Assessing Environmental Footprints: A Comprehensive Life Cycle Assessment of Cement Manufacturing Process

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Assessing Environmental Footprints: A Comprehensive Life Cycle Assessment of Cement Manufacturing Process

A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Bachelor of Science in

Civil Engineering

By

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DEDICATION

Dedicated to our parents, siblings, our instructors at MCE who have guided us during the course of this research and our great institution MCE where we have spent the four most memorable years of our life.

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LIST OF ABBREVIATIONS

M_A	Microalgae
OPC	Ordinary Portland Cement
LCA	Life Cycle Assessment
MCM	Microalgae Cement Mortar
OPCM	Ordinary Portland Cement Mortar
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
AS	Australian Standards
IS	Indian Standards
ISO	International Organization for Standardization
MCE	Military College of Engineering
GWP	Global Warming Potential
CM	Cement Mortar

ABSTRACT

This research focuses on assessing and enhancing the environmental sustainability of cement through a comprehensive life cycle assessment (LCA). The objectives include analyzing the feasibility and importance of cement in civil engineering, emphasizing LCA as the best framework for assessing environmental impacts, and developing a framework to reduce carbon emissions in cement production. The methodology involves conducting LCA on cement using versatile software tool like openLCA, as well as exploring alternative materials with lower greenhouse gas emissions, such as microalgae. Laboratory testing has been carried out to assess the properties of the alternative material to ensure its suitability for construction purposes. The deliverables encompass the significance of LCA in quantifying environmental impacts of cement production, identifying areas for improvement, and introducing sustainable alternatives. The research not only addresses environmental concerns but also contributes to a more resilient construction industry by promoting sustainable materials, fostering innovation, and providing a competitive edge for manufacturers and suppliers.

Keywords: Microalgae, LCA, Cement, OpenLCA, Testing

INTRODUCTION

1.1 General

Concrete is often regarded as the most frequently utilized material on the planet after water. In normal OPC concrete, cement is a primary source that can be employed as a bidding agent. There are many environmental hazards linked to ordinary Portland cement concrete (OPCM). OPC production necessitates burning of conventional hydrocarbons and the calcination of lime, resulting in significant emissions of carbon dioxide (CO_2). One ton of fuel is required to make one ton of OPC, according to current estimates. Only steel and aluminum take more energy to be manufactured than OPC does. (Hardjito & Rangan, 2005). CO_2 is damaging to our environment and causes various health problems such as asthma, bronchitis, and sinus infections, according to estimates that 1.6 billion tonnes of cement manufacturing each year contributes to around 7% of total CO_2 generation per year. (Haseeb, 2017)

Life Cycle Assessment (LCA) emerges as a pivotal tool, offering a holistic view from extraction to disposal, enabling nuanced insights for informed decision-making and improvement strategies.

Simultaneously, microalgae, a byproduct of coal combustion, is gaining prominence as an eco-friendly alternative. Instead of being discarded, microalgae are repurposed as a supplementary cementitious material, addressing waste concerns, and mitigating the environmental impact of traditional cement production. Incorporated into concrete, microalgae enhance properties while diminishing reliance on conventional cement, substantially reducing greenhouse gas emissions.

The tandem application of LCA on cement and the integration of microalgae represents a holistic strategy for environmentally sustainable construction. This approach not only scrutinizes the environmental impact of a widely used material but actively explores and promotes alternatives. The synergy aims not just to enhance the environmental sustainability of cement but also fortify the construction industry's resilience through sustainable practices. This dual strategy embodies a commitment to a construction industry that is both ecologically sustainable and adaptive to evolving environmental challenges.

1.2 Microalgae Based Concrete

Rather than using standard cement, this project uses microalgae based geopolymer as the major binding agent. Like OPCM, a geopolymer based on microalgae is used to bind underacting fine and coarse aggregates that are present in loose form, with or without admixtures.

1.3 Problem Statement

Assessing and Enhancing the Environmental Sustainability of Infrastructure Projects through Comprehensive Life Cycle Assessment (LCA) in Civil Engineering.

1.4 Objectives of Project

a. To assess the environmental suitability of cement production process.

b. To carry out LCA study to compute GHG emissions from cement industry.

c. To develop a framework for reducing carbon emission in cement production.

1.5 Scope of Work

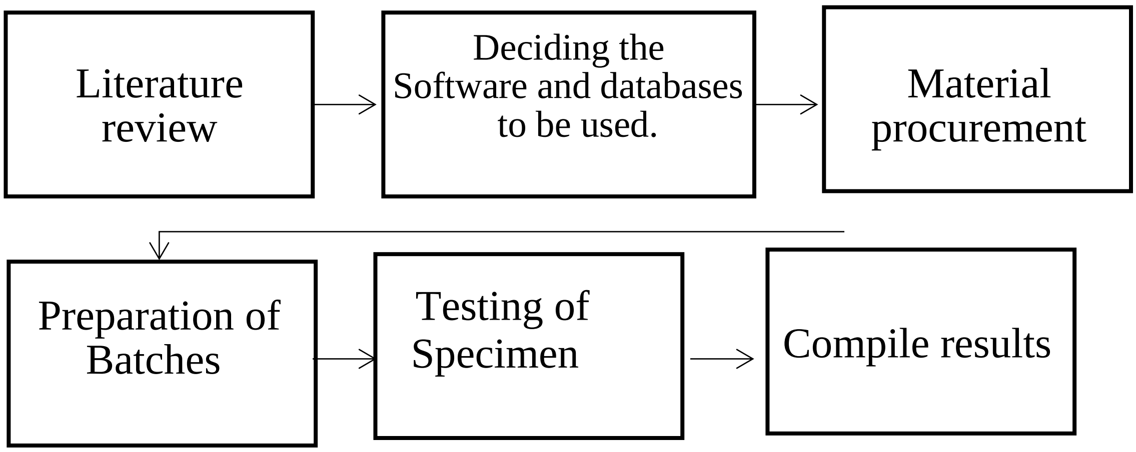

Figure 1.1 Flowchart of our project

Microalgae was procured from MCE training area as a binder material for making MCM. The same method of production and equipment was used for making MCM as is used for OPCM. It was envisaged that the characteristics of concrete were affected by their compressive, indirect tensile, and flexural strengths. Additionally, microalgae affected the GWP of concrete.

1.6 Sustainable Development Goals

The following sustainable development goals which were adopted by the UNGA in 2015 are:

- SDG-9: Industry, Innovation and Economic Growth
- SDG-11: Sustainable Cities and Communities
- SDG-13: Climate Action

1.7 Project Report Outline

The project report is arranged in following manner:

Chapter 2 contains a brief survey of the literature on microalgae, concrete, biogenic limestone and LCA. It also investigates using micro algae as a binder to make concrete and the use of MCM.

Chapter 3 describes the research methodology adopted to investigate the topic. In this chapter the method of performing different test will be discussed and explained. The tests which are used to study the behavior of concrete will also be explained in this chapter.

In chapter 4 the results of the tests are compiled and discussed. The effect of use of micro algae in concrete and curing conditions on the mechanical properties of concrete are discussed.

Chapter 5 provides the summary and conclusion part of the project report and few recommendations will also be given.

The project report ends with a reference list.

CHAPTER 2 LITERATURE REVIEW

2.1 Effects of Concrete on Environment

Carbon trading encompasses the purchase and sale of carbon permits and certificates, serving as a pivotal regulatory instrument across various sectors, including cement manufacturing. It facilitates the oversight of greenhouse gas emissions, which contribute to the escalating global temperatures and climate change. These trading mechanisms incentivize industries to mitigate their emissions, aligning with sustainability objectives for the benefit of the planet. As per V. Malhotra (1999), the trading value of one ton of carbon emission is estimated to be approximately US $10.

The production of cement is on an upward trajectory, increasing by around 3% annually (McCaffrey, 2002). Notably, the manufacturing of one tonne of cement results in the emission of about one tonne of carbon dioxide (CO_2) into the atmosphere. Ordinary Portland Cement (OPC) production alone accounts for roughly 7% of global greenhouse gas emissions, equivalent to 1.35 billion tonnes (V. Malhotra, 2002). Alongside steel and aluminium, OPC stands out as one of the most energy-intensive building materials.

Recognizing these challenges, the concrete industry has embraced initiatives such as 'Vision 2030: A Vision for the U.S. Concrete Industry'. This vision underscores the imperative for concrete technologists to spearhead future development endeavors while prioritizing environmental conservation and addressing public apprehensions regarding climate change driven by greenhouse gas emissions. The objective is to position concrete as the preferred construction material for infrastructure projects while ensuring its environmental sustainability in the long run (Mehta, 2001).

2.2 Microalgae

Microalgae or microphytes are microscopic algae invisible to naked eye. They are phytoplankton typically found in freshwater and marine systems, living in both the water column and sediment. They are unicellular species which exist individually, or in chains or groups.

Microalgae are a promising solution to meet energy and fuel needs. They are unicellular and photoautotrophic microscopic organisms found primarily in aquatic environments. Microalgae can be used as a third-generation feedstock for biofuels. Research has been developed to explore biofuel precursors found in these microorganisms, such as triacylglycerol and starch lipids, which are transformed into biodiesel and bioethanol, respectively, and to produce biogas from algal biomass. Besides, some strain/species can produce biohydrogen, an attractive and clean fuel that helps reduce carbon emissions. Thus, a review of biofuel's production from microalgae biomass was carried out here; highlighting the production methods, advantages, and disadvantages as well as relevant characteristics of each biofuel. It was concluded that microalgae are a potential sustainable technology in the production of biofuels, requiring only the methodological adaptation of production technologies for each strain/species, to enhance the generation of the desired biofuel.

The problem of climate change arising mainly from CO_2 emission is currently a critical environmental issue. Bio fixation using microalgae has recently become an attractive approach to CO_2 capture and recycling with additional benefits of downstream utilization and applications of the resulting microalgal biomass. This review summarizes the history and strategies of microalgal mitigation of CO_2 emissions, photobioreactor systems used to cultivate microalgae for CO_2 fixation, current microalgae harvesting methods, as well as applications of valuable by-products. It is of importance to select appropriate microalgal species to achieve an efficient and economically feasible CO_2-emission mitigation process. The desired microalgae species should have a high growth rate, high CO_2 fixation ability, low contamination risk, low operation cost, be easy to harvest and rich in valuable components in their biomass.

Figure 2.1 Microalgae in MCE Training Area

Figure 2.2 Microalgae in MCE Training Area

Micro Algae has following advantages over OPC as has been investigated by many researchers:

1. Inexpensive material
2. Better Mechanical properties
3. Suitable for high temperature curing conditions
4. Better durability and strength properties
5. Less global warming potential

Table 2.1 Biochemical composition of microalgae

S No	Biochemical composition	Percentage
1	Protein	16
2	Carbohydrate	3.3
3	Total Chlorophyll	2.4
4	Magnesium	24
5	Phosphorous	8
6	Lipids	18
7	Calcium	15
8	Potassium	10.6
9	Sodium	2.7

2.3 Use of Micro Algae in Concrete

One way to decrease the harmful effects of concrete on the environment is to reduce the OPC content of the concrete and it is done in several ways. One option is to use micro algae in exchange of some of the cement in the concrete mix.

The favorable temperatures and high mineral content of the water in tropical countries make them ideal for microalgae growth. Using microalgae to seal cracks has the added benefit of reducing CO_2 emissions compared to conventional concrete.

Microalgae growth rates and photosynthetic rates are higher than terrestrial plants having the ability to sequester 10-50 times more CO_2, with the capacity to grow in a diverse array of conditions. Microalgae have the ability to capture 1.83 kg of CO_2 per kg of algal biomass (Chisti, 2007). Given such efficient growth and photosynthetic rates, microalgae are ideal feedstocks for biomass cultivation and CO_2 mitigation. To reduce the GHG emissions associated with cement production, the approach proposed in this paper is the use of cement flue gas as a source of carbon for microalgae cultivation; once cultivated, microalgae can be digested anaerobically into biogas (methane) to be used in turn to power cement plants — thus creating a closed-loop.

2.4 Carbon Fixation

Microalgal cultures do not require pure CO_2 for growth and photosynthetic processes and are consequently able to sequester the CO_2 present in flue gases produced by combustion processes. The efficiency of CO_2 capture by microalgae depends upon the type of strain selected, the concentration of CO_2, the cultivation system, and environmental and operating conditions such as culture medium, temperature and light intensity. The efficiency of capture and sequestration of CO_2 by microalgae ranges between 40% and 93.7% (Ighalo et al., 2022). Furthermore, as CO_2 concentrations increase, microalgae can adapt to such altering conditions. As a result of this, higher fixation and growth rates can be fostered through a slow increase of CO_2 supply.

2.5 Cultivation Methods and Conditions

Microalgae can be cultivated in open, closed, or hybrid systems. The most common method for cultivating microalgae, which is also used on industrial scale, is an open pond that allows direct CO_2 uptake from the atmosphere (Iglina et al., 2022). It is therefore essential that ponds be established in an area that provides sufficient light irradiation for cultures and promotes the growth of the specific species being cultivated. Ponds are typically 0.2-0.5m deep with mixing and recirculation to promote biomass growth. Benefits associated with open systems include that they are economical, make sufficient use of sunlight, and are easy to maintain (Razzak et al., 2017). However, cultures grown in open systems are exposed to variable weather conditions and contaminants or other organisms that may limit algal growth; they also require large areas. Closed cultivation systems, or photobioreactors, resolve many of these complications. In closed systems, algal growth conditions can be precisely controlled. Photobioreactors allow for ideal mixing, to achieve optimum light for cell growth and to improve gas exchange (Razzak et al., 2017). They can be operated indoors to facilitate temperature control. In general, photobioreactors have higher biomass productivities and cell concentrations than open systems. They are also better able to sustain pure cultures of single species compared to open systems, as they shield cultures from contaminant microorganisms. However, photobioreactors have high initial and operating costs and difficulties in reactor scale-up.

In addition to inorganic carbon requirements, microalgal cultures also require large amounts of water. The use of potable water is unsustainable in large-scale algal cultivation, especially in arid regions. However, the use of waste nutrient and water resources may alleviate environmental impacts and economic constraints (Edmundson and Wilkie, 2013; Lincoln et al., 1996, Wilkie and Mulbry, 2002). Therefore, this paper proposes the use of non-potable wastewater produced by cement plants as the algal culture medium. The use of wastewater removes the barrier posed by high water requirements and provides cultures with nutrients for biomass production (Edmundson and Wilkie, 2013; Wilkie et al., 2011).

2.6 Life Cycle Assessment

One of the most common methodologies for quantifying sustainability is life cycle assessment (LCA). An LCA is a systematic analysis of environmental impact over the course of the entire life cycle of a product, material, process, or other measurable activity. LCA models the environmental implications of the many interacting systems that make up industrial production. When accurately performed, it can provide valuable data that decision-makers can use in support of sustainability initiatives.

The ISO standards describe the principles and full framework for conducting an LCA. The assessment is broken down into the following four phases:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

2.6.1 Goal and Scope Definition

Accounting for all the many potential impacts of an entire manufacturing process would require an incredible amount of time, data, knowledge, and resources—there are limits to the breadth and data quality of any analysis, after all. An LCA analyst makes this task manageable by first clearly defining an LCA's **goal** and **scope**.

Functional units, **system boundaries**, and **limits to the analysis** are set to outline where in the life cycle the study begins and where it ends, and to identify what processes within the technical system will be assessed. A functional unit is the basis for the study. It is a measurement of production or output against which impact indicator metrics are normalized.

The scope of an LCA is determined by the number of life cycle stages and impact categories that will be assessed. One assessment might take in just one life cycle stage and one impact, making it very **targeted and focused**. Another might be far more **comprehensive** in scope, addressing an entire life cycle across many impact categories. Between these two poles stand many possibilities.

2.6.2 Life Cycle Inventory

Once the boundaries of an LCA have been drawn, an LCA analyst is ready to begin collecting data. This is the LCI phase, when an industrial system's inputs and outputs are measured and recorded (according to the functional unit). By the end of this phase, an inventory list is created that details all input/output data for the system under study.

2.6.3 Impact assessment

Once all relevant data has been collected, the LCIA phase begins. The LCA analyst, at this point, evaluates the inventory of data that has been collected in order to make it meaningful in the context of potential damage to the environment or human health. For example, knowing that a process emits 10 megatons of carbon dioxide (CO_2) and 17 megatons of methane (CH_4) does not, in itself, describe a contribution to climate change. An LCIA translates these measurements into meaningful information for expressing their impact. The raw data is characterized to communicate the relative potency of materials, emissions, or other factors. So, in the case of CO_2 and CH_4, an LCIA allows us to say that the latter contributes 25-30 more to climate change than the former.

2.6.4 Interpretation

The final phase of the LCA—when the study's results are interpreted alongside its original goals and scope—may be the most important of all when it comes to turning what was learned into actionable tasks.

The fundamental purpose of this final phase is to identify priorities in light of an LCA's stated goals. So, if the goal was to mitigate waste, strategies for doing so will be highlighted following what was learned through the study.

The ISO standards for LCA dictate that this interpretation should:

- identify significant issues based on the LCI and LCIA phase;
- evaluate the study itself, how complete it is, if it's done sensitively and consistently, and account for uncertainty; and
- provide conclusions, limitations, and recommendations.

2.7 Open LCA Software

OpenLCA is world-wide the only free, open source LCA software that can be used for professional ecological, social and economical life cycle assessments. Among other things, OpenLCA can be used for LCAs, carbon & water footprints, eco-design, environmental product declarations, life cycle costing and social life cycle assessment.

OpenLCA is a free and open-source software tool for conducting Life Cycle Assessments (LCAs) and other sustainability assessments. It is designed to be flexible and customizable, allowing users to adapt the software to their specific needs and conduct a wide range of sustainability assessments.

OpenLCA supports a wide range of impact assessment methods, including CML, ReCiPe, and TRACI, allowing users to choose the method that is most appropriate for their specific LCA.

The software allows users to conduct inventory analysis of their products or services, including data on raw materials, energy consumption, and emissions.

Overall, OpenLCA is a powerful and flexible software tool for conducting LCAs and other sustainability assessments. It is free and open source, making it accessible to a wide range of users, and provides a range of features for conducting detailed sustainability assessments and communicating sustainability performance to stakeholders.

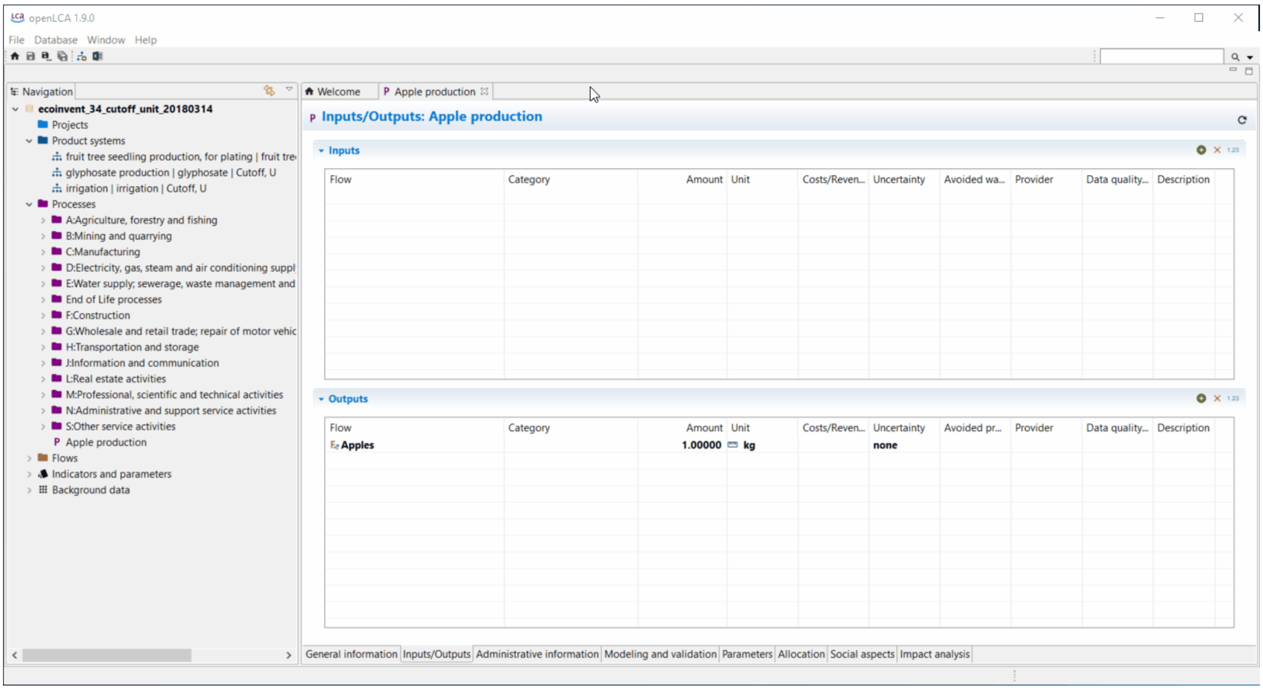

Figure 2.3 OpenLCA Interface

2.7.1 Flows

Flows represent products and materials that move throughout a life cycle, interconnected within the process network, and take form of inputs, outputs, energy, or emissions. Flows can be substances, products, materials, energy carriers, emissions, or other types of inputs or outputs. A flow is characterized by its name, flow type, and reference flow property (unit category in which the flow is expressed). Examples of flows include electricity, water, CO2 emissions, aluminium, and so on.

2.7.2 Processes

A process is a set of interrelated activities that takes place within the life cycle of a product or system and transforms inputs into outputs. A process can be a manufacturing process, a transportation activity, an energy generation process, or any other operation within the life cycle. Processes are defined by their quantitative reference, which represents the amount of product or service that the process provides. For example, a process could be the set of all inputs and outputs occurring in the production of 1 kg of PET granulate.

2.7.3 Product Systems

A "product system" is described by ISO 14040 as a "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product." In openLCA a product system is a set of processes connected by flows, performing one or more defined functions, and modelling the life cycle of a product. A product system has a reference process with a defined amount of the product (referred to the functional unit), which serves as basis for calculating impacts for all connected processes within the system..

2.7.4 CML Baseline

The CML methodology was created by the University of Leiden in the Netherlands in 2001. CML method represents the environmental effects of the evaluated system model using 11 midpoint indicators (e.g., global warming, ozone depletion, water acidification, creation of photochemical oxidant, and water eutrophication), which determinate the five endpoint indicator values.

Midpoint indicators are referred to as ecotoxicity potentials and express the relative impacts of chemicals towards each other. CML is a procedure used to estimate the measure of environmental impact that is caused by the product. This method uses various impact categories such as eutrophication, ionization radiation, aquatic ecotoxicity, land use, and human toxicity.

2.8 Biogenic Limestone

Biogenic limestone is formed through the cultivation of coccolithophores, cloudy white microalgae that sequester and store carbon dioxide in mineral form through photosynthesis. According to researchers, the tiny organisms produce the largest amount of new calcium carbonate on the planet, in the form of limestone shells, and at a faster pace than coral reefs.

Microalgae thrive in both warm, cold, salt and fresh waters, making them ideal candidates for cultivation. Principal investigator and head of CU Boulder's Living Materials Laboratory Wil Srubar tells RIBAJ: 'We estimate that we would need around 1-2 million acres of land area to meet 100 per cent of the demand for cement production in the United States. That’s only around 0.1-0.2 per cent of the total land area and 1-2 per cent of the land area we currently use to grow corn. This is only if the algae are grown in open ponds, but there are other options, including photobioreactors, vertical farms, and continuous offshore cultivation, etc.'

The project explored what would happen if global cement-based construction were replaced with biogenic limestone cement. Calculations revealed that 2 gigatonnes of carbon dioxide would no longer be pumped into the atmosphere each year, and over 250 million tonnes of carbon dioxide would be sucked from the atmosphere and stored in the material.

Conventional cement production, responsible for 7 per cent of annual global greenhouse gas emissions, is energy intensive due largely to the burning of quarried limestone and clay at high temperatures.

The algae-derived biogenic limestone draws down the same amount of CO_2 from the atmosphere during the algae growing process as that released into the atmosphere when the material is burned in a kiln.

A product-based life cycle assessment found that using biogenic limestone alone to make portland cement would reduce its embodied carbon by around 60 per cent. Furthermore, if ground biogenic limestone is also used as a filler material in Portland cement, replacing quarried limestone that often comprises 15 per cent of the mixture, it could enable a reduction in embodied carbon of up to 70 per cent.

When this process is used in combination with the electrification of kilns, powered by renewable energy at scale, the team claims it would be possible to create carbon-neutral or even carbon-negative Portland cement.

2.9 Compressive Strength

Compressive strength is the most common and well-accepted measurement of concrete strength. It is the main criteria used to determine if a given concrete mixture can withstand the structural forces being applied. Compressive strength is the "nameplate" concrete rating. It is the most common attribute cited in construction specifications.

Compressive strength is tested by breaking cylindrical concrete specimens in a special machine. Testing conforms to the ASTM (American Society for Testing & Materials) standard C39.

Pounds per square inch (psi) measures the compressive strength of concrete in terms of a standard unit of force (pounds) over a standard unit of area (square inch or SI). SI values are expressed as megapascals (MPa), the metric unit of pressure.

Force is imposed on the concrete matrix from opposite sides, squeezing until it fractures, establishing the limits of a given cured concrete mix. Aggregate materials within the concrete distribute and counterbalance the applied load.

A higher psi indicates higher compressive strength and, typically, a higher cost. But a stronger concrete mix often correlates to more durability, longevity, and, sometimes, a more efficient volume of material than a lower-strength mix.

The ideal concrete psi for a given project depends on various factors. Different types of concrete structures have normally acceptable psi ranges that are governed by design codes and industry standards. The American Concrete Institute (ACI), American Society of Civil Engineers (ASCE), and regulatory groups such as the American Association of State Highway and Transportation Officials (AASHTO) are often cited for concrete guidelines or minimum requirements.

The bare minimum is usually between 2,000 and 3,000 psi for fill and simple surfaces (e.g., patios or sidewalks). ACI sets 2,500 psi as the structural concrete minimum. Pavement, slabs, and footings can be up to 4,000 psi. Suspended slabs, beams, and girders (typically found in bridges) might be 5,000 psi. High-rise columns and other high-load-bearing members may require compressive strength from 7,500 to 10,000 psi, or even more than 15,000 psi, depending on structure height and load.

Higher psi values result in other benefits, such as better long-term environmental performance. Freeze-thaw cycles in colder climates can compromise weak mixes and may require increased strength to maintain its intended use over years of cold weather. A higher compressive strength usually provides more resistance to this type of degradation over time.

Compressive strength is normally tested at seven days and then again at 28 days. The seven-day test determines early strength gains and verifies that the mix is on track to set properly. The *final cured design strength* (and the basis for minimum design values) is the 28-day test as noted in the ACI standards.

2.9.1 Curing Temperature

Concrete curing is the process of maintaining adequate moisture in concrete within a proper temperature range to aid cement hydration at early ages. Hydration is the chemical reaction between cement and water that results in the formation of various chemicals contributing to setting and hardening. Some of the factors that affect the hydration process are the initial concrete temperature, the ambient air temperature, the dimensions of the concrete, and the mix design. Therefore, for the success of this process, in-situ concrete must have sufficient moisture and a temperature that favours this chemical reaction at a rapid and continuous rate.

The American Concrete Institute (ACI) recommends a minimum curing period corresponding to attaining 70% of the compressive strength of concrete. The specifications say that this can happen after seven days of curing. However, 70% strength can be reached quickly when concrete cures at higher temperatures, or when certain admixtures are used in the concrete mix. Similarly, more time may be needed for curing when concrete or ambient temperatures are lower. Typically, the ideal curing temperature would be 20°F or 68°F. Careful control of moisture and temperature of your in-situ concrete during curing is an essential part of quality control and quality assurance of your concrete structure. Proper curing techniques will prevent in-situ concrete from drying, shrinking, and/or cracking. This ultimately affects the performance of your structure, particularly at the cover zone. Curing of concrete should occur as soon as it has been placed. It is also essential that monitoring of concrete curing conditions take place continuously for seven days. If the water evaporates from the concrete before it has attained its maximum strength, there will not be enough remaining to fully hydrate the cement and achieve the maximum compressive strength of concrete. This is especially true during extreme weather conditions because various environmental factors can affect the concrete slab. Thus, the strength development of your concrete can be compromised.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Introduction

This Chapter presents the details of the process that is required to take place for the manufacturing MCM. Up till now no widely used calculation method has been defined to calculate the mix proportion by established standards organization like ACI, AS and IS etc. Generally, the researchers have been using trial and error processes to develop the mix proportion of the MCM for required parameters. In this study the mix proportion was taken from (Hardjito & Rangan, 2005) which was similar to that of our control (OPCM).

To keep the testing and manufacturing process less complex existing practices used in the manufacturing and testing of OPCM were adopted for MCM. The aim of this action was to ascertain the adequacy of MCM if it is manufactured by the existing practices in the field. By doing this it would be easier to introduce this new material in the field of construction in Pakistan in the future.

Various materials can be used to produce geopolymer concrete, but we have selected microalgae for this purpose due to its availability in Pakistan. The Cement was procured from structural lab MCE. Microalgae was tested using aggregates from only one source, the Environmental lab, to ensure that the effects of aggregate qualities on microalgae parameters were minimized.

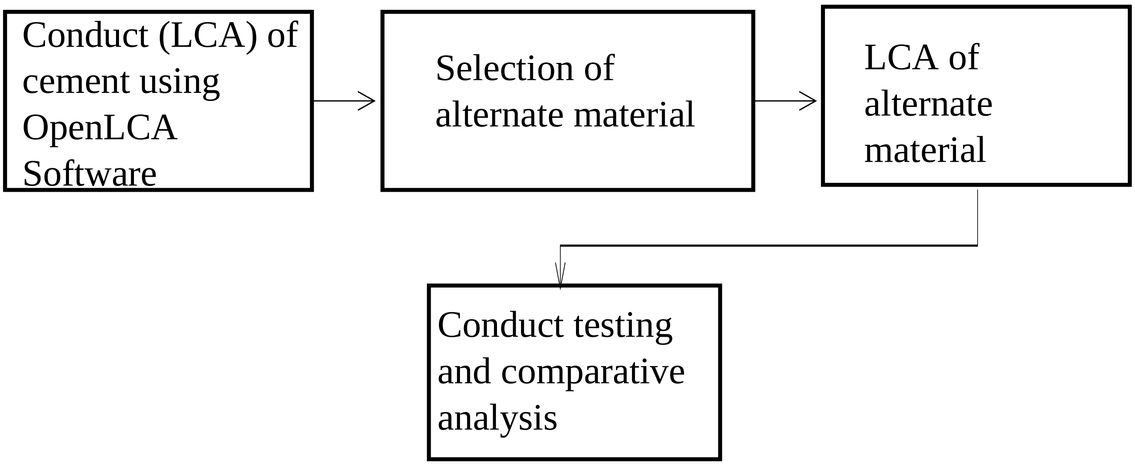

Figure 3.1 Flowchart of our methodology

3.2 Materials used in this study

3.2.1 Microalgae

In this project microalgae were obtained from training area MCE. It was used as replacement for cement to produce MCM.

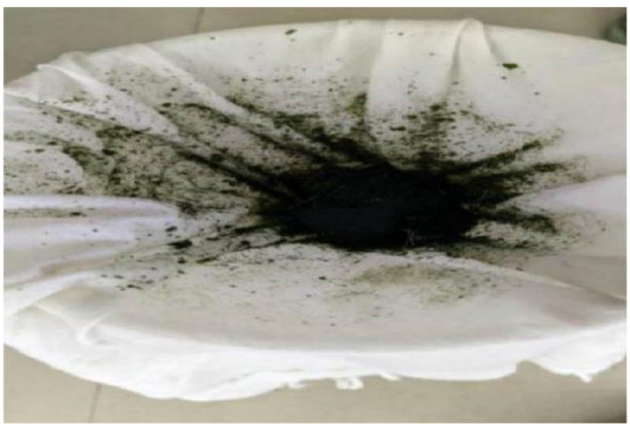

Figure 3.2 Sample of Microalgae

Figure 3.3 Dry Sample of Microalgae

3.2.2 Fine Aggregates

In this study, we made use of the fine aggregates that were made available in the concrete laboratory.

Figure 3.4 Fine Aggregates

3.3 Mixture Proportions

First a control mixture of CM was prepared, with which all other mixtures would have to be compared. MPM mixture proportion as mentioned earlier was taken from existing research by (Hardjito & Rangan, 2005). That mixture proportion was selected which was similar with control mixture proportion. A third mixture was also prepared which contained 5 % cement as an admixture in MPM mixture. The Mixture proportion of this mixture was exactly as that of MPM with just an addition of 5 % of cement by weight of MPM. Mixture proportions are shown below.

Table 3.1 Mixture Proportion of Control and Modified Batches

Materials	OPCM (g)	MCM (g) 10% M_A	MCM (g) 20% M_A
Cement	127	114	102
Water	50	50	50
Microalgae	-	13	25
Fine Aggregate	262	262	262

3.4 Manufacturing Process

The manufacturing process of OPCM is well known and standard practices were used to produce control batches for the comparison purposes. The manufacturing process of MCM is quite like that of OPCM with some exceptions. The manufacturing steps involved in production of MCM are:

- Mixing of materials and casting
- Curing of test specimens

3.4.1 Mixing of Materials and Casting

The solid components of the mixture were mixed for 2-3 minutes by hand after which the liquid portion of the mix was added and the constituents were further mixed for 7 minutes.

Figure 3.5 Mixing of Mortar

3.4.3 Curing

To investigate their effects on the properties of MCM. The first curing method involved dry curing in an oven. Following casting, the specimens remained in their moulds at ambient temperature for a day. Subsequently, the specimens were removed from their moulds and placed in an oven in the Structural Dynamics Laboratory of MCE. The oven temperature was set to 60°C for 24 hours, after which the specimens were returned to ambient curing for 7 days.

Care had to be taken to ensure the accurate input of data into the industrial oven interface, which was in the Structural Dynamics Laboratory of MCE. If any negligence occurred while inputting data into the machine, the curing process of MCM would be compromised, and the required strength gain in MCM would not occur.

3.5 Test Matrix

3.5.1 Compressive Strength Test

Compressive strength tests were conducted on specimens using the 3000 KN Automatic Servo Plus machine available in the Structural Dynamics Lab, MCE, following ASTM C39 standards. The cubes measured 70.6mmx 70.6 mmx 70.6mm. For the OPC batch, the cylinders were taken from the curing tank and promptly subjected to testing, as per ASTM standards which require testing on moist specimens.

The tests were performed at standard room temperature. Sulphur capping was performed for MCM specimens due to their rough surface at the top and bottom. After applying sulphur to the faces of the cylinders, the specimens were left to cure for 5 hours before testing. Subsequently, the specimens were placed in the machine, and the relevant testing mode was selected from the menu. The test was stress-controlled, with the load applied at "0.25 MPa/s in accordance with ASTM C39". The machine automatically stopped the application of load when the ultimate strength of the specimen was achieved. Finally, the results of the compressive strength test were recorded from the machine interface.

Figure 3.6 Automatic Servo Plus machine

3.6 OpenLCA Software

3.6.1 Databases

For the purposes of this project needs database was utilized and downloaded from OpenLCA Nexus.

3.6.2 Processes

Two processes were created using flows as inputs and outputs, namely cement and cement with microalgae incorporated as a component.

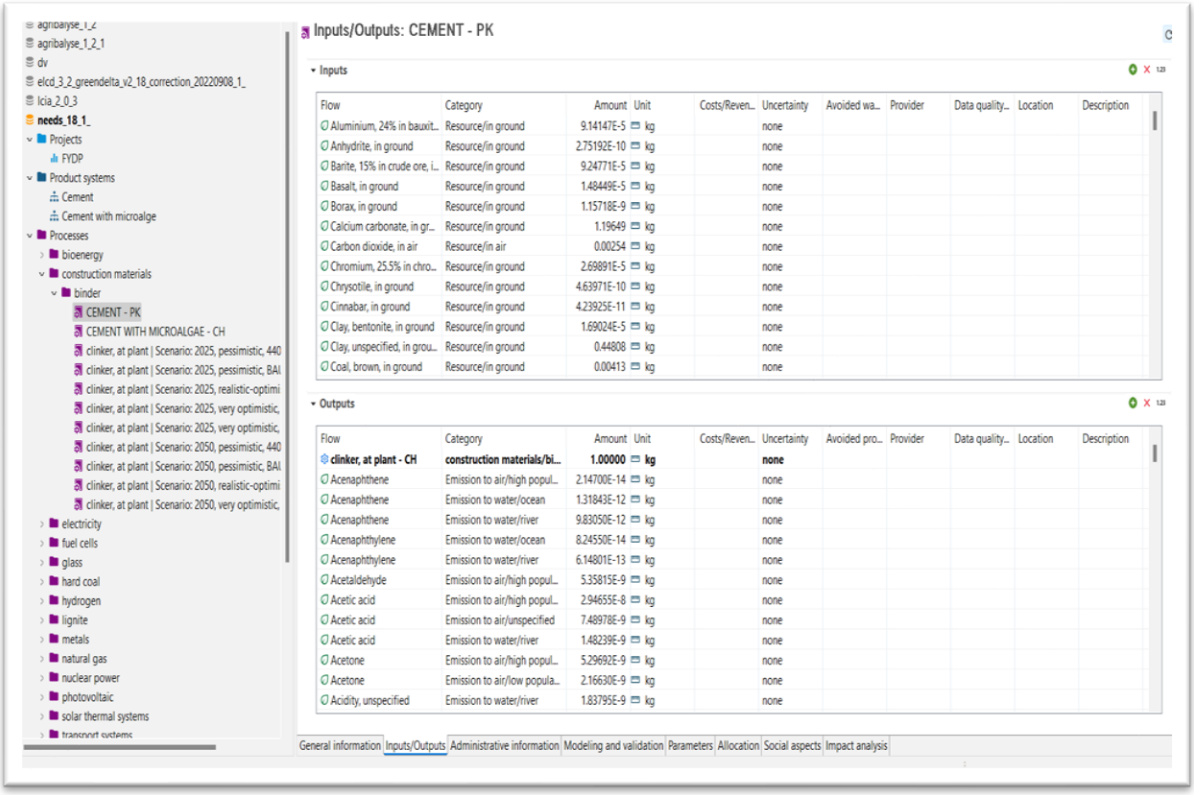

Figure 3.7 Inputs and outputs of cement

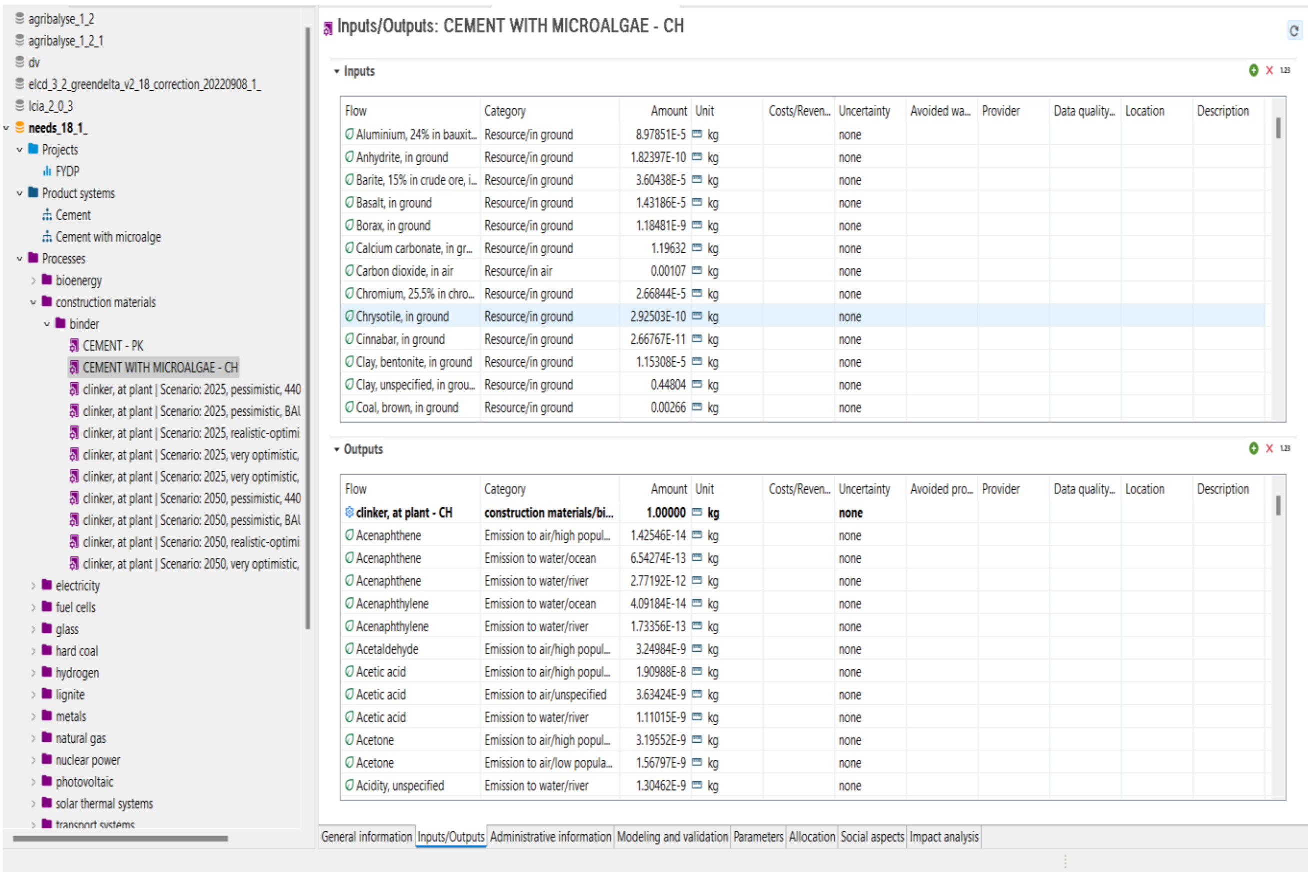

Figure 3.8 Inputs and outputs of cement with microalgae

3.6.3 Product system

The processes were combined to make a product system which in turn formed a project. The project was analyzed and compared.

3.6.4 Assumptions

The following assumptions will be applied to the models:

3.6.4.1 Transport

Where no transport data is available, general "market" models will be used.

3.6.4.2 Electricity

About the electricity demands, this brings a regional aspect to the LCA of algae bioproducts. Two approaches will be taken. The first will be the EU-27 average electricity mix, to ensure that the studies are not essentially purely proxy studies of electricity impacts, but actually show the differences in terms of algal technologies. To provide comparable information to the Techno-economic Analysis, then models will also be created which do use regional electricity impacts. However, there is also a time factor. It is expected that in two years' time, by the year 2026, the European electricity grid will contain a far higher penetration of renewable and low carbon energy sources [31], therefore the GWP impact of electricity used for algae bioproducts will be lower.

3.7 Impact categories

3.7.1 Acidification

Acidic gases such as sulphur dioxide (SO2) react with water in the atmosphere to form "acid rain", a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas (e.g. Sweden receives the acid rain caused by gases emitted in the UK), it causes ecosystem impairment of varying degree, depending upon the nature of the landscape ecosystems. Gases that cause acid deposition include ammonia (NH3), nitrogen oxides (NOx) and sulphur oxides (SOx). Acidification potential is expressed using the reference unit, kg SO2 equivalent. The model does not take account of regional differences in terms of which areas are more or less susceptible to acidification. It accounts only for acidification caused by SO2 and NOx.

This includes acidification due to fertiliser use, according to the method developed by the Intergovernmental Panel on Climate Change (IPCC). CML has based the characterisation factor on the RAINS model developed by the University of Amsterdam.

3.7.2 Ecotoxicity

Environmental toxicity is measured as three separate impact categories which examine freshwater, marine and land. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecosystems. Ecotoxicity Potentials are calculated with the USESLCA, which is based on EUSES, the EU's toxicity model. This provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterisation factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DB), and are measured separately for impacts of toxic substances on:

- Fresh-water aquatic ecosystems
- Marine ecosystems
- Terrestrial ecosystems

3.7.3 Eutrophication

Eutrophication is the build-up of a concentration of chemical nutrients in an ecosystem which leads to abnormal productivity. This causes excessive plant growth like algae in rivers which causes severe reductions in water quality and animal populations. Emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water all have an impact on eutrophication. This category is based on the work of Heijungs, and is expressed using the reference unit, kg PO_4^{3-} equivalents. Direct and indirect impacts of fertilisers are included in the method. The direct impacts are from production of the fertilisers and the indirect ones are calculated using the IPCC method to estimate emissions to water causing eutrophication.

3.7.4 Human toxicity

The Human Toxicity Potential is a calculated index that reflects the potential harm of a unit of chemical released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose. These by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources. These are potentially dangerous chemicals to humans through inhalation, ingestion, and even contact. Cancer potency, for example, is an issue here. This impact category is measured in 1,4- dichlorobenzene equivalents.

3.7.5 Ozone layer depletion

(Stratospheric ozone depletion) Ozone-depleting gases cause damage to stratospheric ozone or the "ozone layer". There is great uncertainty about the combined effects of different gases in the stratosphere, and all chlorinated and brominated compounds that are stable enough to reach the stratosphere can have an effect. CFCs, halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth’s atmosphere, increasing the amount of carcinogenic UVB light reaching the earth’s surface. The characterisation model has been developed by the World Meteorological Organisation (WMO) and defines the ozone depletion potential of different gases relative to the reference substance chlorofluorocarbon-11 (CFC-11), expressed in kg CFC-11 equivalent.

3.7.6 Photochemical oxidation

(Photochemical ozone creation potential) Ozone is protective in the stratosphere, but on the ground-level it is toxic to humans in high concentration. Photochemical ozone, also called “ground level ozone”, is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The impact category depends largely on the amounts of carbon monoxide (CO), sulphur dioxide (SO2), nitrogen oxide (NO), ammonium and NMVOC (non-methane volatile organic compounds). Photochemical ozone creation potential (also known as summer smog) for emission of substances to air is calculated with the United Nations Economic Commission for 21 Europe (UNECE) trajectory model (including fate) and expressed using the reference unit, kg ethylene (C2H4) equivalent.

3.8 Summary

In this chapter the materials required for producing MCM were discussed in detail along with the methods of preparation of MCM. It was found that MCM can be produced by following the same manufacturing process which is used for OPCM. Mixture proportion of the control and modified batch were also discussed. In the end a testing matrix was discussed, the tests involved in this research will tell us about the mechanical properties of concrete and we can also infer some extra observations regarding the use of MCM and its impact of environment through LCA using OpenLCA Software.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter the experimental results are evaluated and analyzed. The tests which were performed during this research pertains to the mechanical properties of the cement mortar. The test data of following tests is discussed here:

- Compressive Strength Test
- Life Cycle Assessment through Software

After the presentation of data, study of the effects of all the batches of concrete involved in this research will be carried out. Feasibility of the MCM in construction was studied and its impact in GWP of the cement industry was observed.

4.2 Compressive Strength Test

Table 4.1 Compressive Strength Test Data

Sample	**Compressive Strength(psi)**
CM	3750
MCM (10% M_A)	3872
MCM (20% M_A)	3790

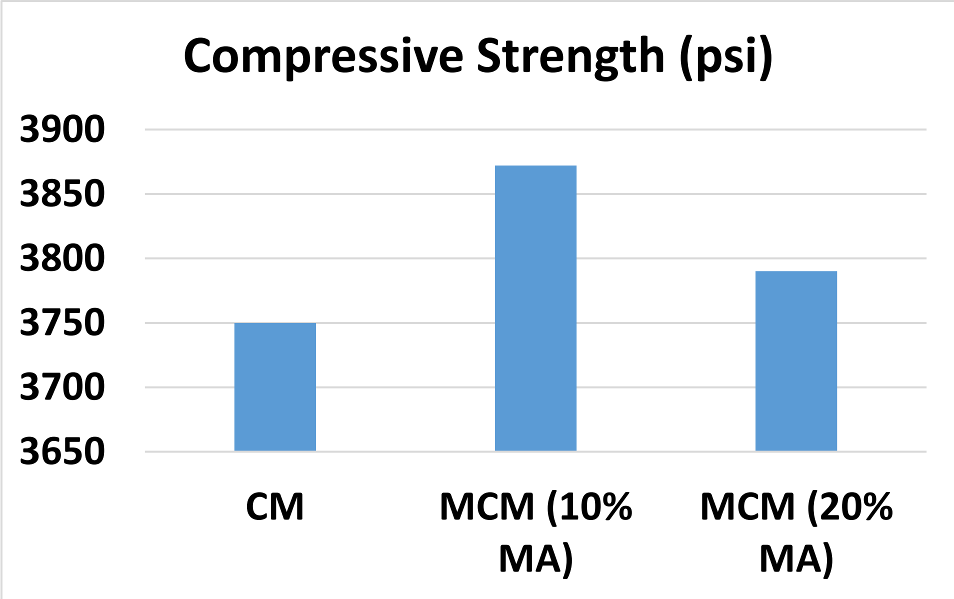

Figure 4.1 Compressive Strength Test Data

It is evident from figure 4.1 that the highest compressive strength was gained by MCM 10% MA (3872 psi) from all the batches. The compressive strength of 20% replaced MCM has the second highest compressive strength (3790 psi). It is evident from the results that both the batches containing microalgae as replacement were able to get higher compressive strength values than that of OPCM.

Figure 4.2 Compressive Strength Test Sample

4.3 OpenLCA Results

4.3.1 Cement

The results of impact assessment of cement are:

Table 4.2 Test Data from OpenLCA of cement

Indicator	Cement	Unit
Acidification – CML-IA baseline	1.22441e-3	kg SO2 eq
Eutrophication – CML-IA baseline	1.82475e-4	kg PO4--- eq
Fresh water aquatic ecotox. – CML-IA baseline	3.17557e-3	kg 1,4-DB eq
Global warming (GWP100a) – CML-IA baseline	9.04207e-1	kg CO_2 eq
Human toxicity – CML-IA baseline	2.45880e-2	kg 1,4-DB eq
Marine aquatic ecotoxicity – CML-IA baseline	1.31496e+1	kg 1,4-DB eq
Ozone layer depletion (ODP) – CML-IA baseline	2.42447e-8	kg CFC-11 eq
Photochemical oxidation – CML-IA baseline	4.47820e-5	kg C2H4 eq
Terrestrial ecotoxicity – CML-IA baseline	1.11988e-3	kg 1,4-DB eq

4.3.2 Cement with microalgae

The results of impact assessment of cement with microalgae are:

Table 4.3 Test Data from OpenLCA of cement with microalgae

Indicator	Cement with 20% microalgae	Cement with 10% microalgae	Unit
Acidification – CML-IA baseline	2.59100e-4	2.98374e-4	kg SO2 eq
Eutrophication – CML-IA baseline	-4.89085e-2	5.67242e-5	kg PO4--- eq
Fresh water aquatic ecotox. – CML-IA baseline	2.43358e-3	2.73443e-3	kg 1,4-DB eq
Global warming (GWP100a) – CML-IA baseline	6.93104e-1	8.18477e-1	kg CO_2 eq
Human toxicity – CML-IA baseline	2.05538e-2	2.17840e-2	kg 1,4-DB eq
Marine aquatic ecotoxicity – CML-IA baseline	8.59467e+0	9.65643e+0	kg 1,4-DB eq
Ozone layer depletion (ODP) – CML-IA baseline	7.32161e-9	1.73967e-8	kg CFC-11 eq
Photochemical oxidation – CML-IA baseline	9.23831e-6	1.37392e-5	kg C2H4 eq
Terrestrial ecotoxicity – CML-IA baseline	1.08066e-3	1.09987e-3	kg 1,4-DB eq

4.3.3 Comparative Analysis

Impact assessment results

The graph below shows the comparison of impact assessment results of the cement with microalgae and cement.

Relative results

The chart below shows the relative indicator results of the respective project variants. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.

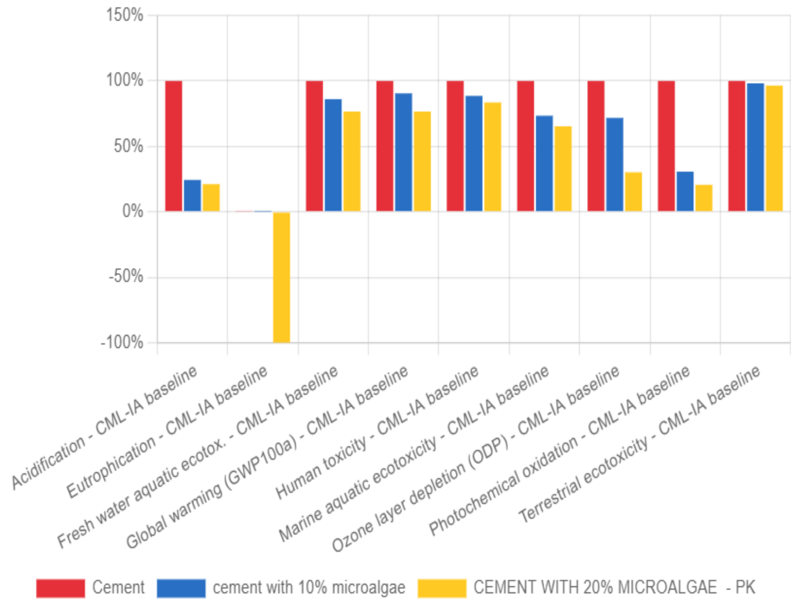

Figure 4.3 Test Data of comparative analysis

4.4 Cost Benefit Analysis

In cement manufacturing process if microalgae are added instead of limestone then the cost of one ton of concrete decreases by approximately $30. This estimate is made by professionals in Arkavadi Limestone Quarry. The manufacturing of one ton of cement is around $100 so microalgae decrease the manufacturing cost of cement per ton by 30%. (Indexbox)

4.5 Inputs of cement in OpenLCA

Amount	Flow	Category
9.14147E-05	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Elementary flows/Resource/in ground
2.75192E-10	Anhydrite, in ground	Elementary flows/Resource/in ground
9.24771E-05	Barite, 15% in crude ore, in ground	Elementary flows/Resource/in ground
1.48449E-05	Basalt, in ground	Elementary flows/Resource/in ground
1.15718E-09	Borax, in ground	Elementary flows/Resource/in ground
1.19649	Calcium carbonate, in ground	Elementary flows/Resource/in ground
0.00253698	Carbon dioxide, in air	Elementary flows/Resource/in air
2.69891E-05	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	Elementary flows/Resource/in ground
4.63971E-10	Chrysotile, in ground	Elementary flows/Resource/in ground
4.23925E-11	Cinnabar, in ground	Elementary flows/Resource/in ground
1.69024E-05	Clay, bentonite, in ground	Elementary flows/Resource/in ground
0.448082	Clay, unspecified, in ground	Elementary flows/Resource/in ground
0.00412809	Coal, brown, in ground	Elementary flows/Resource/in ground
0.057784	Coal, hard, unspecified, in ground	Elementary flows/Resource/in ground
1.35195E-10	Cobalt, in ground	Elementary flows/Resource/in ground
2.88816E-08	Colemanite, in ground	Elementary flows/Resource/in ground
6.06819E-07	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
3.36678E-06	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
8.9187E-07	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
4.42988E-06	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
3.62034E-12	Diatomite, in ground	Elementary flows/Resource/in ground
1.63161E-06	Dolomite, in ground	Elementary flows/Resource/in ground
0.0277722	Energy, gross calorific value, in biomass	Elementary flows/Resource/biotic
0.00317717	Energy, kinetic (in wind), converted	Elementary flows/Resource/in air
0.213151	Energy, potential (in hydropower reservoir), converted	Elementary flows/Resource/in water

0.000204657	Energy, primary, from solar energy	Elementary flows/Resource/in air
1.89502E-11	Feldspar, in ground	Elementary flows/Resource/in ground
6.3923E-08	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Elementary flows/Resource/in ground
2.85702E-08	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Elementary flows/Resource/in ground
2.46685E-06	Fluorspar, 92%, in ground	Elementary flows/Resource/in ground
0.000925655	Gas, mine, off-gas, process, coal mining	Elementary flows/Resource/in ground
0.00531199	Gas, natural, in ground	Elementary flows/Resource/in ground
3.55675E-09	Granite, in ground	Elementary flows/Resource/in ground
0.0177206	Gravel, in ground	Elementary flows/Resource/in ground
7.342E-09	Gypsum, in ground	Elementary flows/Resource/in ground
0.581253	Heat, waste	Elementary flows/Emission to air/low population density
0.000697149	Iron, 46% in ore, 25% in crude ore, in ground	Elementary flows/Resource/in ground
8.73144E-07	Kaolinite, 24% in crude ore, in ground	Elementary flows/Resource/in ground
2.90206E-09	Kieserite, 25% in crude ore, in ground	Elementary flows/Resource/in ground
5.99526E-06	Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore, in ground	Elementary flows/Resource/in ground
-1.28402E-14	Lithium, 0.15% in brine, in ground	Elementary flows/Resource/in ground
0.000419576	Magnesite, 60% in crude ore, in ground	Elementary flows/Resource/in ground
2.40724E-10	Magnesium, 0.13% in water	Elementary flows/Resource/in water
4.23127E-06	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Elementary flows/Resource/in ground
-1.72742E-15	Metamorphous rock, graphite containing, in ground	Elementary flows/Resource/in ground
8.23236E-08	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Elementary flows/Resource/in ground
1.17148E-08	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Elementary flows/Resource/in ground
1.4813E-06	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Elementary flows/Resource/in ground
4.29851E-08	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Elementary flows/Resource/in ground
2.98961E-06	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Elementary flows/Resource/in ground
3.63148E-07	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Elementary flows/Resource/in ground
5.59661E-05	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Elementary flows/Resource/in ground

-2.68008E-14	Occupation, arable	Elementary flows/Resource/land
2.91831E-06	Occupation, arable, non-irrigated	Elementary flows/Resource/land
3.85147E-06	Occupation, construction site	Elementary flows/Resource/land
0.000260144	Occupation, dump site	Elementary flows/Resource/land
4.11052E-06	Occupation, dump site, benthos	Elementary flows/Resource/land
1.46197E-05	Occupation, forest, intensive	Elementary flows/Resource/land
0.00343324	Occupation, forest, intensive, normal	Elementary flows/Resource/land
0.000147437	Occupation, industrial area	Elementary flows/Resource/land
5.19151E-08	Occupation, industrial area, benthos	Elementary flows/Resource/land
2.14887E-05	Occupation, industrial area, built up	Elementary flows/Resource/land
2.33487E-05	Occupation, industrial area, vegetation	Elementary flows/Resource/land
0.000383455	Occupation, mineral extraction site	Elementary flows/Resource/land
1.87921E-06	Occupation, permanent crop, fruit, intensive	Elementary flows/Resource/land
7.39185E-14	Occupation, sea and ocean	Elementary flows/Resource/land
7.7443E-07	Occupation, shrub land, sclerophyllous	Elementary flows/Resource/land
1.74279E-05	Occupation, traffic area, rail embankment	Elementary flows/Resource/land
1.92712E-05	Occupation, traffic area, rail network	Elementary flows/Resource/land
3.70277E-05	Occupation, traffic area, road embankment	Elementary flows/Resource/land
7.79671E-05	Occupation, traffic area, road network	Elementary flows/Resource/land
-8.90332E-16	Occupation, urban, continuously built	Elementary flows/Resource/land
6.93871E-09	Occupation, urban, discontinuously built	Elementary flows/Resource/land
8.63628E-05	Occupation, water bodies, artificial	Elementary flows/Resource/land
0.000181806	Occupation, water courses, artificial	Elementary flows/Resource/land
0.0372658	Oil, crude, in ground	Elementary flows/Resource/in ground
1.17149E-10	Olivine, in ground	Elementary flows/Resource/in ground
1.62653E-11	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
3.90884E-11	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground

6.36631E-08	Peat, in ground	Elementary flows/Resource/biotic
2.55692E-07	Phosphorus(MA), 18% in apatite, 4% in crude ore, in ground	Elementary flows/Resource/in ground
1.3602E-07	Phosphorus, 18% in apatite, 12% in crude ore, in ground	Elementary flows/Resource/in ground
5.96717E-13	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground
2.13918E-12	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
3.69998E-13	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground
1.15887E-12	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
9.11656E-13	Rhenium, in crude ore, in ground	Elementary flows/Resource/in ground
9.26111E-13	Rutile, in ground	Elementary flows/Resource/in ground
2.31282E-08	Sand, unspecified, in ground	Elementary flows/Resource/in ground
7.80457E-10	Shale, in ground	Elementary flows/Resource/in ground
9.68398E-11	Silver, 0.01% in crude ore, in ground	Elementary flows/Resource/in ground
4.04657E-05	Sodium chloride, in ground	Elementary flows/Resource/in ground
5.12674E-07	Sodium sulphate, various forms, in ground	Elementary flows/Resource/in ground
3.76231E-13	Stibnite, in ground	Elementary flows/Resource/in ground
2.17886E-16	Sulfite	Elementary flows/Emission to water/ocean
2.84149E-08	Sulfur, in ground	Elementary flows/Resource/in ground
1.98307E-07	Sylvite, 25 % in sylvinite, in ground	Elementary flows/Resource/in ground
9.05601E-08	Talc, in ground	Elementary flows/Resource/in ground
2.13599E-07	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Elementary flows/Resource/in ground
1.77721E-06	TiO2, 45-60% in Ilmenite, in ground	Elementary flows/Resource/in ground
6.45254E-08	Transformation, from arable	Elementary flows/Resource/land
5.37667E-06	Transformation, from arable, non-irrigated	Elementary flows/Resource/land
1.10868E-08	Transformation, from arable, non-irrigated, fallow	Elementary flows/Resource/land
1.09566E-07	Transformation, from dump site, inert material landfill	Elementary flows/Resource/land
4.13297E-08	Transformation, from dump site, residual material landfill	Elementary flows/Resource/land
3.22712E-09	Transformation, from dump site, sanitary landfill	Elementary flows/Resource/land

6.97036E-10	Transformation, from dump site, slag compartment	Elementary flows/Resource/land
3.23084E-05	Transformation, from forest	Elementary flows/Resource/land
2.40457E-05	Transformation, from forest, extensive	Elementary flows/Resource/land
1.13489E-07	Transformation, from industrial area	Elementary flows/Resource/land
6.41286E-11	Transformation, from industrial area, benthos	Elementary flows/Resource/land
9.12878E-11	Transformation, from industrial area, built up	Elementary flows/Resource/land
1.55726E-10	Transformation, from industrial area, vegetation	Elementary flows/Resource/land
1.79483E-05	Transformation, from mineral extraction site	Elementary flows/Resource/land
1.17534E-06	Transformation, from pasture and meadow	Elementary flows/Resource/land
4.33283E-09	Transformation, from pasture and meadow, intensive	Elementary flows/Resource/land
4.12394E-06	Transformation, from sea and ocean	Elementary flows/Resource/land
1.0343E-06	Transformation, from shrub land, sclerophyllous	Elementary flows/Resource/land
2.32251E-05	Transformation, from unknown	Elementary flows/Resource/land
5.72554E-06	Transformation, to arable	Elementary flows/Resource/land
5.38102E-06	Transformation, to arable, non-irrigated	Elementary flows/Resource/land
1.6582E-06	Transformation, to arable, non-irrigated, fallow	Elementary flows/Resource/land
2.13438E-06	Transformation, to dump site	Elementary flows/Resource/land
4.11052E-06	Transformation, to dump site, benthos	Elementary flows/Resource/land
1.09566E-07	Transformation, to dump site, inert material landfill	Elementary flows/Resource/land
4.13302E-08	Transformation, to dump site, residual material landfill	Elementary flows/Resource/land
3.22712E-09	Transformation, to dump site, sanitary landfill	Elementary flows/Resource/land
6.97036E-10	Transformation, to dump site, slag compartment	Elementary flows/Resource/land
1.07466E-05	Transformation, to forest	Elementary flows/Resource/land
9.73948E-08	Transformation, to forest, intensive	Elementary flows/Resource/land
2.36751E-05	Transformation, to forest, intensive, normal	Elementary flows/Resource/land
1.55885E-06	Transformation, to heterogeneous, agricultural	Elementary flows/Resource/land
3.42311E-06	Transformation, to industrial area	Elementary flows/Resource/land

1.34199E-08	Transformation, to industrial area, benthos	Elementary flows/Resource/land
4.85066E-07	Transformation, to industrial area, built up	Elementary flows/Resource/land
4.99091E-07	Transformation, to industrial area, vegetation	Elementary flows/Resource/land
4.46896E-05	Transformation, to mineral extraction site	Elementary flows/Resource/land
9.98625E-09	Transformation, to pasture and meadow	Elementary flows/Resource/land
3.06844E-08	Transformation, to permanent crop, fruit, intensive	Elementary flows/Resource/land
6.41286E-11	Transformation, to sea and ocean	Elementary flows/Resource/land
1.5482E-07	Transformation, to shrub land, sclerophyllous	Elementary flows/Resource/land
4.05533E-08	Transformation, to traffic area, rail embankment	Elementary flows/Resource/land
4.45751E-08	Transformation, to traffic area, rail network	Elementary flows/Resource/land
2.41826E-07	Transformation, to traffic area, road embankment	Elementary flows/Resource/land
9.38234E-07	Transformation, to traffic area, road network	Elementary flows/Resource/land
7.6031E-06	Transformation, to unknown	Elementary flows/Resource/land
1.38215E-10	Transformation, to urban, discontinuously built	Elementary flows/Resource/land
1.5821E-06	Transformation, to water bodies, artificial	Elementary flows/Resource/land
2.09053E-06	Transformation, to water courses, artificial	Elementary flows/Resource/land
1.55418E-09	Ulexite, in ground	Elementary flows/Resource/in ground
8.48974E-07	Uranium, in ground	Elementary flows/Resource/in ground
7.03765E-08	Vermiculite, in ground	Elementary flows/Resource/in ground
1.75369E-09	Volume occupied, final repository for low-active radioactive waste	Elementary flows/Resource/in ground
3.92179E-10	Volume occupied, final repository for radioactive waste	Elementary flows/Resource/in ground
0.00260652	Volume occupied, reservoir	Elementary flows/Resource/in water
6.2445E-10	Volume occupied, underground deposit	Elementary flows/Resource/in ground
0.000547496	Water, cooling, unspecified natural origin	Elementary flows/Resource/in water
7.38719E-05	Water, lake	Elementary flows/Resource/in water
0.000514358	Water, river	Elementary flows/Resource/in water
0.000037212	Water, salt, ocean	Elementary flows/Resource/in water

1.94638E-05	Water, salt, sole	Elementary flows/Resource/in water
1.42456	Water, turbine use, unspecified natural origin	Elementary flows/Resource/in water
0.00176181	Water, unspecified natural origin	Elementary flows/Resource/in water
0.00026936	Water, well, in ground	Elementary flows/Resource/in water
1.62305E-06	Wood, hard, standing	Elementary flows/Resource/biotic
7.62793E-07	Wood, soft, standing	Elementary flows/Resource/biotic
1.0545E-11	Wood, unspecified, standing	Elementary flows/Resource/biotic
2.38532E-06	Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	Elementary flows/Resource/in ground

4.6 Inputs of cement with microalgae in OpenLCA

Amount	**Flow**	**Category**
8.97851E-05	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Elementary flows/Resource/in ground
1.82397E-10	Anhydrite, in ground	Elementary flows/Resource/in ground
3.60438E-05	Barite, 15% in crude ore, in ground	Elementary flows/Resource/in ground
1.43186E-05	Basalt, in ground	Elementary flows/Resource/in ground
1.18481E-09	Borax, in ground	Elementary flows/Resource/in ground
1	**Calcium**	Elementary flows/Resource/in ground
1.19632	Calcium carbonate, in ground	Elementary flows/Resource/in ground
0.00107178	Carbon dioxide, in air	Elementary flows/Resource/in air
2.66844E-05	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	Elementary flows/Resource/in ground
2.92503E-10	Chrysotile, in ground	Elementary flows/Resource/in ground
2.66767E-11	Cinnabar, in ground	Elementary flows/Resource/in ground
1.15308E-05	Clay, bentonite, in ground	Elementary flows/Resource/in ground
0.448035	Clay, unspecified, in ground	Elementary flows/Resource/in ground
0.00266122	Coal, brown, in ground	Elementary flows/Resource/in ground
0.0118383	Coal, hard, unspecified, in ground	Elementary flows/Resource/in ground
1.18863E-10	Cobalt, in ground	Elementary flows/Resource/in ground
3.81355E-08	Colemanite, in ground	Elementary flows/Resource/in ground

4.44748E-07	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
2.62766E-06	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
8.15074E-07	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
4.04845E-06	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Elementary flows/Resource/in ground
2.97745E-12	Diatomite, in ground	Elementary flows/Resource/in ground
1.30583E-06	Dolomite, in ground	Elementary flows/Resource/in ground
0.0118824	Energy, gross calorific value, in biomass	Elementary flows/Resource/biotic
0.0191378	Energy, kinetic (in wind), converted	Elementary flows/Resource/in air
0.210695	Energy, potential (in hydropower reservoir), converted	Elementary flows/Resource/in water
0.0940721	Energy, primary, from solar energy	Elementary flows/Resource/in air
1.79691E-11	Feldspar, in ground	Elementary flows/Resource/in ground
2.87655E-08	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Elementary flows/Resource/in ground
1.29843E-08	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Elementary flows/Resource/in ground
1.53068E-06	Fluorspar, 92%, in ground	Elementary flows/Resource/in ground
0.000179551	Gas, mine, off-gas, process, coal mining	Elementary flows/Resource/in ground
0.00362769	Gas, natural, in ground	Elementary flows/Resource/in ground
2.60079E-09	Granite, in ground	Elementary flows/Resource/in ground
0.0156604	Gravel, in ground	Elementary flows/Resource/in ground
6.97533E-09	Gypsum, in ground	Elementary flows/Resource/in ground
0.433473	Heat, waste	Elementary flows/Emission to air/low population density
0.000540892	Iron, 46% in ore, 25% in crude ore, in ground	Elementary flows/Resource/in ground
8.24531E-07	Kaolinite, 24% in crude ore, in ground	Elementary flows/Resource/in ground
2.64518E-09	Kieserite, 25% in crude ore, in ground	Elementary flows/Resource/in ground
4.7223E-06	Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore, in ground	Elementary flows/Resource/in ground
1	**lipids**	Elementary flows/Resource/in ground/Lipids
-1.61134E-16	Lithium, 0.15% in brine, in ground	Elementary flows/Resource/in ground
0.000417545	Magnesite, 60% in crude ore, in ground	Elementary flows/Resource/in ground

1	**Magnesium (MA)**	Elementary flows/Resource/in ground
1.60819E-10	Magnesium, 0.13% in water	Elementary flows/Resource/in water
3.97485E-06	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Elementary flows/Resource/in ground
2.02837E-10	Metamorphous rock, graphite containing, in ground	Elementary flows/Resource/in ground
7.52351E-08	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Elementary flows/Resource/in ground
1.07061E-08	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Elementary flows/Resource/in ground
1.39152E-06	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Elementary flows/Resource/in ground
3.35485E-08	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Elementary flows/Resource/in ground
2.80842E-06	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Elementary flows/Resource/in ground
3.609E-07	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Elementary flows/Resource/in ground
5.37015E-05	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Elementary flows/Resource/in ground
-3.36328E-16	Occupation, arable	Elementary flows/Resource/land
2.23518E-06	Occupation, arable, non-irrigated	Elementary flows/Resource/land
1.9628E-06	Occupation, construction site	Elementary flows/Resource/land
7.51566E-05	Occupation, dump site	Elementary flows/Resource/land
2.53782E-06	Occupation, dump site, benthos	Elementary flows/Resource/land
0.000013521	Occupation, forest, intensive	Elementary flows/Resource/land
0.00109474	Occupation, forest, intensive, normal	Elementary flows/Resource/land
0.000166187	Occupation, forest, intensive, short-cycle	Elementary flows/Resource/land
4.64547E-05	Occupation, industrial area	Elementary flows/Resource/land
2.67775E-08	Occupation, industrial area, benthos	Elementary flows/Resource/land
1.88869E-05	Occupation, industrial area, built up	Elementary flows/Resource/land
2.15179E-05	Occupation, industrial area, vegetation	Elementary flows/Resource/land
0.000248873	Occupation, mineral extraction site	Elementary flows/Resource/land
1.17796E-06	Occupation, permanent crop, fruit, intensive	Elementary flows/Resource/land
7.00665E-07	Occupation, shrub land, sclerophyllous	Elementary flows/Resource/land
1.40368E-05	Occupation, traffic area, rail embankment	Elementary flows/Resource/land

1.55216E-05	Occupation, traffic area, rail network	Elementary flows/Resource/land
1.31262E-05	Occupation, traffic area, road embankment	Elementary flows/Resource/land
0.000060453	Occupation, traffic area, road network	Elementary flows/Resource/land
-1.11729E-17	Occupation, urban, continuously built	Elementary flows/Resource/land
5.25226E-09	Occupation, urban, discontinuously built	Elementary flows/Resource/land
7.76036E-05	Occupation, water bodies, artificial	Elementary flows/Resource/land
0.000177474	Occupation, water courses, artificial	Elementary flows/Resource/land
0.0105216	Oil, crude, in ground	Elementary flows/Resource/in ground
9.04492E-11	Olivine, in ground	Elementary flows/Resource/in ground
7.23764E-12	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
1.73933E-11	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground
6.08631E-08	Peat, in ground	Elementary flows/Resource/biotic
1	Phosphorus	Elementary flows/Emission to air/high population density
1.15062E-07	**Phosphorus (MA)**, 18% in apatite, 4% in crude ore, in ground	Elementary flows/Resource/in ground
7.29393E-08	Phosphorus, 18% in apatite, 12% in crude ore, in ground	Elementary flows/Resource/in ground
1	**Potassium**	Elementary flows/Resource/in ground
3.7912E-13	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground
1.35911E-12	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
1.63647E-13	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Elementary flows/Resource/in ground
5.12561E-13	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Elementary flows/Resource/in ground
3.32596E-13	Rhenium, in crude ore, in ground	Elementary flows/Resource/in ground
7.7881E-13	Rutile, in ground	Elementary flows/Resource/in ground
9.97152E-08	Sand, unspecified, in ground	Elementary flows/Resource/in ground
5.17171E-10	Shale, in ground	Elementary flows/Resource/in ground
1.23171E-10	Silver, 0.01% in crude ore, in ground	Elementary flows/Resource/in ground
2.75277E-05	Sodium chloride, in ground	Elementary flows/Resource/in ground
2.29028E-07	Sodium sulphate, various forms, in ground	Elementary flows/Resource/in ground

3.09422E-13	Stibnite, in ground	Elementary flows/Resource/in ground
2.08741E-16	Sulfite	Elementary flows/Emission to water/ocean
6.03302E-08	Sulfur, in ground	Elementary flows/Resource/in ground
1.75333E-07	Sylvite, 25 % in sylvinite, in ground	Elementary flows/Resource/in ground
8.61788E-08	Talc, in ground	Elementary flows/Resource/in ground
2.13024E-07	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Elementary flows/Resource/in ground
1.07613E-06	TiO2, 45-60% in Ilmenite, in ground	Elementary flows/Resource/in ground
6.1984E-08	Transformation, from arable	Elementary flows/Resource/land
4.11439E-06	Transformation, from arable, non-irrigated	Elementary flows/Resource/land
1.8948E-08	Transformation, from arable, non-irrigated, fallow	Elementary flows/Resource/land
1.02156E-07	Transformation, from dump site, inert material landfill	Elementary flows/Resource/land
3.4394E-08	Transformation, from dump site, residual material landfill	Elementary flows/Resource/land
2.89052E-09	Transformation, from dump site, sanitary landfill	Elementary flows/Resource/land
6.37241E-10	Transformation, from dump site, slag compartment	Elementary flows/Resource/land
0.000017142	Transformation, from forest	Elementary flows/Resource/land
8.29483E-06	Transformation, from forest, extensive	Elementary flows/Resource/land
1.00583E-07	Transformation, from industrial area	Elementary flows/Resource/land
1.21372E-10	Transformation, from industrial area, benthos	Elementary flows/Resource/land
9.26558E-11	Transformation, from industrial area, built up	Elementary flows/Resource/land
9.07058E-11	Transformation, from industrial area, vegetation	Elementary flows/Resource/land
1.67492E-05	Transformation, from mineral extraction site	Elementary flows/Resource/land
1.14715E-06	Transformation, from pasture and meadow	Elementary flows/Resource/land
3.31553E-09	Transformation, from pasture and meadow, intensive	Elementary flows/Resource/land
2.54968E-06	Transformation, from sea and ocean	Elementary flows/Resource/land
1.00003E-06	Transformation, from shrub land, sclerophyllous	Elementary flows/Resource/land
2.52226E-05	Transformation, from unknown	Elementary flows/Resource/land
4.66004E-06	Transformation, to arable	Elementary flows/Resource/land

4.11773E-06	Transformation, to arable, non-irrigated	Elementary flows/Resource/land
1.65782E-06	Transformation, to arable, non-irrigated, fallow	Elementary flows/Resource/land
5.97084E-07	Transformation, to dump site	Elementary flows/Resource/land
2.53782E-06	Transformation, to dump site, benthos	Elementary flows/Resource/land
1.02156E-07	Transformation, to dump site, inert material landfill	Elementary flows/Resource/land
3.43944E-08	Transformation, to dump site, residual material landfill	Elementary flows/Resource/land
2.89052E-09	Transformation, to dump site, sanitary landfill	Elementary flows/Resource/land
6.37241E-10	Transformation, to dump site, slag compartment	Elementary flows/Resource/land
1.06534E-05	Transformation, to forest	Elementary flows/Resource/land
9.00752E-08	Transformation, to forest, intensive	Elementary flows/Resource/land
8.09571E-06	Transformation, to forest, intensive, normal	Elementary flows/Resource/land
8.32655E-06	Transformation, to forest, intensive, short-cycle	Elementary flows/Resource/land
5.12931E-07	Transformation, to heterogeneous, agricultural	Elementary flows/Resource/land
8.69469E-07	Transformation, to industrial area	Elementary flows/Resource/land
1.18777E-08	Transformation, to industrial area, benthos	Elementary flows/Resource/land
4.17848E-07	Transformation, to industrial area, built up	Elementary flows/Resource/land
4.48498E-07	Transformation, to industrial area, vegetation	Elementary flows/Resource/land
2.87734E-05	Transformation, to mineral extraction site	Elementary flows/Resource/land
1.29292E-08	Transformation, to pasture and meadow	Elementary flows/Resource/land
1.92316E-08	Transformation, to permanent crop, fruit, intensive	Elementary flows/Resource/land
1.05899E-10	Transformation, to sea and ocean	Elementary flows/Resource/land
1.40078E-07	Transformation, to shrub land, sclerophyllous	Elementary flows/Resource/land
3.26625E-08	Transformation, to traffic area, rail embankment	Elementary flows/Resource/land
3.59069E-08	Transformation, to traffic area, rail network	Elementary flows/Resource/land
8.66118E-08	Transformation, to traffic area, road embankment	Elementary flows/Resource/land
7.85027E-07	Transformation, to traffic area, road network	Elementary flows/Resource/land
7.58475E-06	Transformation, to unknown	Elementary flows/Resource/land

1.04622E-10	Transformation, to urban, discontinuously built	Elementary flows/Resource/land
1.39769E-06	Transformation, to water bodies, artificial	Elementary flows/Resource/land
2.04161E-06	Transformation, to water courses, artificial	Elementary flows/Resource/land
9.27901E-09	Ulexite, in ground	Elementary flows/Resource/in ground
7.67595E-07	Uranium, in ground	Elementary flows/Resource/in ground
6.74227E-08	Vermiculite, in ground	Elementary flows/Resource/in ground
1.58338E-09	Volume occupied, final repository for low-active radioactive waste	Elementary flows/Resource/in ground
3.49604E-10	Volume occupied, final repository for radioactive waste	Elementary flows/Resource/in ground
0.00261533	Volume occupied, reservoir	Elementary flows/Resource/in water
4.85699E-10	Volume occupied, underground deposit	Elementary flows/Resource/in ground
0.000294487	Water, cooling, unspecified natural origin	Elementary flows/Resource/in water
7.07797E-05	Water, lake	Elementary flows/Resource/in water
0.000459599	Water, river	Elementary flows/Resource/in water
0.000030558	Water, salt, ocean	Elementary flows/Resource/in water
6.27499E-06	Water, salt, sole	Elementary flows/Resource/in water
1.39228	Water, turbine use, unspecified natural origin	Elementary flows/Resource/in water
0.00168462	Water, unspecified natural origin	Elementary flows/Resource/in water
0.000209898	Water, well, in ground	Elementary flows/Resource/in water
3.94678E-07	Wood, hard, standing	Elementary flows/Resource/biotic
7.41754E-07	Wood, soft, standing	Elementary flows/Resource/biotic
1.85061E-11	Wood, unspecified, standing	Elementary flows/Resource/biotic
9.96973E-13	Xenon, in air	Elementary flows/Resource/in air
1.96869E-06	Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	Elementary flows/Resource/in ground

CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Introduction

In this chapter conclusion and recommendations have been given. These conclusions and recommendations have been derived from literature review and all the experimental work that has taken place and afterwards some recommendations have been given in the end for further development of MCM in field of construction. Some outcomes are stated in below sections.

5.2 Manufacturing Process

5.2.1 Preparing the Materials

The standard practices which are used for selecting sand for CM was also used for selecting sand for MCM. The aggregates were in saturated surface dry condition.

5.2.2 Curing

Two types of curing were carried out. The MCM batches were dry cured for 24 hours at 60 C in an incubator. After that they were taken out of the incubator and placed in the lab for ambient curing for 7 days, after which all the tests on that batch took place.

For both MCM ambient curing was adopted to study the effects of ambient curing on MCM. For this the specimens were left for curing in the lab at ambient conditions for 7 days after which the relevant tests were performed.

5.3 Conclusions

Based on literature review and experimental work performed on MCM following conclusions were drawn:

- **MCM** with 10% M_A has **more** compressive strength than OPCM
- **MCM** with 20% M_A has **less** compressive strength than MCM with 10% M_A
- Cement with microalgae exhibits **negative** eutrophication which means nutrients which pollute water are being removed.

- Cement with microalgae has **less** GWP than ordinary cement.
- From cost analysis, cement with microalgae is **30%** cheaper than cement with limestone.

5.4 Recommendations

After the conduct of research following recommendation were proposed:

- Further research needs to be carried out to find the short- and long-term effects of water curing on MCM.
- Due to non-availability of resources, it was not possible to practically verify the production of cement by incorporating microalgae.
- To promote the usage of MCM, it is necessary to promote and facilitate the production of biogenic limestone.
- Further research is necessary to find out the application of MCM in other fields of construction.

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