined by the mean particle size (D50, 0.41mm) with a specific surface area of 29.61m2/kg. The biochar particle distribution of biochar 1 and biochar 2 was determined by mean particle size (D50, 0.0698mm) and (D50, 0.0172mm) with a specific area of 126.3m2/kg and 818m2/kg respectively. Whereas the particle size distribution of cement was determined by the mean particle size (D50, 0.0197mm with the specific surface area of 377.4m2/kg. From this, it can be observed that 50% of the particles of biochar 2 were finer than the particles of biochar 1 and cement. The finer biochar particles can act as a filler material and fill the voids between coarser cement and sand particles which can contribute to the improved packaging of the mortar.

Flowability

There are various ways in which biochar influences the flowability of cement mortar such as biochar being a high porous material. Thus, it affects the flowability of the mixture. It also affects the water absorption, particle shape and the specific surface area.

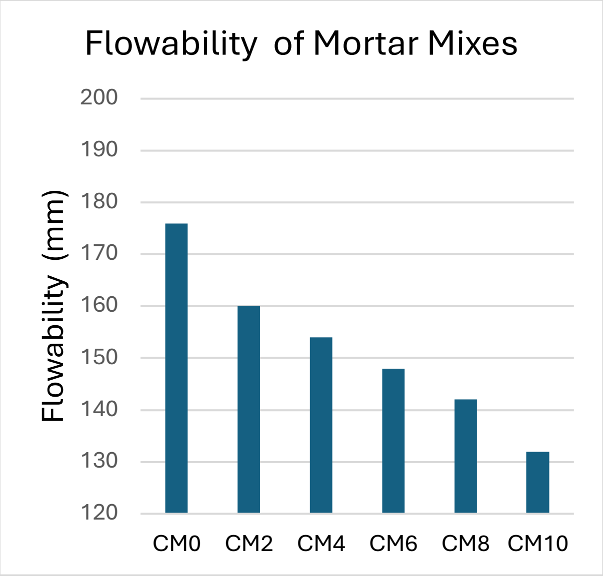

Figure 17: Biochar 1 Flowability of Mortar Mixes

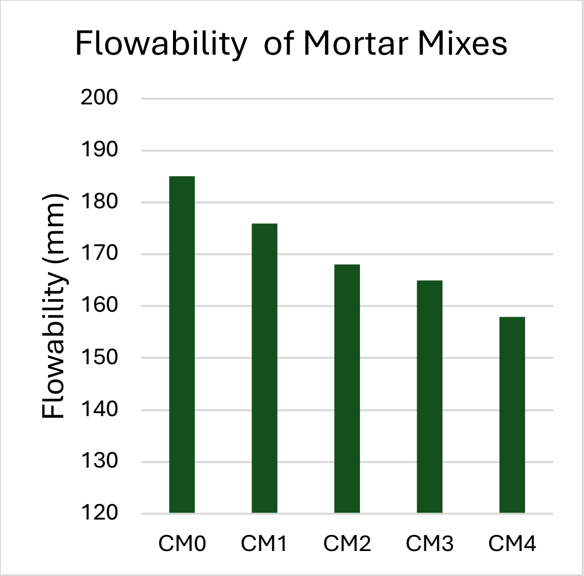

Figure 18: Biochar 2 Flowability of Mortar Mixes

Flowability decreased with an increase in biochar replacement ratio as shown in Figure 17 and 18. The flowability of cement mortar (CM10) showed a decrease of 25.05% as compared to plain cement mortar (CM0). The flowability of biochar blended with cement mortar (CM4) is showing low flowability as compared to the control mix (CM0), showing a decrease of 14.59% after replacement of cement of 4% by weight in the mortar mix shown in Figure 17. Flowability of CM2 and CM4 after incorporating finer biochar 1 showed increase in flowability as compared to CM2 and CM4 with biochar 2 as the cement replacement, this increase can be attributed to the particle size of biochar 2 which is finer as compared to the particle size of biochar 1 as shown in the Figure 17 above. The loss of flowability of biochar blended with cement mortar is mainly due to the porosity of biochar (Chen et al, 2020). The particle size distribution also shows that the particle size of biochar 1 has coarser particles compared to biochar 2, which also influences the flow diameter of cement mortar to a certain extent.

The angular shape of biochar particles creates some friction between the cement and sand particles which then decreases the flow diameter of the mortar mix. The increase of biochar replacement with cement in cement mortar increases the water absorption while mixing due to the porosity of biochar, affecting the flow diameter of the fresh mortar (G, Ren et al., 2021). This flow is also depends on the type of feedstock of the biochar and the preparation. According to Chen et al. (2020), the biochar that is prepared at a very high temperature has higher pore fraction which can rapidly absorb moisture during mixing and can also reduce the flow of mix. From this experimental study it can be said that finer biochar particles tend to have high flowability; which can improve the packaging of mortar and increase the densification of mortar.

Compressive Strength

1st Batch of Testing

The first batch of compressive strength test of biochar 1 blended with cement mortar after 7, 28, and 56 days are shown in the figure below in Figure 19:

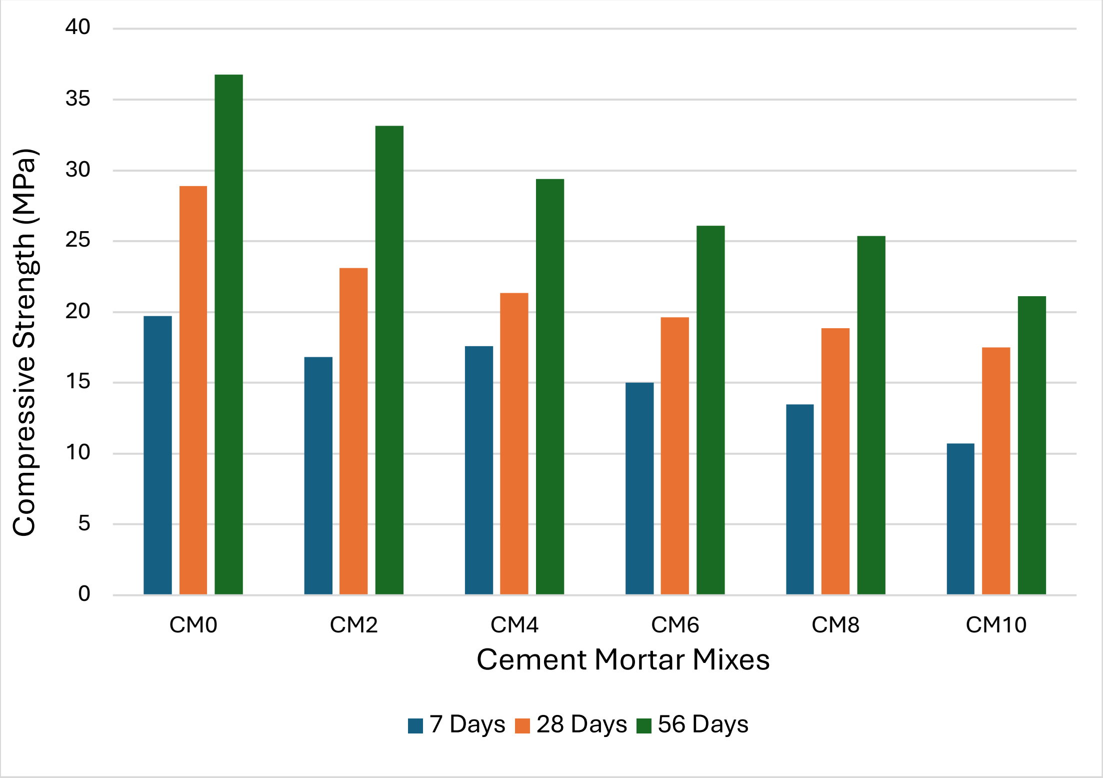

Figure 19: Batch 1 – Compressive Strength Test

It can be observed from Figure 19 that with the percentage increase of biochar, the compressive strength decreases after 7, 28 and 56 days of curing. As observed, the compressive strength of each mix shows an increase in compressive strength individually when compared between curing periods.

The compressive strength of CM2 after 28 days and 56 days increased by 37.54% and 43.5% respectively. The compressive strength of CM2 after 7, 28 and 56 days showed decreased strength as compared to CM0 by 14.75%, 20.05% and 9.75% respectively. It is observed that the percentage reduction of CM2 decreased from 28 days to 56 days.

The results show how biochar helps in increasing the compressive strength during the later stages of curing and also proves the increase in strength over a longer period of time.

Whereas, when compared to the control mix, the biochar incorporated cement mortar shows a decreasing pattern in compressive strength, which is due to the porosity of biochar. Another reason for the decrease in compressive strength can also be attributed to the particle size of biochar shown in Figure 16. Same result has been noted by Xu Yang and Xiao (2021). In this research, it is stated that an increase in biochar decreases the compressive strength of biochar blended cement mortar.

In the experiment done by Xu Yang and Xiao (2021), the strength of 2% of biochar and 5% of biochar were reduced by 10.8% and 11.4% after 7 days of curing whereas it reduced by 4.9% and 5.5% during the 28 day curing. The similarity to Xu Yang Xiao’s results compared to the results of this study suggests the possibility of getting decreasing compressive strength results due to certain factors such as particle size and different internal pore sizes.

Although the first batch of testing showed such results, the succeeding batches have shown a different set of results, showing an increase in compressive strength to 2% which is similar to the results collected in an experimental study by Gupta et al. (2018) The biochar used in the first batch was not as fine as compared to the biochar used in the succeeding tests (biochar 2). The mean particle size distribution of biochar used in the first batch was (D50, 0.0698mm). One probable cause to this is that the coarse biochar particles increase the voids around it which can lead to the weak interaction between the biochar and cement particles.

2nd Batch of Testing

The compressive strength tests results of biochar 2 blended in cement mortar after 7, 28, and 56 days are as shown in Figure 20 below:

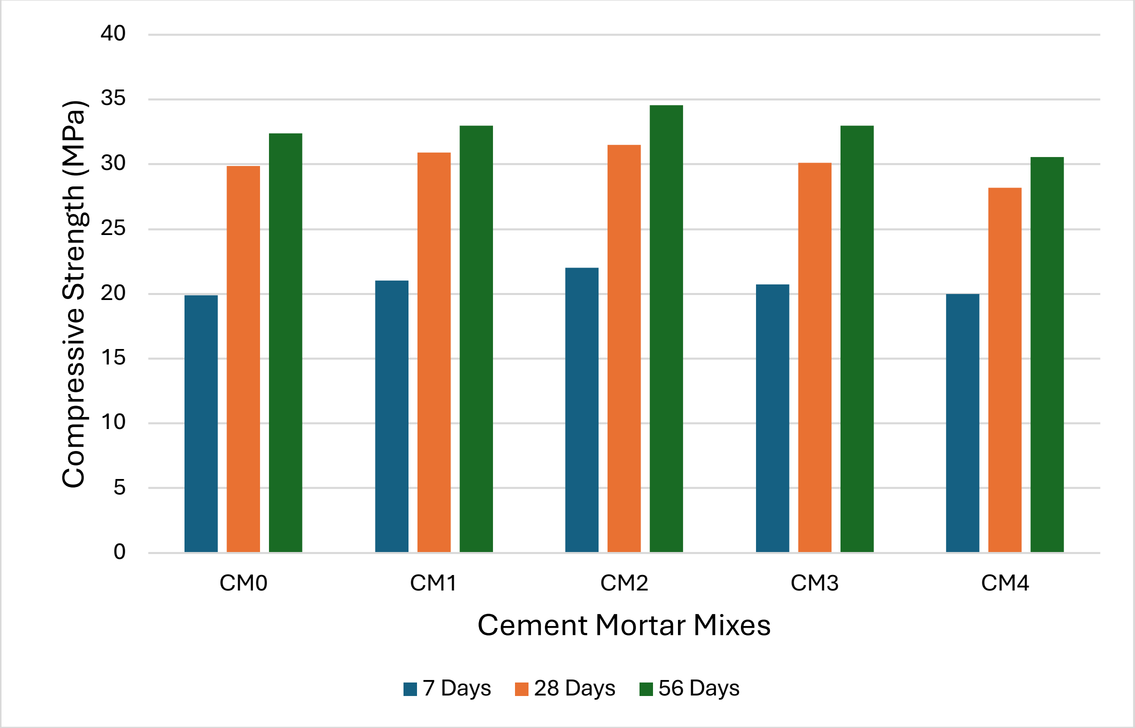

Figure 20: Batch 2- Compressive Strength Test

The 7, 28, and 56 day-test of compressive strength showed an increase in compressive strength results. During this experiment, all the tested samples showed consistent results. At the initial stages of curing cement mortar with the biochar from 1-3% showed significant increase in early strength gain.

It is observed from 7-day test, that the compressive strength of CM1, CM2, and CM3 shows a 5.85%, 10.69%, and 4.32% increase in strength as compared to CM0 whereas, the 28-day test shows that the compressive strength of CM1, CM2, and CM3 shows a 3.35%, 5.29%, and 0.67% increase as compared to CM0. Lastly, the 56-day test shows that CM1, CM2, and CM3, has an increase of 1.78%, 6.59%, and 1.77% in compressive strength compared to CM0.

Figure 20 also shows that CM4, throughout the 7, 28, and 56 day-test had decreased in compressive strength by 0.54%, 5.71%, and 5.69% when compared to CM0.

From the results above, it shows that 2% of Pinus Radiata Sawdust (biochar used in this study) is the optimum biochar percentage in cement mortar mix.

The difference in results between the 1st and the 2nd batch was due to the fact that the biochar mixed in the cement mortar of batch 2was finer as compared to the 1st batch. The biochar, during this test was also pre-heated for 15 minutes prior to the mixing to eliminate the moisture content in the biochar, if any. The finer biochar particles are contributing to the densification of the microstructure which increases the compressive strength. The biochar particles absorb the portion of water during the mixing of in the mortar, lowering the water-cement ratio and causing the densification of the hardened mortar due to decrease in the amount of water which can be evaporated causing the formation of capillary pores. Same results have been found by Gupta and Kua (2019) which in this research, it is observed that 1-2% of biochar blended cement mortar resulted in increased compressive strength by 38% and 29.50% at the age of 1 day. The same trend of increased strength is followed after 28 days of 1-2% of biochar blended cement mortar by 8.75%. Similar results were found by (Ahmad et al, 2015) after adding 0.08 wt% and 0.20 wt% of bamboo based biochar the compressive strength increased by 30% and 18% respectively. However, compared to this it should be noted that the weight percentage replacement is less as compared to this experimental study. Same results have been found by Choi et al. (2012) it is stated that 5 wt% of hardwood biochar replacement with cement showed increased compressive strength of 28 and 56 days.

The water retained by the biochar later released during the hardening which is attributed as the biochar particles act as the self-curing agent in the mortar (Choi et al. 2012).

3rd Batch of Testing

The 3rd batch of testing consists of similar results to that of the 2nd batch of testing. Figure 21 illustrates the results of compressive strength obtained from this batch of experiment.

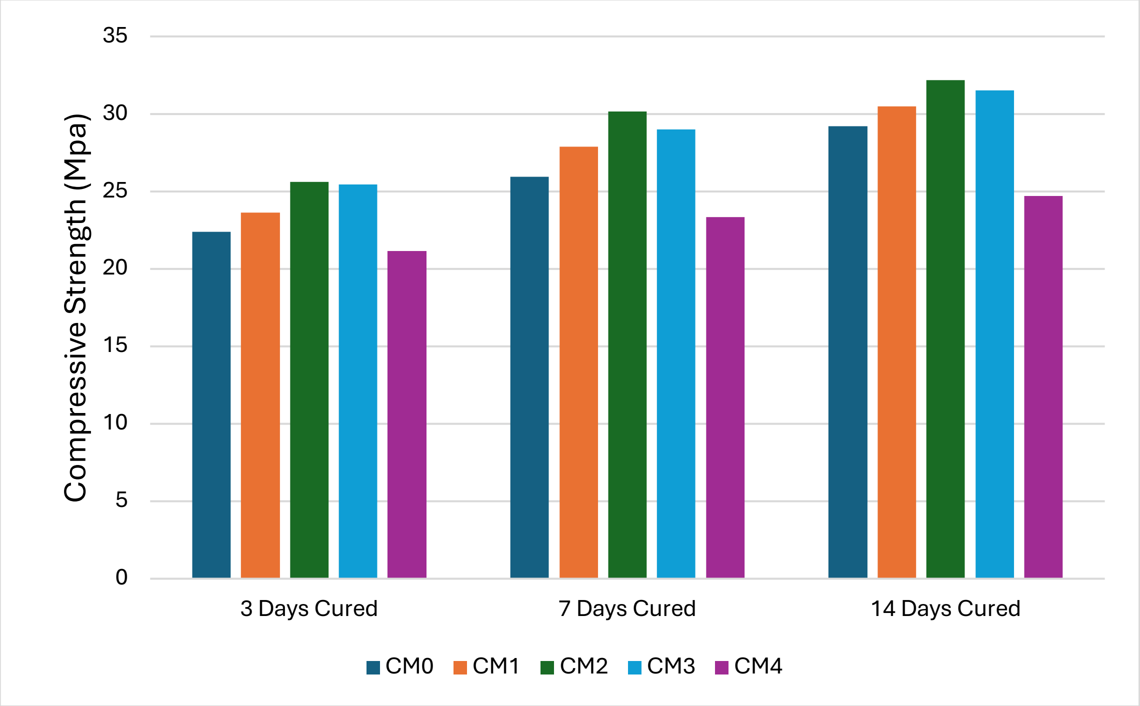

Figure 21: Batch 3 – 28-Day Compressive Strength Test

Although having very similar results to the 2nd batch of testing, this batch has a different curing condition. During this batch, 9 cube samples were made for each mix, having 3 cubes samples for 3, 7, and 14 days. The same cubes of each mix were pulled out of water at 3, 7, and 14 days and kept exposed to environmental conditions for 25, 21, and 14 days respectively. All of these cube samples used the same Pilot Pro compressive strength test after 28 days from casting.

As shown in Figure 21, the compressive strength of CM2 after 3 days of water curing shows approximately the same results shown by CM0 after 7 days of curing. The compressive strength of CM1, CM2 and CM3 shows consistent increase in all different days of curing as compared to plain cement mortar.

CM1 showed an increase in compressive strength at 3, 7 and 14 days by 5.57%, 7.38% and 6.05% respectively. CM3 showed consistent increase in strength compared to CM0 by 13.69%, 11.72% and 7.90% respectively. This study has shown results of CM2 having the maximum increased strength compared to CM0 at 3, 7 and 14 days by 14.38%,16.18% and 10.14% respectively. The increase in compressive strength may be attributed to the biochar as an internal curing agent (Gupta et al 2018). The biochar is absorbing the water during the mixing, which means biochar is acting as an internal reservoir and resulting in the continuity of the hydration process even without external supply of water (Gupta et al. 2018). The blended mortar with pre-soaked biochar BC 500 and got increased compressive strength at 7 and 28 days by 42.09% and 50.25% respectively. which indicates water moisture retained by the biochar which supported the hydration even after the absence of external water attributing to higher compressive strength. Same trend has been observed in this study where CM1,CM2 and CM3 showed increased strength in all curing stages. The finer biochar particles act as a filler material resulting in the reduction in voids and also restricting the bound water to evaporate which leads to the hydration. The finer biochar fills the voids between coarser cement grains and sand resulting in improved packaging. In a research done by Gupta and Kua (2019), their research found that GBC (fine biochar) biochar blended mortar under air curing showed less reduction in compressive strength compared to moist cured, as compared NBC (coarse biochar). Same results was observed by Choi et al (2012) that air cured biochar blended mortar with 5 wt% of biochar showed the same strength as compared to plain cement mortar 37.1 Mpa. It is also reported that the release of physically bound water in the biochar enhances the strength of the mortar under air curing conditions through the internal curing factor.

In this experimental study it is clearly observed that 1-3% of biochar blended mortar showed increased strength in all different days of curing. It is also worth noting that CM2 after 3 days of curing showed the same compressive strength shown by CM0 after 7 days of curing.

Flexural Strength

The researcher conducted a 7 and 28-day flexural test to find out the flexural strength of the sample cubes. This was done by using Instron 100 KN. The results are as shown below in Figure 22.

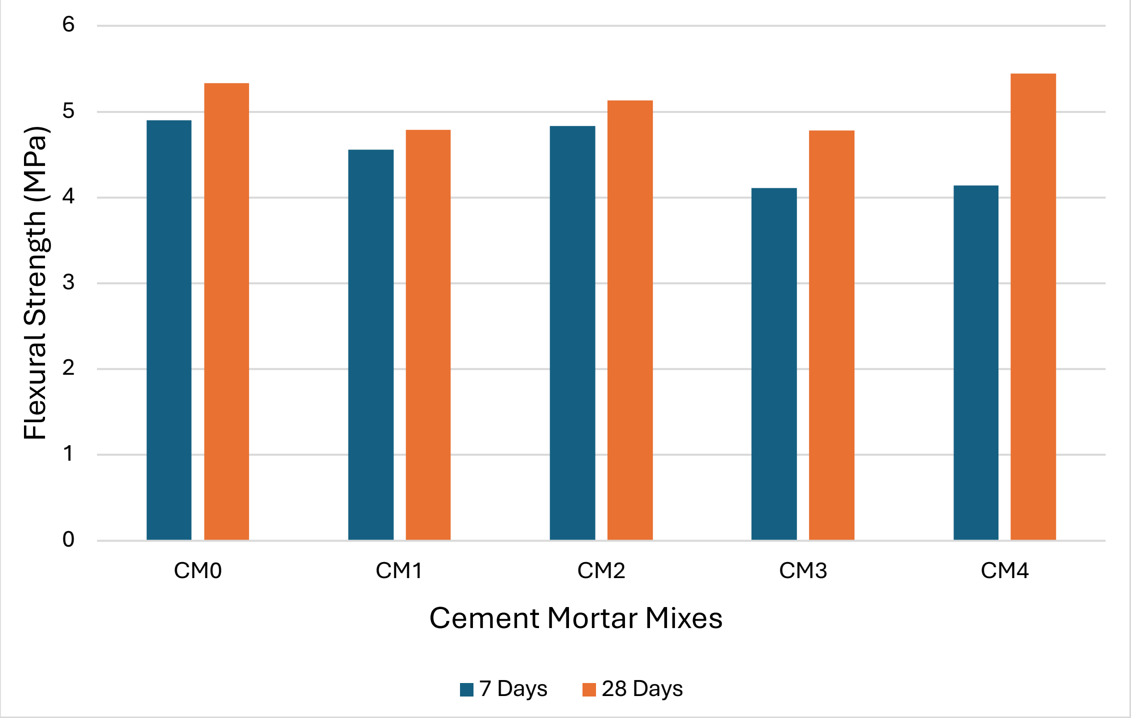

Figure 22: Flexural Strength Test

The Figure (Figure 22) above shows that apart from CM4, none of the other samples depicts an increase in flexural strength when compared to CM0. The flexural strength of CM0 from 7 to 28 days went up by 8.07% whereas, the flexural strength of CM1, CM2, and CM3, from the 7 to 28-day test increased by 4.82%, 3.10%, and 16.58% respectively. The flexural strength of CM1, CM2, and CM3 then proceeded to show a decrease in strength when compared to that of CM0. CM4 showed an increase in strength in its 7 to 28-day test by 31.2%. It can also be seen that during the 7-day test, as compared to CM0, CM4 had a 15.56% decrease but showed a 2.06% increase during the 28-day test when compared to CM0.

This flexural test indicated that given the number of samples done, there is no specific trend that is being followed when comparing the percentages of biochar mixed in cement mortar but it shows a constant change when comparing the 7-day test and the

28-day test for each individual mix. Only CM4 showed the increased strength as compared to control mix and all other biochar blended mortar mix. Same was noted by (Gupta and Kua. 2018) that while testing the low dosage of biochar there is no significant improvement in flexural strength, but higher dosage of biochar blended mortar shows a significant improvement in flexural strength. This improvement was attributed to the air void which forms on the plane resulting from the finer particles and high porosity of the biochar. They also found that the mortar with pre-soaked and dry biochar exhibited highest flexural strength, crediting to the increase the formation of voids in the tensile plane. It is also noted that flexural strength also depends on the feedstock from which the biochar is derived. Khushnood, RA et al. (2016) stated that there is a 42% increase when it comes to flexural strength when incorporation hazelnut shell-derived biochar to cement mix.

Limited samples were tested for flexural strength; it is observed that no specific strength development has been found in flexural strength.

Thermogravimetric Analysis (TGA)

The effects of biochar incorporation in mortar at different percentages and the formation of hydration and carbonation products is illustrated by using thermogravimetric analysis. The TGA and DTG curve of CM0, CM2, CM4, and CM10 is shown below in Figures 23 to 28.

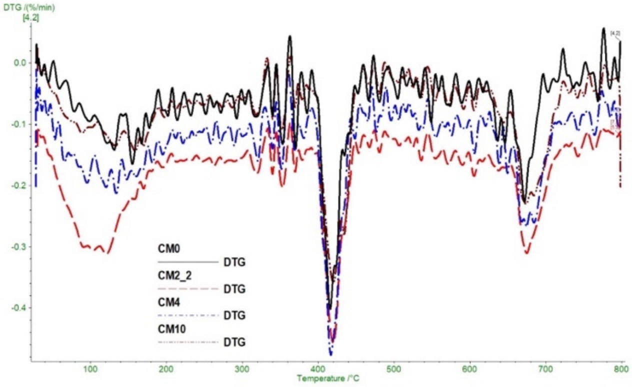

Figure 23: DTG Curve CM0-CM10

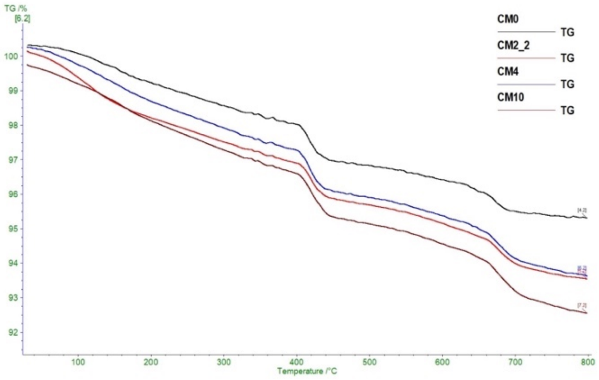

Figure 24: TGA Curve CM0-CM10

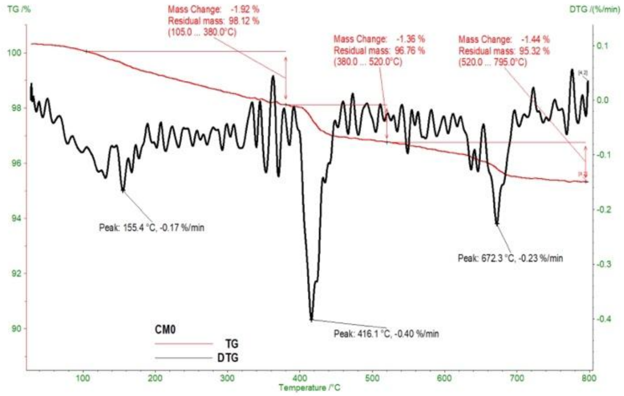

Figure 25: CM0 TGA & DTG Curve

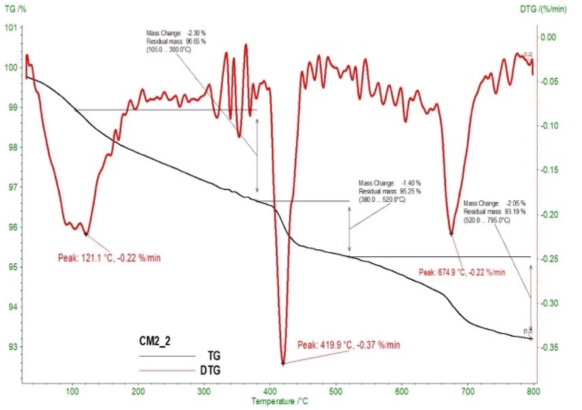

Figure 26: CM2 TGA & DTG Curve

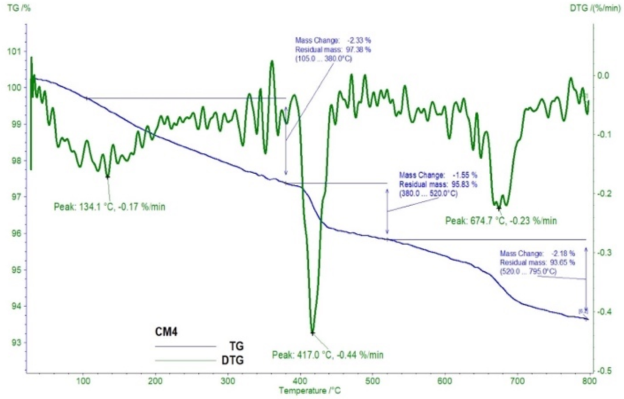

Figure 27: CM4 TGA & DTG Curve

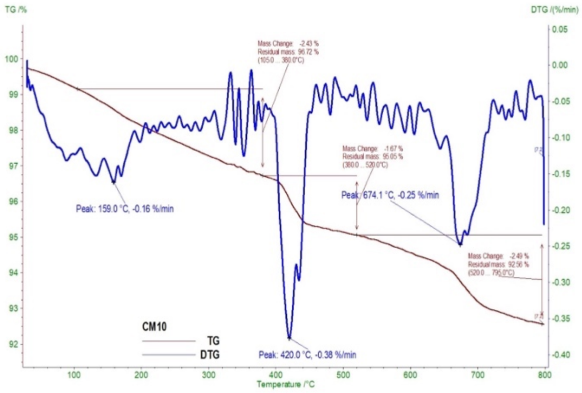

Figure 28: CM10 TGA & DTG Curve

During this experimental study, the best performing samples from batch 2 which underwent compressive strength after 28 days of curing were used. The temperature range between 105°C-380°C corresponds to the decomposition C-S-H gel, ettringite. The temperature ranging between 380°C-520°C refers to the decomposition of calcium hydroxide (portlandite) (Rostami et al., 2012b) and (Sharma & Pandey, 1999b). The temperature range between 520°C-795°C refers to the decomposition of carbon carbonate (CC) (Zhang et al., 2021b) and (Mo et al., 2021b).

In Figure 25, it can be observed that the mass loss between different mixes increased with an increase in biochar, with the maximum mass loss was in between the temperature range of 105°C-380°C and 520°C-795°C with the range of 380°C-520°C having a much lesser mass loss compared to the other two ranges. A significant loss of mass can be seen between the temperature range of 400°C-500°C which corresponds to the pyrolysis of cellulose. The same peak has been found in the temperature range of 400°C-500°C in plain cement mortar; the mass loss can be attributed mainly to the decomposition of calcium hydroxide(portlandite).

The DTG curve represents the maximum mass loss occurring at a particular temperature, indicating thermal decompositions and varying reactions. The DTG curve illustrates the detection within each region.

The degree of hydration was calculated according to Bhatty's Method (Bhatty, 1986), used to calculate the mass loss in the peaks mentioned above using the calculation of:

$$Wb = Ldh + Ldx + 0.41Ldc$$

$$\alpha\ (\%) = \frac{Wb}{m_{800} * 0.24} \times 100\%,$$

$$CH = \frac{Ldx \times 4.11}{m_{800}},$$

where the mass loss per unit part as a result of dehydration, dehydroxylation, and decarbonation are represented by the letters Ldh, Ldx, and Ldc. At 800°C, the residual mass is m800, which is the greatest amount of water that might theoretically be needed for the cement particles to fully hydrate. This can vary from 0.23 to 0.25 g/g; CS is the quantity of CA(OH)2 produced per gram of cement, while α is the degree of hydration. Table 4 below lists the results of the calculation:

Table 4: Mass Loss

Temperature	**CM0**	**CM2**	**CM4**	**CM10**
105-380	1.92	2.29	2.32	2.43
380-520	1.36	1.40	1.55	1.67
520-800	1.44	2.05	2.18	2.50
Wb	3.87	4.53	4.76	5.12
DOH, α (%)	84.21	80.09	90.23	97.63
CH	0.291	0.244	0.289	0.314

From the calculation, it is found that the hydration degree of CM0,CM2,CM4 and CM10 were 95.32%, 93.19%, 93.65% and 92.56% respectively.

SEM Analysis

The SEM investigation carried out on mortar mixes is an important area of research that offers critical insights into the microstructural characteristics of this mortar treated with biochar. The addition of biochar to mortar influences the microstructure of the mortar paste, as will be observed in this study. The number of crucial characteristics that was studied from most of the samples found ettringite. Micro and mesopores have been observed in the SEM analysis. Crack pattern is also observed on the surface of the mix. The needle-like structure forming inside the pores is ettringite. The ettringite formation inside the pores can be seen which helps in better interlocking of the biochar filler particles inside and increase the densification of the matrix.

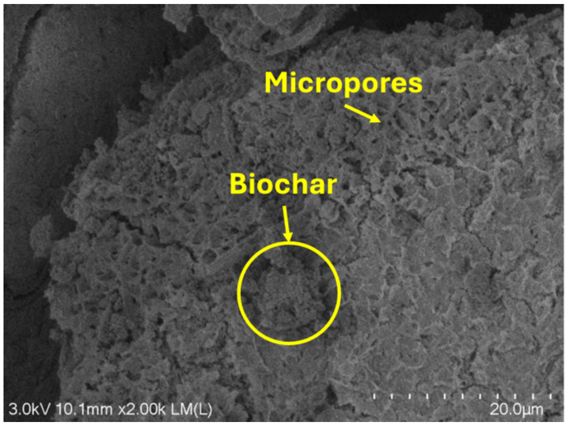

Figure 29: SEM Image-CM4

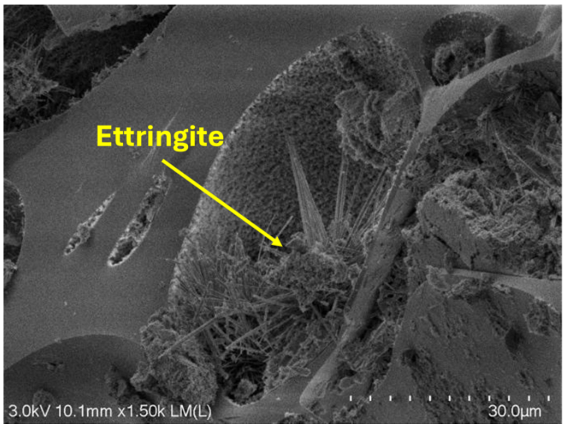

Figure 30: SEM Image-CM2

Ettringite formed during the hydration phase in cement results in earlier strength and development of volume stability. It can be observed the biochar incorporation did not prevent the formation of ettringite which is required for the strength development and durability property of cement mortar. The finer biochar particles acting as a micro filler in the voids increase the level of hydration, which results in the formation of a dense matrix.

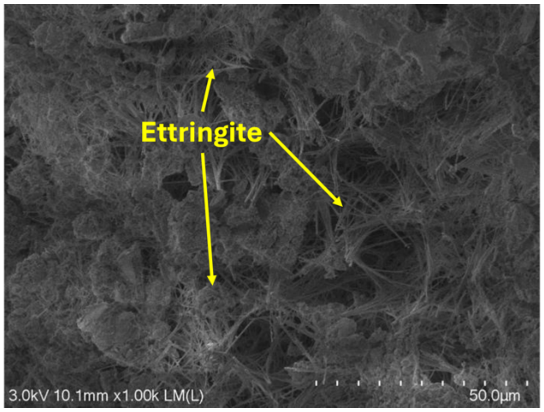

Figure 31: SEM Image-CM4 (2)

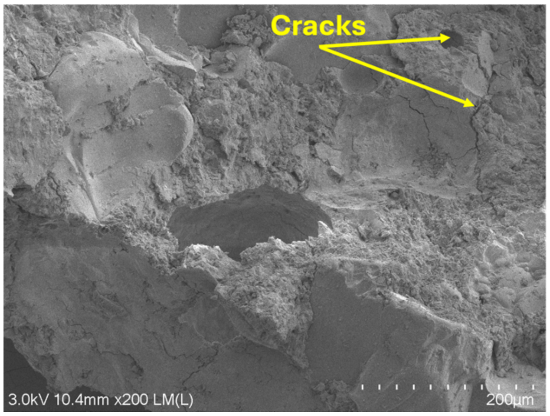

Figure 32: SEM Image-CM0

The strength also increases because the pore structure of biochar resembles a honeycomb due to the escape of organic and volatile components during the pyrolysis.

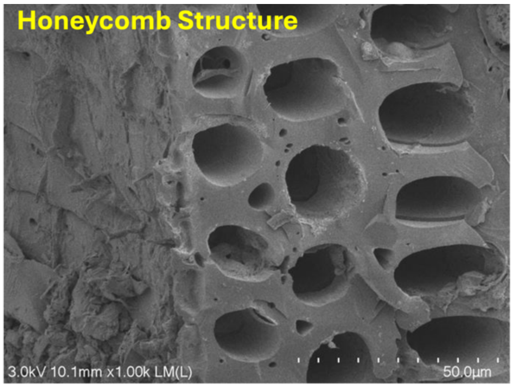

Figure 33: SEM Image-CM2 (2)

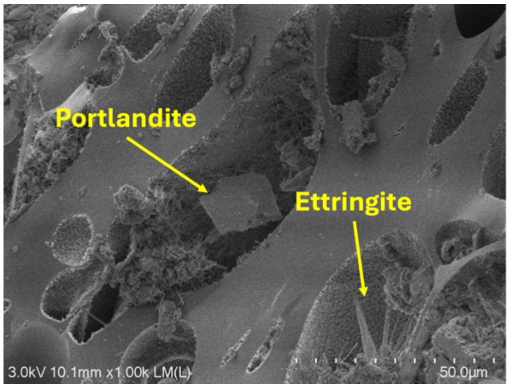

Figure 34: SEM Image-CM2 (3)

Das, O et al. (2015) and Mrad, R et al. (2019) mentioned that the cause of the densification that surrounds biochar particles that wrestles during internal curing of cement mortar is caused by porous morphology holding onto the free water. Whereas, Gupta, S et al. (2021) stated that the decreasing micropores in cement mortar is due to the fact that finer biochar particles act as a filler. Furthermore, because of the hydroxyl functional groups, the biochar particles have a tendency to attract other biochar and cement particles to form flocs and cluster. These serve as a nucleation site in the cement matrix for the precipitation of additional hydration products. Even after the larger incorporation of biochar, ettringite formation is consistent throughout. Micropores have the water retaining capacity and help in reducing shrinkage cracks.

XRD ANALYSIS

X-ray diffraction for phase identification of control and biochar incorporated cement mortar is shown in Figure 35. The XRD is performed on 28 days of cured samples in this experimental procedure. The main crystalline phases detected in XRD graphs are (CH) calcium hydroxide, (CC) calcium carbonate, Quartz ($SiO2$). The main peaks of Calcium hydroxide are formed at 18°, 28.5° and 34.14°. There are no major changes observed in the position of 2 Theta. The biochar is affecting the intensity of peaks when increased in replacement percentage.

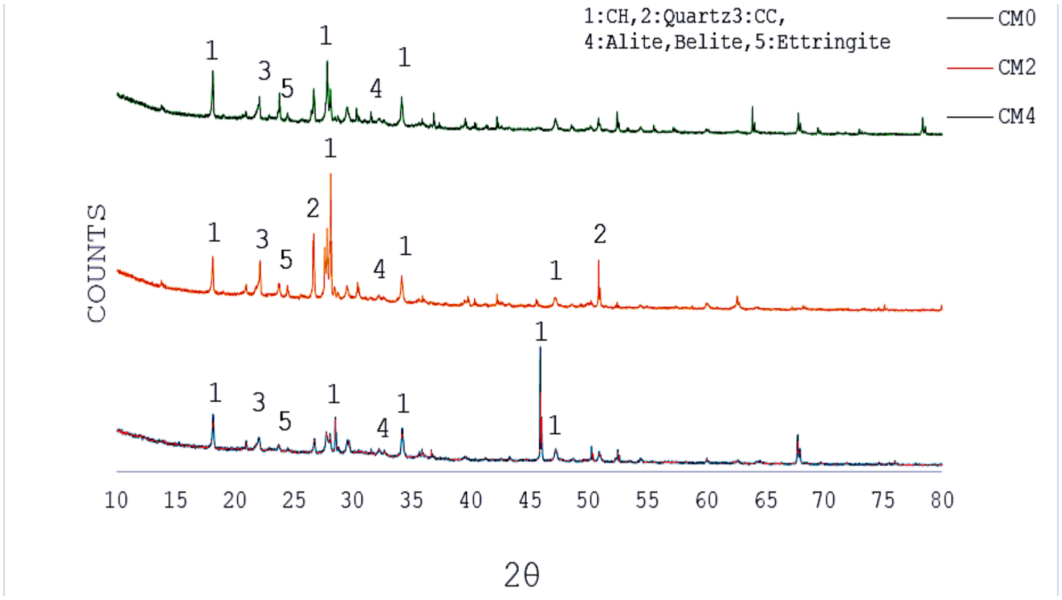

Figure 35: XRD Analysis

XRD of cement mortar with 0%, 2% and 4% of biochar in comparison with plain cement mortar at the age of 28 days; 1: CH, 2: Quartz, 3:CC, 4:Alite and Belite, 5:Ettringite.

It can be observed that the intensity decreases from 0-4% of biochar incorporation in the cement mortar. Same reported by Gupta et al wherein he also believed that the moist pores of biochar creates an environment for the hydration growth. It is observed that the intensity of CH peak increased in CM2 as compared to plain cement mortar CM0 as shown in Figure 35. The Intensity of CH peak is less in CM4 as compared to CM2 and CM0 which results in low hydration formation in CM4 that is affecting the compressive strength of CM4 as compared to CM2. The intensity of calcium hydroxide peaks suggest generation of hydration products due to finer particles of biochar which provides a filler effect that increases the densification of the matrix and also acts as a nucleation site for hydration. The SEM images show the presence of ettringite in the pores of biochar blended cement mortar. The ettringite with high intensity peaks are observed in CM2 and CM4 at an angle 24.46° as compared to CM0. It can be said that biochar incorporation increasing the formation of hydration products. The XRD result shows the high intensity peaks of CH in CM2 as compared to CM0 and CM4, which suggests that formation of hydration products and ettringite inside the pores which increase the pore filling and dense matrix and resulting in higher compressive strength. Quartz is also observed in biochar blended cement mortar CM2 at an angle of 26.67° and 50.85°, this increased peak intensity results in the improvement of crystalline growth. This peak is observed in biochar blended cement mortar with high intensity specifically in CM2. The CH peak at angle 28.58° which was same for CM0 and CM2 shifted in CM4 to 27.83° which suggests that 4% incorporation changes the crystalline phase of CH which resulting in less formation of hydration product and attributing to less densification of matrix leading to decrease in compressive strength. The enhanced peak of CH and the formation of Quartz in CM2 are the possible explanation of hydration products that is resulting in higher compressive strength as compared to plain cement mortar mix and other biochar blended mix proportions.

CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS

SUMMARY AND CONCLUSION

The researcher hereby presents the conclusion, based on the multiple experiments and comparisons towards past research done by other researchers, with the aim of answering the study's objectives and statement of the problem.

To provide an answer to the first research question, it is concluded that when incorporating biochar to cement mortar mix, the particle size distribution affects the behavior and effectivity of biochar. The finer the biochar, the more benefits it gives when dealing with cement mortar's compressive strength. While biochar does not necessarily result in significant TGA and DTG results variations, the response gained from XRD suggests changes in hydration products with higher dose rates of biochar. During the dose rate tests, it concludes that biochar does not affect the flexural strength of cement mortar after incorporation.

To answer the second question that this study asks, it is found that 2-3% of biochar as a partial replacement of cement gives the best benefits and improvements in compressive strength performance. Anything more than these percentages decreases the compressive strength of cement mortar. While the researcher acknowledges that different kinds of biochar and preparation methods contributes to possible discrepancies in results, the researcher concludes that Pinus Radiata Sawdust biochar with a D50, 0.0172mm particle size and with an 818m2/kg specific area has an optimum percentage of 2-3%.

Lastly, the researcher states that the production of biochar from forest waste contributes to the proper preservation of forests and areas around it. Being put to good use, the incorporation of biochar to cement mortar mix finds a way to allow forest wastes to house better uses rather than just being left to eventually be washed by the flood which may then result in extreme environmental conditions such as flooding.

RECOMMENDATIONS

With the results of this study showing that Pinus Radiata Sawdust biochar, used as a partial replacement to cement has a 2-3% optimum percentage, the results of this research suggests that:

- Not only does it enhance the mechanical properties of cement mortar, the use of biochar also benefits the environment as a permanent carbon capture.
- The incorporation of biochar to cement mortar is directly affected by factors such as particle size distribution, curing conditions, raw materials used, etc., for future recommendation it is suggested that this can be carefully considered in future research.
- Other kinds of raw materials similar to sand and cement, can be used to explore the different options of managing forest wastes with the idea of biochar production.
- Take into consideration properties such as pyrolysis process and temperature, a key information normally used to be able to produce a carbon-rich biochar, were not taken into consideration when choosing the kind of biochar to be used.
- Different curing conditions can be taken into consideration to know biochar potential as an internal curing agent.
- Establishing standards and guidelines for using biochar in concrete will ensure performance and consistency,
- Additional long term studies on the durability of biochar blended concrete and mortar under various environment condition can be taken into consideration.

APPENDIX

Table A: Particle Size Distribution

Characteristics	Cement	Sand	Biochar 1	Biochar 2
Specific surface area	377 m2/kg	29.61 m2/kg	126.3 m2/kg	818 m2/kg
D[3,2] mm	0.011	0.203	0.0317	0.00733
D[4,3] mm	0.0229	0.467	0.281	0.0289
Dv (10) mm	0.00543	0.191	0.0136	0.00301
Dv (50) mm	0.0197	0.410	0.0698	0.0172
Dv (90) mm	0.0451	0.837	0.887	0.0684
Dv (95) mm	0.054	1	1.210	0.106
Volume below (10) microns	22.38%	0.80%	6.05%	35.35%
Volume below (20) microns	50.87%	1.27%	17.16%	54.75%
Volume below (31) microns	74%	1.53%	28.01%	69.97%

Table B: Compressive Strength Test Results from Batch 1 (Biochar 1)

Cement Mortar Mix	Compressive Strength (Mpa)		
	7 Days	28 Days	56 Days
CM 0	19.7	28.9	36.7
CM 2	16.8	23.1	33.1
CM 4	17.5	21.3	29.3
CM 6	14.9	19.6	26.1
CM 8	13.4	18.8	25.3

CM 10	10.7	17.5	21.1
Batch 1			

Table C: Compressive Strength Test Results from Batch 2 (Biochar 2)

Cement Mortar Mix	Compressive Strength (Mpa)		
	7 Days	28 Days	56 Days
CM 0	19.8	29.8	32.4
CM 1	21.0	30.8	32.9
CM 2	21.9	31.4	34.5
CM 3	20.7	30.1	32.9
CM 4	19.9	28.1	30.5
Batch 2			

Table D: Compressive Strength Test Results from Batch 3 (Biochar 2)

Cement Mortar Mix	Compressive Strength (Mpa)		
	3 Days	7 Days	14 Days
CM 0	22.3	25.9	29.2
CM 1	23.6	27.8	30.9
CM 2	25.6	30.1	32.1
CM 3	25.4	29.1	31.5
CM 4	21.1	23.3	24.6
Batch 3			

Table E: Flexural Strength Test

Cement Mortar Mix	Flexural Strength (Mpa)	
	7 Days	28 Days
CM 0	4.9	5.3
CM 1	4.5	4.7
CM 2	4.8	4.9
CM 3	4.1	4.7
CM 4	4.1	5.4

Table F: Chemical Composition of Cement

Oxides	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	SO_3 (%)

Cement(%)	19.82	3.44	0.313	0.081	3.28407	0.977	64.456	0.268	0.46	0.111	2.36

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