VALORIZATION OF DEMOLITION CONCRETE FOR POST-COMBUSTION CARBON CAPTURE

by
Talal Abdulrazzak Al Raas

Submitted to Graduate School of Natural and Applied Sciences
in Partial Fulfillment of the Requirements
for the Degree of Master of Science in
Materials and Nanotechnology Engineering

Yeditepe University
2023

VALORIZATION OF DEMOLITION CONCRETE FOR POST-COMBUSTION CARBON CAPTURE

APPROVED BY:

Assoc. Prof. Dr. Ahmet Turan ……
(Supervisor)
(Yeditepe University)

Asst. Prof. Dr. Z. Cansu Canbek Özdil
(Co-Supervisor)
(Yeditepe University)

Asst. Prof. Dr. Hatice Kübra Akben ……
(Yeditepe University)

Assoc. Prof. Dr. Mehmet Şeref Sönmez ……
(Istanbul Technical University)

DATE OF APPROVAL: …./…./……

I hereby declare that this thesis is my own work and that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I have fully cited and referenced all material and results as required by these rules and conduct, and this thesis study does not contain any plagiarism. If any material used in the thesis requires copyright, the necessary permissions have been obtained. No material from this thesis has been used for the award of another degree.

I accept all kinds of legal liability that may arise in case contrary to these situations.

Name, Last name Talal Abdul Razzak Al Raas

Signature …..…….……..

ACKNOWLEDGEMENTS

It is with immense gratitude that I acknowledge the support and help of my Assoc. Prof. Dr. Ahmet Turan. Pursuing my thesis under his supervision has been an experience that broadens the mind and presents an unlimited source of learning.

I thank Asst. Prof. Dr. Z. Cansu Canbek Ozdil for their continuous support. I thank Prof. Shareq Mohd for his help regarding CO_2 capture analysis at KTH Royale University in Sweden. I thank Prof Murat Alkan for his help in the XRD analysis in Izmir. I thank Kagan and Selcuk from ITU for their help in my grinding and sieve analysis for my materials. I thank Azer Vurkir for his help in taking the SEM images for my samples.

I also thank Umay Çinarli and İlayda Özbağ for their help throughout my thesis at Yeditepe University.

Finally, I would like to thank my family for their endless love and support, making everything more beautiful.

ABSTRACT

VALORIZATION OF DEMOLITION CONCRETE FOR POST-COMBUSTION CARBON CAPTURE

In this thesis, the potential use of demolition concrete was examined as a post-combustion carbon capture material. This study's main objective was to use demolished concrete, which is typically regarded as waste and has an adverse effect on the environment, to adsorb carbon dioxide. This research intends to contribute to the reduction of these emissions by creating sustainable techniques of carbon capture in light of the rising levels of carbon dioxide emissions and their detrimental effects on the environment. Concrete is a cementitious substance with a high calcium and silicate content, making it a great substance for carbon capture. Two leaching techniques, acidic and alkaline, were used to the concrete samples to extract the resultant materials, which were then utilized to investigate the potential of destroyed concrete for carbon capture. The materials were subsequently employed for carbon capture studies at the KTH Royal Institute of Technology in Sweden utilizing thermogravimetric analysis (TGA). The trials' findings illustrate how successful demolition concrete is at absorbing carbon dioxide, with the acidic leached material performing best. Additionally, the material's cation release was assessed, and it was determined to be safe for the aquatic environment. These findings have important ramifications for the creation of ecologically responsible and sustainable carbon capture and storage methods.

ÖZET

YANMA SONRASI KARBON YAKALAMA İÇİN YIKIM BETONUNUN DEĞERLENDİRİLMESİ

Bu tezde, yanma sonrası karbon yakalama malzemesi olarak yıkım betonunun potansiyel kullanımı incelenmiştir. Bu çalışmanın ana amacı, tipik olarak atık olarak kabul edilen ve çevre üzerinde olumsuz etkisi olan yıkım betonunun karbondioksiti adsorplamak için kullanılmasıdır. Bu araştırma, artan karbondioksit emisyon seviyeleri ve çevre üzerindeki zararlı etkileri ışığında sürdürülebilir karbon yakalama teknikleri oluşturarak bu emisyonların azaltılmasına katkıda bulunmayı amaçlamaktadır. Beton, yüksek kalsiyum ve silikat içeriğine sahip çimentodan üretilen bir yapı malzemesidir ve bu da onu karbon tutma için önemli bir malzeme yapmaktadır. İlgili adsorbentlerin üretimi için beton numunelerine asidik ve alkali olmak üzere iki liç tekniği uygulanmıştır ve elde edilen adsorbentler daha sonra yıkım betonunun karbon yakalama potansiyelini araştırmak için kullanılmıştır. Üretilen adsorbentler daha sonra İsveç'teki KTH Kraliyet Teknoloji Enstitüsünde termogravimetrik analiz (TGA) ile karbon yakalama çalışmaları için kullanılmıştır. Deneysel sonuçlar, yıkım betonunun karbondioksiti yakalamada başarılı olduğunu ve asidik liç ile üretilmiş malzemenin en iyi performansı karbon yakalama performansını gösterdiğini kanıtlamıştır. Ayrıca deneysel çalışmalarda üretilen malzemelerin deniz suyu ortamında katyon salınımı da değerlendirilmiş ve deniz suyu ortamında dolgu malzemesi olarak kullanılabilecekleri de belirlenmiştir. Bu tez çalışmasında elde edilen bulguların, ekolojik ve sürdürülebilir karbon yakalama ve depolama yöntemlerinin geliştirilmesine destek olabilecek nitelikte olduğu kanaati oluşmuştur.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

ITU	Istanbul Technical University
DC	Demolition concrete
TGA	Thermogravimetric analysis
ICP-MS	Inductively coupled plasma mass spectrometry
SEM	Scanning electron microscopy
RCA	Recycled concrete aggregate
GHG	Green house gases
IPCC	Intergovernmental panel on climate change
CCUS	Carbon capture, usage and storage
CCS	Carbon capture storage
EOR	Enhanced oil recovery
DAC	Direct air capture
XRD	X-Ray crystallography
EDX	Energy dispersive x-ray
DI	Distilled water
TPP	Temperature, pressure and phase
R	Raw demolition concrete
A	Arabic gum

1. INTRODUCTION

Concrete is one of the most often utilized construction materials in the world because of its adaptability, strength, and durability. Cement, aggregates, and water make up the majority of the chemical components of concrete, which has been used in building for generations. In recent years, as the world's population has continued to rise and urbanization has expanded more widely, concrete manufacturing has grown dramatically [1,2].

However, there are certain environmental effects associated with the manufacture of concrete. The world's present carbon dioxide issue has been considerably exacerbated by the rising amount of carbon dioxide (CO_2) emissions brought on by the creation of concrete. In response, there has been an increase in interest in figuring out how to lessen the carbon footprint of producing concrete, and carbon capture is one viable strategy [1], [2].

The technique of capturing and storing carbon dioxide emissions from industrial activities so they don't reach the atmosphere is referred to as carbon capture. Because of its capacity to collect and store carbon dioxide through the use of different composites, concrete is a potential material for carbon capture. Concrete that can collect and store carbon dioxide by mineral carbonation must contain calcium-based materials, particularly calcium silicate hydrates [3].

A potential strategy that might greatly reduce the carbon footprint of concrete manufacturing is the use of concrete for carbon capture as opposed to alternative disposal techniques, such as dumping or recycling. Additionally, as concrete may offer a strong and long-lasting foundation without endangering the aquatic ecosystem, it has been thought of as a way to lessen the environmental effect of ocean building operations [3].

Therefore, the purpose of this thesis was to research the possibilities of employing concrete as a carbon capture medium and the function that silicates and calcium-based content play in this process. In order to shed light on the possible advantages of these uses, the thesis also evaluated the environmental effect of utilizing concrete to absorb carbon dioxide and as a marine filler [3].

2. PROPERTIES OF CONCRETE

2.1. BACKGROUND

Concrete is a versatile and often used building material made of cement, water, coarse aggregates (like gravel or crushed stone), and fine aggregates (like sand), Figure 2.1 shows the process of production for cement and concrete. These elements are combined to generate a paste, which hardens over time and fuses the aggregates to form a sturdy and long-lasting substance [4].

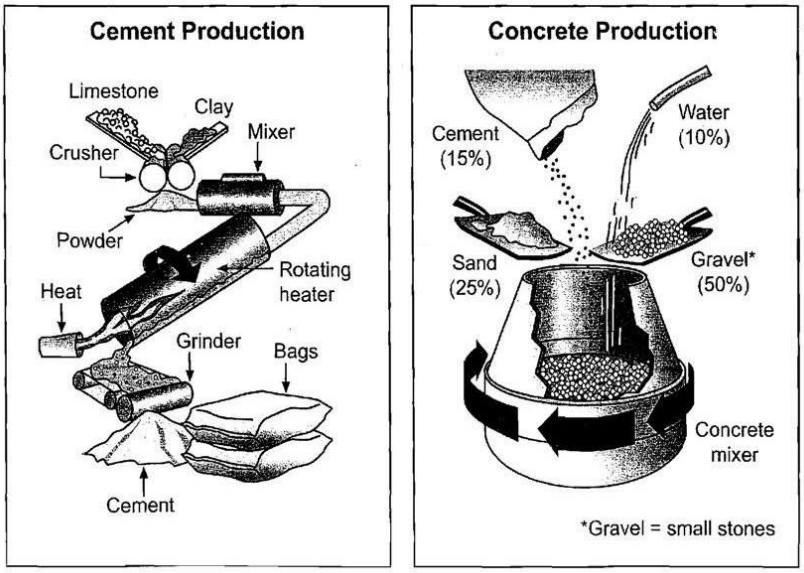


Figure 2.1. The production process of cement and concrete [5]

Concrete's compressive strength, or the highest weight it can support without breaking under compression, is one of its most important characteristics. The kind and quantity of cement used, the water-cement ratio, and the size and distribution of the aggregates can all have an impact on the strength of concrete [6,7].

Durability, or the capacity to withstand damage and degradation over time owing to environmental variables such freeze-thaw cycles, exposure to chemicals or moisture, and abrasion, is another crucial quality of concrete. Concrete's durability may be increased by using the right mix design, the right curing procedures, and the use of admixtures or additives like fly ash or silica fume [7].

Aside from its workability, which refers to how easily it can be mixed, transported, and poured into forms, concrete also has a setting time, which refers to how long it takes for the concrete to become stiff and begin to harden. Additionally, concrete may be given various surface treatments, such as smooth or textured surfaces, and it can be dyed or stained to provide a particular aesthetic result [7,8].

Overall, concrete's qualities make it a flexible and often utilized material in the building sector. Because of its versatility, strength, and workability, it may be used for everything from bridges and roads to constructing foundations and walls. Ongoing research is also looking into methods to improve the qualities of concrete, including by adding new components or enhancing its sustainability and environmental effect [9].

2.2. THE CLASSIFICATION OF CONCRETE MATERIALS

Concrete materials may be categorized according to a number of factors, including composition, structure, and purpose. Based on their main components, concrete materials can be categorized in a variety of ways. The most popular form of concrete is created using Portland cement, which serves as the binding agent. Figure 2.2 shows different types of concrete materials depending on the purpose. Aluminates, ferrites, calcium silicates, and other minerals make up Portland cement. Calcium hydroxide (CH) crystals and calcium silicate hydrates (C-S-H) are produced when water is added to Portland cement, a process known as hydration. Portland cement concrete's main binding component, C-S-H, gives the material its strength and longevity. Since Portland cement concrete is readily available, inexpensive, and simple to use, it is frequently utilized in construction [10,11].

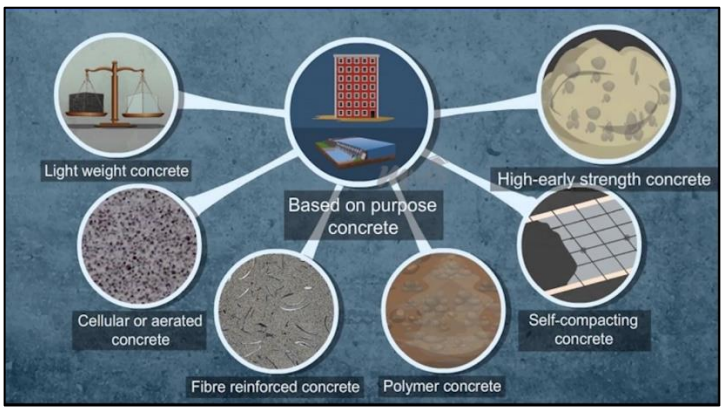


Figure 2.2. Different types of concrete materials [12]

A more recent form of concrete called geopolymer concrete is created by alkali-activating elements like fly ash, slag, or other industrial wastes as shown in Figure 2.3. An alkaline solution and a source material, like fly ash or slag, react at high temperatures to create geopolymers. This reaction creates a three-dimensional polymeric network with characteristics akin to Portland cement concrete. In comparison to Portland cement concrete, geopolymer concrete provides a number of benefits, including greater strength, less permeability, and a less carbon impact. Additionally more resistant to acid and sulfate assault, geopolymer concrete is suited for hostile settings [13].

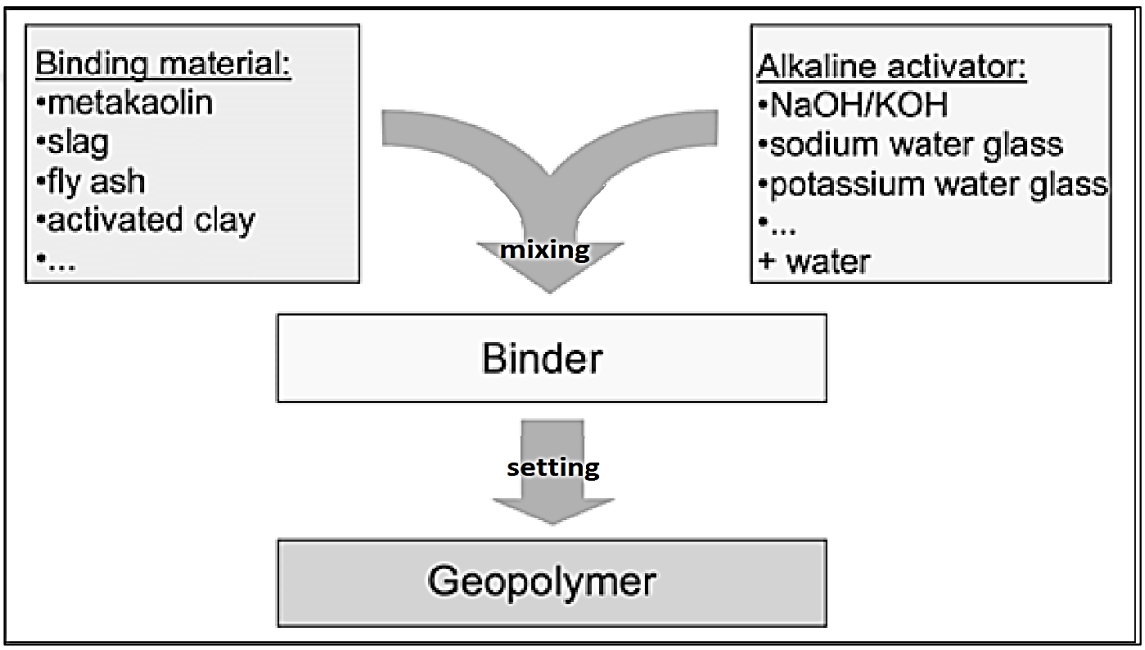


Figure 2.3. Geopolymer concrete production [14]

Based on their density, concrete materials are divided into various categories that are crucial. Lightweight aggregates like expanded clay, shale, or perlite are used to create lightweight concrete. Low density concrete produced by the use of lightweight aggregates provides a number of benefits, including less dead load, greater insulating qualities, and increased seismic resistance. When weight reduction is crucial, such as in high-rise structures, bridges, and tunnels, lightweight concrete is employed. On the other side, high-strength concrete is intended to have more compressive strength than regular concrete. Low water-cement ratio, increased cement content, and occasionally additional admixtures like fly ash or silica fume are used to create high-strength concrete. When a high compressive strength is needed, such in towering structures, high-strength concrete is chosen [4,7].

There are various different types of concrete materials that are created to adhere to particular performance specifications in addition to the categories mentioned above. Concrete that self-consolidates is made to flow and fill intricate forms without the need of vibration. High flowability, viscosity, and stability work together to provide concrete that self-consolidates the ability. To increase the tensile strength and toughness of concrete, fibers composed of steel, polypropylene, or glass are used in fiber-reinforced concrete. Concrete can take greater loading and impact pressures because to the inclusion of fibers, which also increases concrete's durability and fracture resistance. Finally, there are special concretes that are created to satisfy certain building needs, such as shotcrete, pervious concrete, and underwater concrete [7].

Concrete technology's classification of concrete materials is crucial because it enables engineers and construction professionals to choose the best type of concrete for a particular application based on the application's qualities and performance criteria. Builders may improve their design and building procedures to achieve the highest possible performance and durability by studying the features and traits of various types of concrete. Additionally, the creation of novel concrete materials keeps expanding the realm of what is practical in building, opening the door to future sustainable and effective construction techniques [8].

2.3. CALCIUM BASED MATERIALS IN CONCRETE/CEMENT

Concrete and cement are mostly made of calcium-based elements. They are in charge of giving the finished product strength, setting, and hardening. Portland cement, which is created by heating a combination of limestone and clay or shale to around 1450°C, is the calcium-based component of concrete that is most often employed. The calcium carbonate in the limestone breaks down during this process to produce calcium oxide, which then combines with the other components to create the different cement-making compounds, such as tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite [15,16].

Concrete's strength and durability are greatly influenced by calcium-based compounds. The dry combination of cement and aggregates undergoes a chemical process called hydration when water is introduced, which results in the development of a solid mass. Figure 4 shows the concretes hydration. This solid mass, often referred to as hardened concrete, is incredibly

strong and resilient and can withstand a variety of environmental factors. Concrete's strength and durability are influenced in diverse ways by the numerous compounds that are created during the hydration process. For instance, tricalcium silicate is in charge of the early strength of concrete, but dicalcium silicate is involved in the strength and durability over the long term [17,18].

The large carbon footprint of calcium-based compounds in concrete is one of its drawbacks. One of the major causes of climate change, Portland cement manufacture is responsible for around 7% of the world's CO_2 emissions. Figure 2.4 shows the global CO_2 emissions from cement production from 1928-2018. To solve this problem, scientists are looking at alternate calcium-based material sources, such as slag and fly ash from industrial waste. The quantity of CO_2 emissions related to the manufacturing of concrete can be decreased by using these materials in place of Portland cement on a partial basis [15,16].

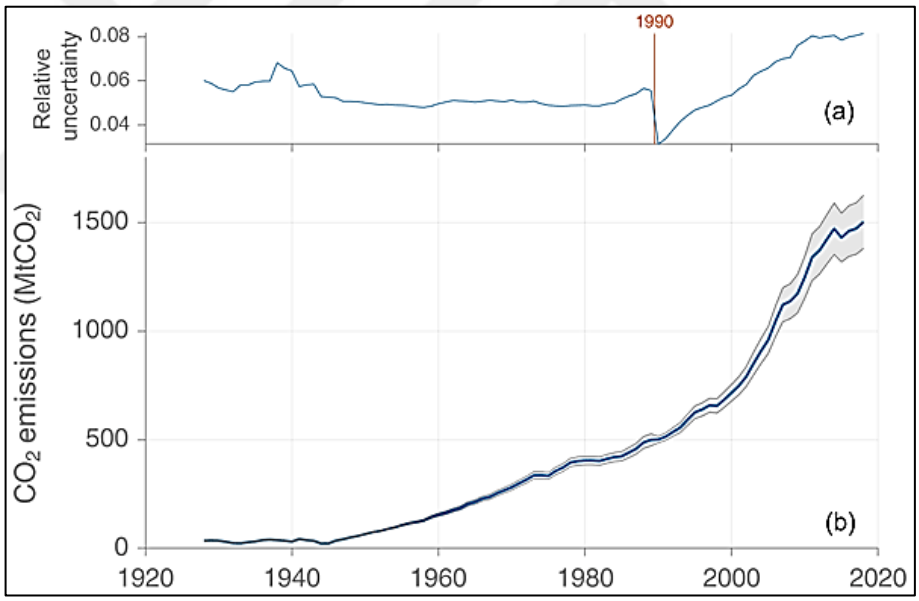


Figure 2.4. Global CO2 emissions from cement production from 1928-2018 [19]

Overall, calcium-based minerals provide cement and concrete their strength and durability, which is why these materials are so valuable in building. Although their manufacture has a substantial carbon footprint, attempts are being done to create more environmentally friendly substitutes that can help lessen the effect of these materials [20].

2.4. CRYSTAL STRUCTURE

Concrete's crystal structure is a key factor in defining its mechanical characteristics and durability. Cement, aggregates, and water are just a few of the components that make up the composite substance known as concrete. The strength and stiffness of concrete are because of the crystal structure of cement, which serves as the binder ingredient [21].

Alite, belite, tricalcium aluminate, and tetracalcium aluminoferrite are only a few of the minerals that make up the crystal structure of cement. The two most significant minerals, alite and belite, make up around 80% of the total mineral composition of cement. Calcium, silicon, oxygen, and aluminum form the hexagonal-shaped crystal structure of alite. Calcium, silicon, and oxygen make up the monoclinic crystal structure of belite, on the other hand [7,21].

Cement's reaction with water and how strong it gets over time are both governed by its crystal structure. Calcium silicate hydrate and calcium hydroxide are two examples of the new compounds that are created when cement is combined with water in a process known as hydration. The longevity and strength of concrete are a result of these substances [7,21].

The strength, durability, and workability of concrete are substantially influenced by the crystal structure of the aggregates. Concrete's mechanical qualities are improved by crushed stones with high strength and precise shapes. On the other hand, lightweight aggregates with a porous structure lessen the density of concrete, making it appropriate for situations where weight is an issue. Shrinkage, creep, and chemical resistance are a few more qualities influenced by the structural makeup of aggregates. For concrete to perform and last as desired, aggregates must be properly chosen and assessed based on their crystal structure and qualities [7,21].

The qualities and performance of concrete are largely governed by the crystal structure of its constituent parts. It is now feasible to develop and make more enduring and long-lasting concrete materials because of our improved understanding of the crystal structure of concrete. This understanding ultimately has the potential to result in the creation of new and enhanced concrete goods that provide higher functionality and durability [6].

2.5. LIFE CYCLE ASSESSMENT OF CONCRETE

Ecology is significantly impacted by the extensively used building material concrete. Several environmental problems are a result of its production, use, and disposal. Depending on its quality, location, and upkeep, concrete can last a long time or very little time. But the typical lifespan of a concrete building is between 30 and 100 years as shown in Figure 2.5 [22].

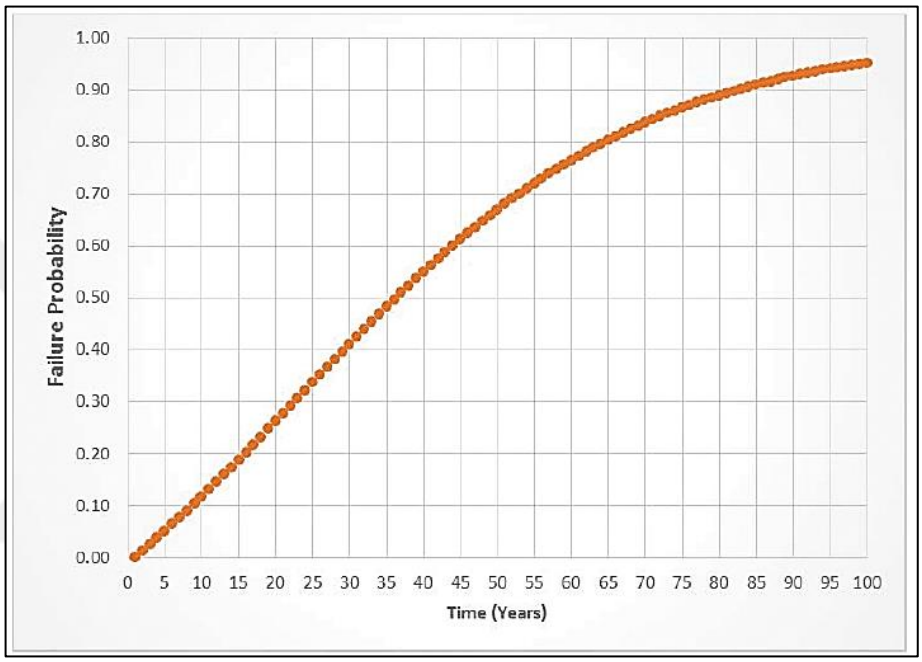


Figure 2.5. Life span of concrete [23]

A concrete construction must be appropriately disposed of once its useful life is through. Concrete is a heavy and clumsy substance, making disposal difficult. Concrete used to be simply destroyed and dumped (Figure 2.6), which might have an adverse effect on the environment. Hazardous chemicals are released into the soil and groundwater when concrete breaks down. Along with taking up valuable landfill space, the abundance of concrete trash also has the potential to boost greenhouse gas emissions [22].

Figure 2.6. Concrete dumps [24]

More sustainable methods of disposing of concrete have been sought in order to overcome these problems. Recycling concrete scrap is one approach. For usage as a foundation material in brand-new building projects, concrete can be broken down into smaller pieces. Using already-existing materials not only saves energy and resources but also lessens the amount of garbage that ends up in landfills [25].

Waste from the production of concrete can also be reused. Road bases, erosion control materials, and aggregate for fresh concrete can all be made from crushed concrete. This may offer a more economical and ecologically responsible way to dispose of unwanted concrete. Reusing concrete debris can also lessen the requirement for new materials, which can aid in resource conservation [25].

Cement manufacture, a vital component of concrete, also contributes significantly to carbon dioxide emissions. Around 7% of the world's carbon dioxide emissions are attributed to cement production, primarily as a result of the chemical reaction known as calcination that takes place during the manufacturing process. In order to create cement clinker, which is subsequently crushed to a fine powder and combined with water and aggregates to create concrete, this process includes heating limestone and other materials at extremely high temperatures [26].

Diverse initiatives to create more environmentally friendly alternatives to conventional concrete production methods are in progress as a response to these environmental concerns. Use of other materials as partial substitutes for cement, such as fly ash, slag, and other waste products, is one strategy. Utilizing carbon capture and storage (CCS) technologies is another strategy for capturing carbon dioxide emissions from industrial processes such as cement production [27].

Efforts are being undertaken to increase the lifespan of concrete structures in addition to minimizing the environmental effect of concrete manufacture. Despite the fact that concrete is renowned for its strength and lifespan, after time it may still degrade and need to be repaired or replaced. This causes problems with trash and disposal in addition to using more energy and resources [22].

In order to address this, researchers are looking at ways to improve the resilience and durability of concrete buildings, including the use of novel mix designs, additives, and surface coatings. Regular maintenance, inspection, and repair can also serve to increase the lifespan of existing concrete structures and lessen the need for expensive replacements [22].

Overall, the extraction and transportation of raw materials, waste disposal, and emissions all have an effect on the environment over the life cycle of concrete. Through innovation and maintenance techniques, efforts are being made to create production processes that are more environmentally friendly and to increase the lifespan of concrete structures. The building sector may reduce its environmental effect and help create a more sustainable future by tackling these concerns [28].

In addition, the manufacture of cement, a crucial component of concrete, contributes significantly to greenhouse gas emissions. About 7% of the world's carbon dioxide emissions come from cement production. There have been initiatives to lessen the carbon footprint of concrete manufacturing in order to solve this problem. Utilizing substitute materials for cement production, such as fly ash, blast furnace slag, and rice husk ash, is one strategy. Compared to conventional cement components, these compounds have a smaller carbon impact and can increase the toughness of concrete [28].

Concrete might be utilized for carbon capture as an alternative strategy to decrease its environmental impact. Concrete can carbonate to absorb carbon dioxide from the air, according to studies. During this process, the concrete takes in carbon dioxide, which reacts

with calcium molecules to form calcium carbonate. Calcium carbonate is a stable mineral that becomes trapped in concrete. Concrete may be made more durable and ecologically friendly via the carbonation process by lowering the amount of carbon dioxide in the atmosphere [28].

In conclusion, the production, use, and disposal of concrete has a significant detrimental effect on the environment. There have been attempts made to find more ecologically friendly ways to dispose of surplus concrete and reduce the carbon footprint of concrete production in an effort to mitigate these consequences (Figure 2.7). These attempts include making cement from alternative materials, using concrete to trap carbon, and recycling and reusing concrete debris. By employing these methods, concrete may become a more sustainable and environmentally friendly building material [22,27,28].

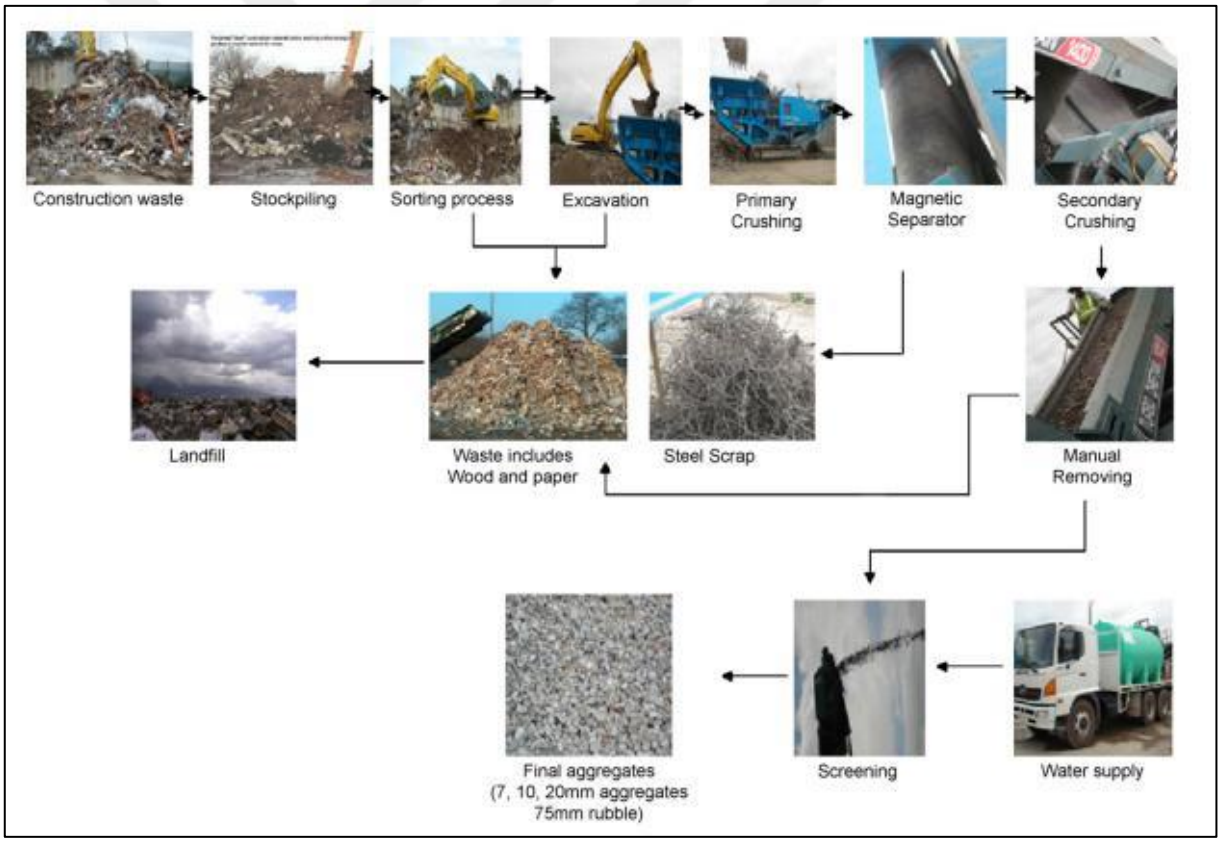


Figure 2.7. Concrete recycling method [29]

2.6. FACTS AND FIGURES ON CONCRETE MARKET

The worldwide market for concrete is a sector that is booming and has been growing significantly in recent years. Zion Market Research assessed the worldwide market for concrete to be worth USD 365.2 billion in 2019 (Figure 2.8). From 2020 to 2027, this market is expected to grow at a CAGR of 5.6%, reaching USD 562.1 billion. Urbanization, population growth, and the need for infrastructure expansion are some of the factors propelling the sector [30,31].

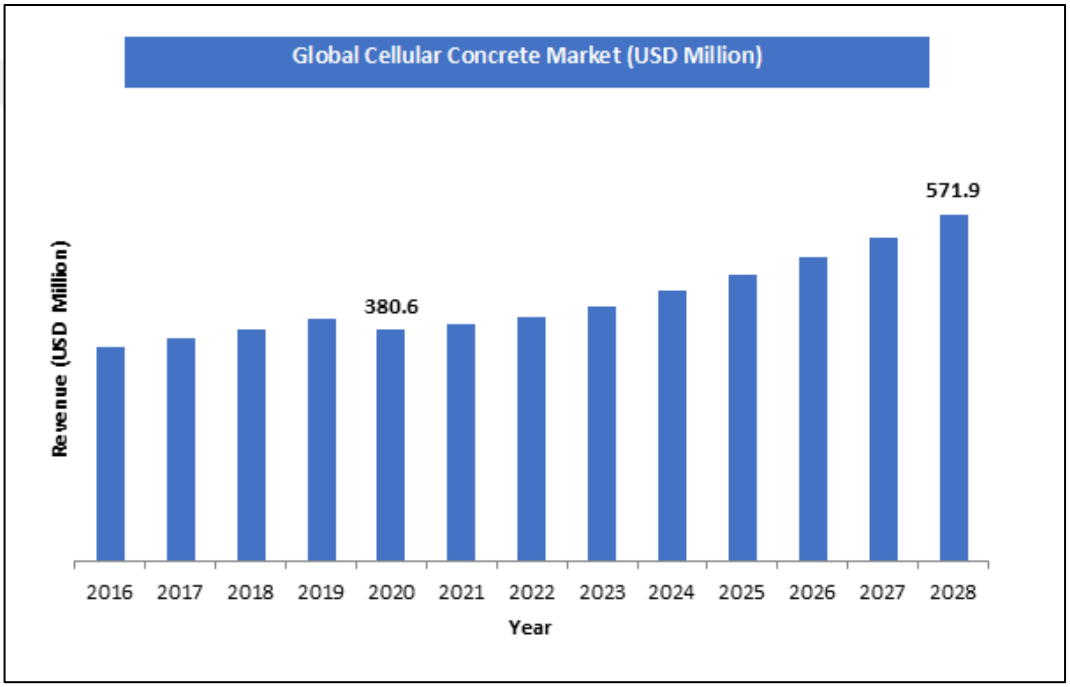


Figure 2.8. ZION market research revenue [32]

More than 80% of the world's need for concrete is met by the building industry, which is also its largest consumer. The construction of infrastructure projects including roads, bridges, tunnels, and airports is what primarily drives the global demand for concrete. Environmentally friendly concrete is now more in demand as green building techniques and sustainable building materials gain popularity (Figure 2.9) [33].

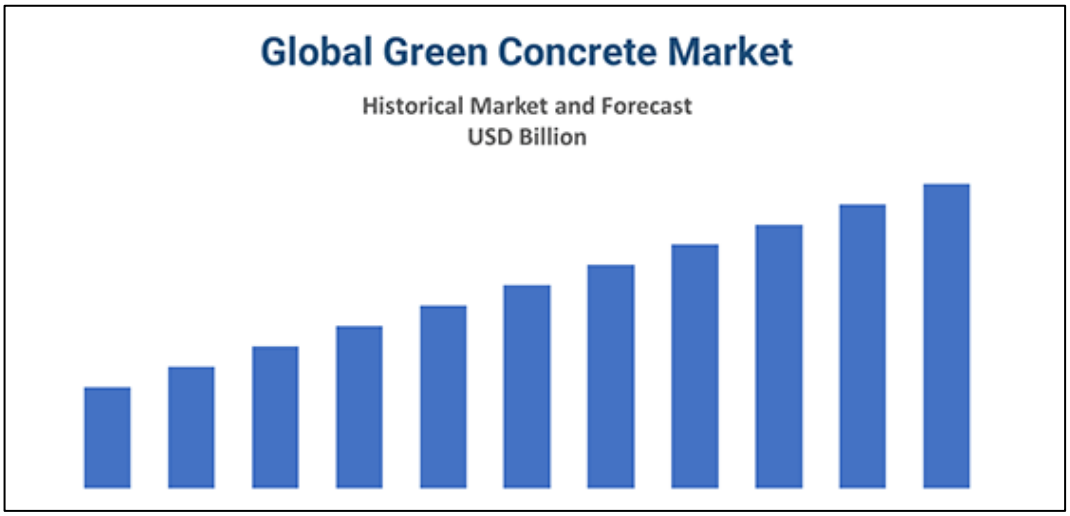


Figure 2.9. The global green concrete market reached a value of about USD 6.31 billion in 2022. The market is further expected to grow at a CAGR of about 10.6% in the forecast period of 2023-2028 to reach a value of around USD 11.45 billion by 2028 [34]

Over 50% of the world's demand for concrete is accounted for by the Asia-Pacific region. Rapid urbanization, population growth, and economic expansion in the area have increased demand for infrastructure and building projects. With more than 60% of the overall consumption in the Asia Pacific area, China is the world's biggest user of concrete (Figure 2.10) [35].

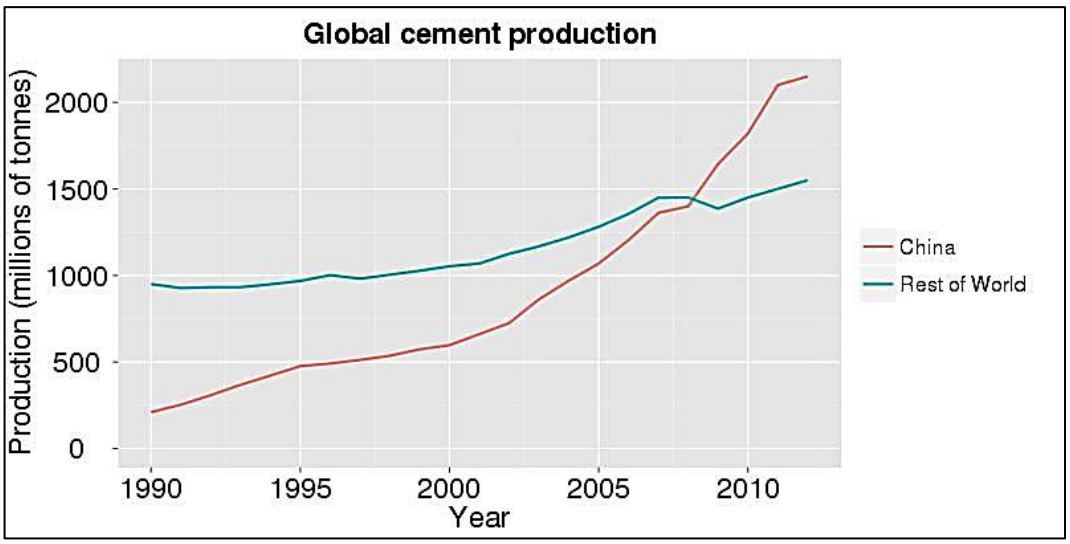


Figure 2.10. China's cement consumption [36]

The major users of concrete in both of these areas, North America and Europe, respectively, are the United States and Germany. Construction of office and residential buildings

dominates the North American industry, whilst infrastructure projects including highways, bridges, and tunnels dominate the European market [31].

The worldwide concrete business is extremely cutthroat, with a few major competitors controlling the sector. LafargeHolcim, HeidelbergCement AG, CRH plc, CEMEX SAB de CV, Buzzi Unicem S.p.A., Vicat SA, UltraTech Cement Limited, China National Building Material Company Limited, and Eurocement Holding AG are some of the key competitors [35].

The market for specialty concrete goods, such as self-compacting concrete, high-performance concrete, and precast concrete products, is expanding in addition to the standard concrete market. These specialist materials are frequently employed in high-profile building projects like airports, stadiums, and skyscrapers because they outperform and last longer than conventional concrete [37].

Cement production's enormous carbon footprint, which contributes to around 7% of the world's carbon dioxide emissions, is one issue the concrete sector must address. Through the use of eco-friendly methods and resources in place of fossil fuels, it is being tried to lessen the carbon footprint of cement production [33,38].

In conclusion, the need for infrastructure and building projects is a major factor in the growth of the worldwide concrete market. In the upcoming years, the industry is anticipated to keep expanding, with the Asia Pacific region having the largest and fastest-growing market. The industry does, however, confront concerns with sustainability and the influence on the environment, and attempts are being made to solve these problems by utilizing sustainable and eco-friendly procedures [39].

3. CLIMATE CHANGE AND CCUS TECHNOLOGIES

3.1. CLIMATE CHANGE

Long-term changes in temperature and weather that have happened in recent decades are referred to as climate change. The burning of fossil fuels and deforestation, both of which emit greenhouse gases like carbon dioxide and methane into the atmosphere, are the main human activities that are responsible for these changes (Figure 3.1) [40].

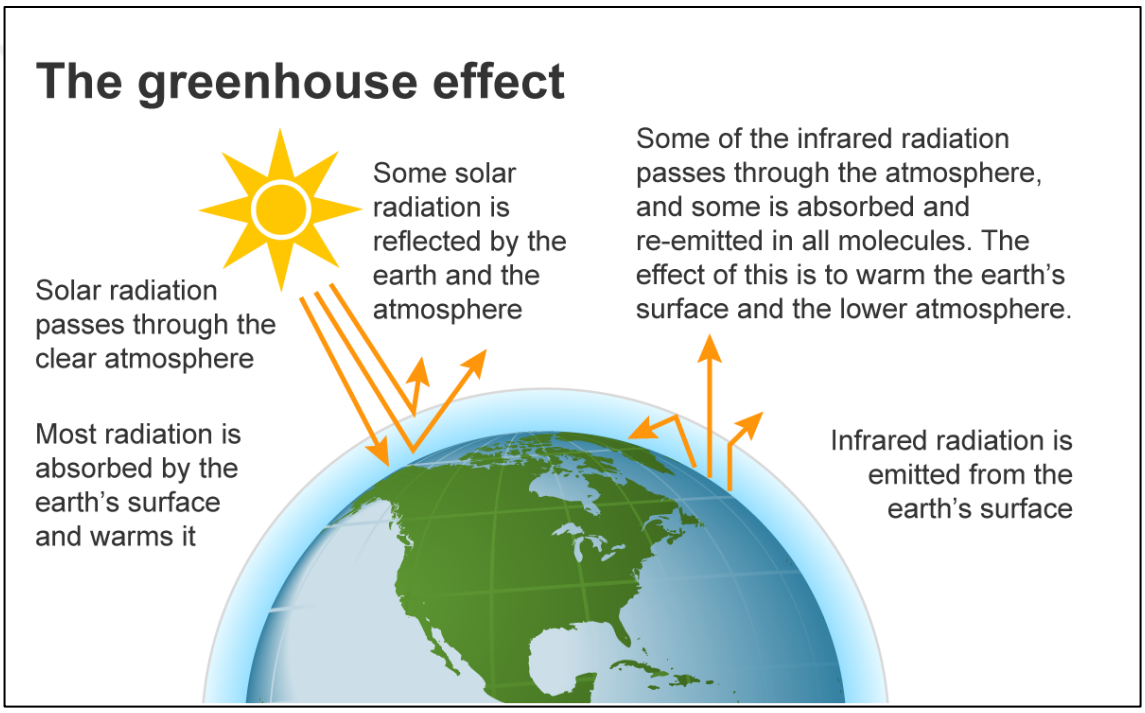


Figure 3.1. The greenhouse gas effect [41]

The public is already aware of many of the consequences that scientists have long anticipated will result from climate change. Global temperatures rising is one of the most obvious repercussions. Since the beginning of the industrial revolution, the average global temperature has risen by roughly 1 degree Celsius; if we don't take action, it is predicted to rise another 1.5 degrees by the end of the century (Figure 3.2) [42].

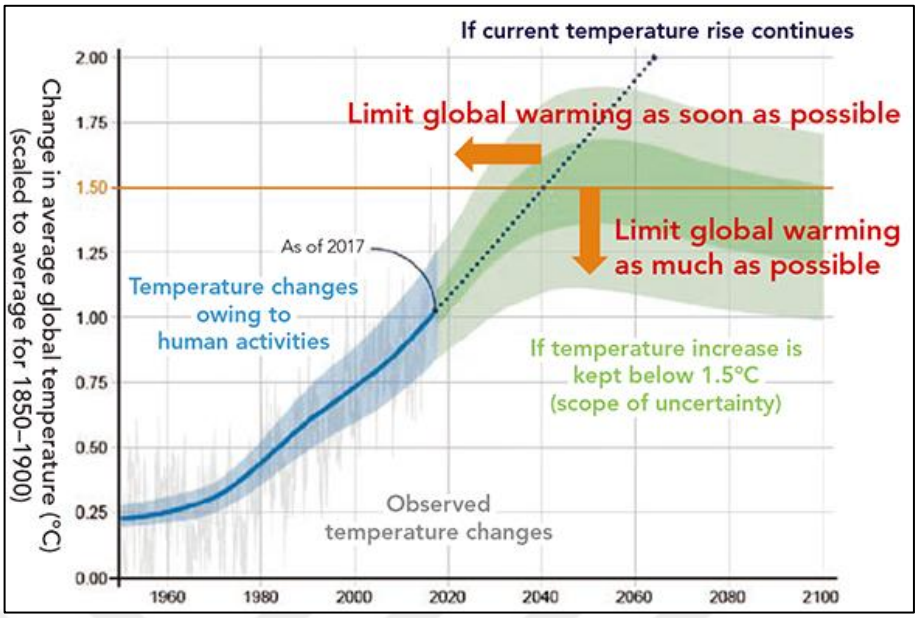


Figure 3.2. Temperature increase by 1.5 °C expectancy [43]

Numerous effects of this temperature increase include more frequent and intense heatwaves, modifications to precipitation patterns, and rising sea levels (Figure 3.3). Heat waves may be harmful to people's health, especially if they affect weaker demographics like the elderly and young children. A lack of food may result from droughts and floods brought on by changes in precipitation patterns, which can impact agriculture. Flooding, coastal erosion, and the eviction of residents of low-lying regions are all consequences of rising sea levels [40,44].

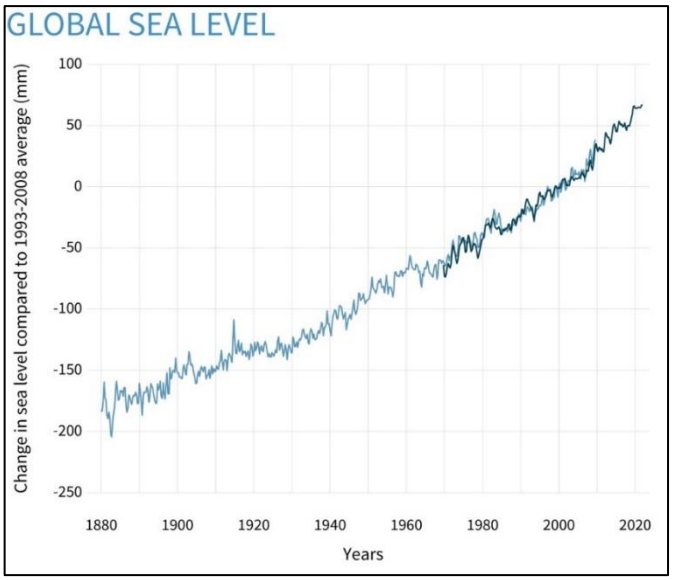


Figure 3.3. Global sea level [45]

In addition to these direct effects, climate change may make already-existing environmental and socioeconomic problems worse. By changing the habitats of creatures that transmit illnesses, for instance, it can help spread disease. Conflict over scarce resources like food and water may also develop, which may lead to the eviction of residents from their homes [46,47].

A number of initiatives have been taken to address the issue of climate change on a global, national, and local basis. Goals for limiting global warming to 1.5 degrees Celsius over pre-industrial levels and far below 2 degrees are outlined in the historic Paris Agreement (Figure 3.4), which was signed in 2015. Goals for reducing greenhouse gas emissions have been set by several countries, and initiatives to support renewable energy and energy efficiency have already been put in place [40,46,47].

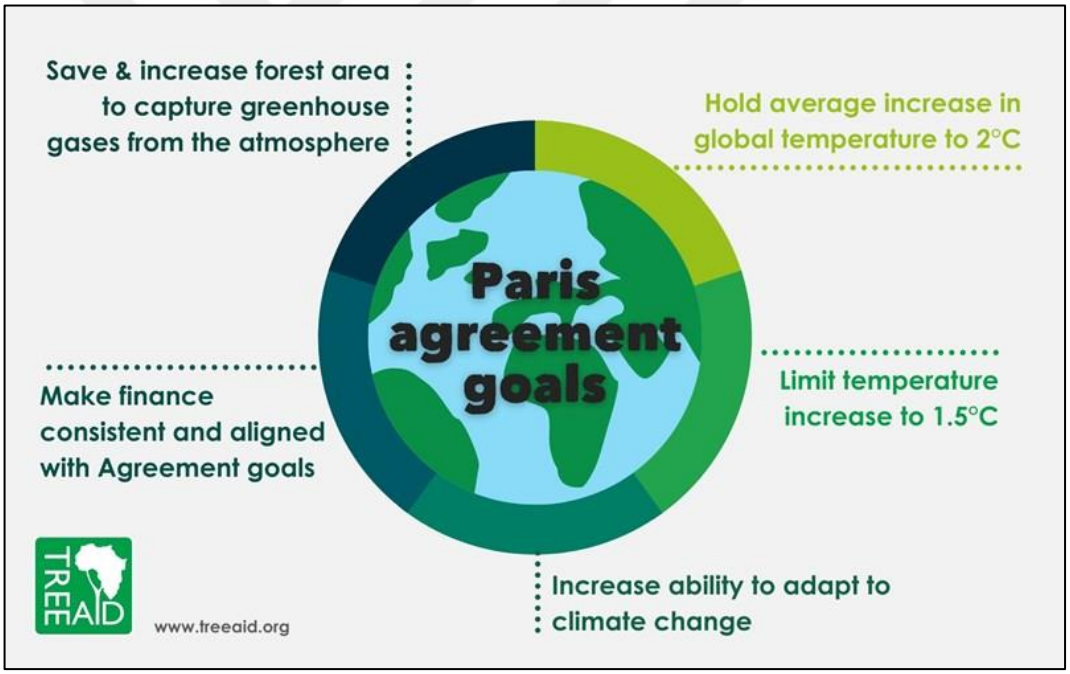


Figure 3.4. Paris agreement goals [48]

The problem of climate change still requires more effort to be done, despite achievements. We must transition to a more robust and resilient civilization while keeping our emissions of greenhouse gases low. Our infrastructure for transportation, land usage, and energy will thus need to undergo considerable modifications. But preventing climate change has advantages as well, such as bettering general health, boosting economic stability, and creating a society that is more just and equitable [40,42].

3.2. GREENHOUSE GASES

Greenhouse gases are essential elements of the Earth's atmosphere because they control the planet's temperature and uphold favorable conditions for life. However, the burning of fossil fuels and other human activities have significantly increased the atmospheric concentration of greenhouse gases, altering the Earth's climate system [49].

The main greenhouse gas causing climate change brought on by humans is carbon dioxide (CO_2). The amount of CO_2 in the atmosphere has increased at an unheard-of rate as a result of human activities including the burning of fossil fuels for electricity and transportation, deforestation, and industrial operations. The atmospheric CO_2 content has grown by around 40% since pre-industrial times, the Intergovernmental Panel on Climate Change (IPCC) claims, and in 2015 it exceeded 400 parts per million (ppm) (Figure 3.5) [50].

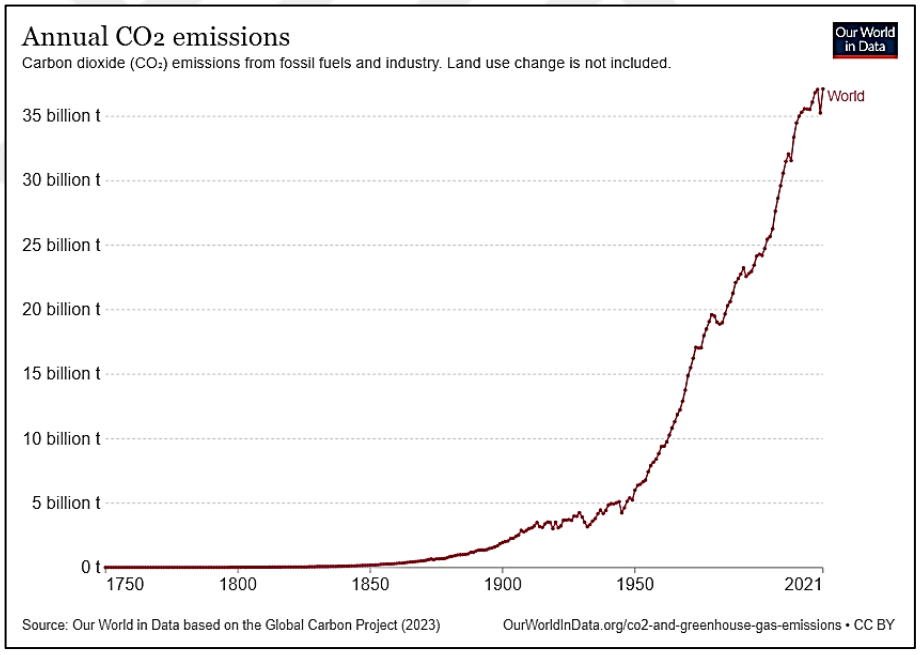


Figure 3.5. Annual CO2 emissions from fossil fuels [51]

Methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases) are additional greenhouse gases that contribute to climate change. Methane is a strong greenhouse gas with a potential for 28 times more global warming than CO_2 over a 100-year horizon. Numerous natural and man-made processes, such as the raising of livestock, landfills, and the extraction of oil and gas, emit methane. Nitrous oxide, which is largely released during industrial and

agricultural processes, has a 265-fold larger global warming potential than CO_2 over a 100-year time horizon [49].

Because they control the planet's temperature and uphold favorable conditions for life, greenhouse gases are essential elements of the Earth's atmosphere. However, the burning of fossil fuels and other human activities have significantly increased the atmospheric concentration of greenhouse gases, altering the Earth's climate system [46].

In order to solve the greenhouse gas issue, international action is required to limit emissions connected to human activities. Increasing energy efficiency and promoting environmentally friendly transportation are essential to reducing emissions from other industries and agriculture. It is necessary to use more renewable energy. The amount of greenhouse gases generated might be significantly decreased by implementing carbon pricing laws and using low-carbon technology [46,47].

Taking everything into account, the serious problem of greenhouse gas emissions causing climate change necessitates an immediate reaction. The worst consequences of climate change may be avoided and the environment preserved for future generations if greenhouse gas emissions are reduced and sustainable practices are promoted [46].

3.3. MITIGATION OF GREENHOUSE GASES

The process of reducing or stopping the atmospheric emissions of greenhouse gases is known as mitigation of greenhouse gases. There are several methods for reducing greenhouse gas emissions, such as enhancing energy efficiency, switching to renewable energy sources, enhancing agricultural practices, and carbon capture and storage. Figure 3.6 shows the principles of mitigation of GHGs emission. The use of public transportation is encouraged as well as the improvement of building insulation and the swapping out of inefficient equipment for more energy-efficient models. By taking these actions, greenhouse gas emissions can be decreased since less resources are required to run houses and businesses [52].

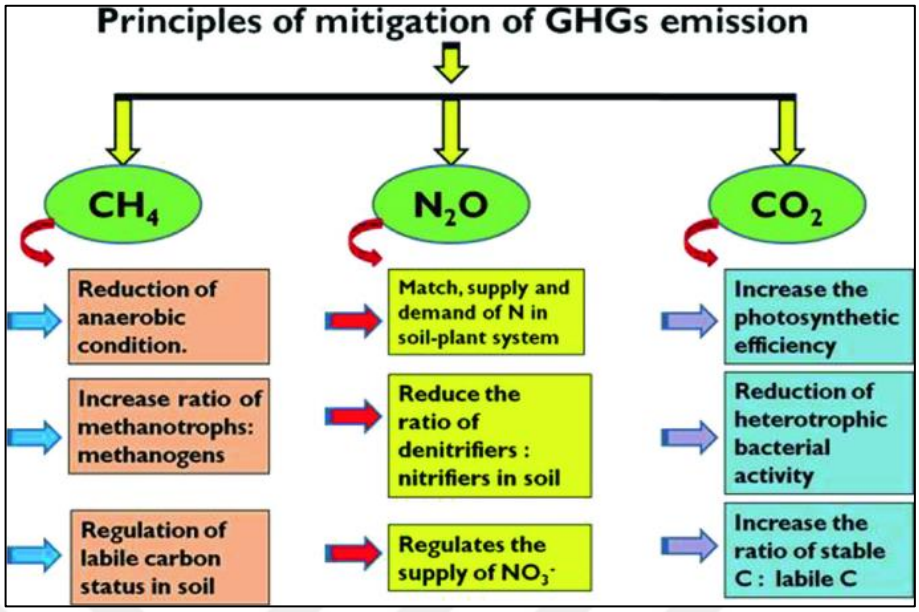


Figure 3.6. Principles of mitigation of GHGs emission [53]

One of the most significant strategies for reducing greenhouse gas emissions is the transition to renewable energy sources like hydropower, solar, and wind. The quantity of carbon dioxide and other greenhouse gases released into the atmosphere can be decreased by burning fewer fossil fuels. Renewable energy sources support economic growth and employment creation in addition to lowering emissions [54].

Enhancing agricultural techniques is crucial for reducing greenhouse gas emissions. For instance, lowering the quantity of fertilizer used in agriculture can lower nitrous oxide emissions, a strong greenhouse gas. Furthermore, environmentally friendly farming methods like crop rotation and conservation tillage can boost soil carbon absorption, lowering greenhouse gas emissions even further [54].

A method known as carbon capture and storage (CCS) collects carbon dioxide emissions from factories, power stations, and other industrial operations and stores them underground. Figure 3.7 shows CCS. CCS has the potential to drastically cut greenhouse gas emissions from some of the biggest sources even though it is still in the early phases of research and implementation [54].

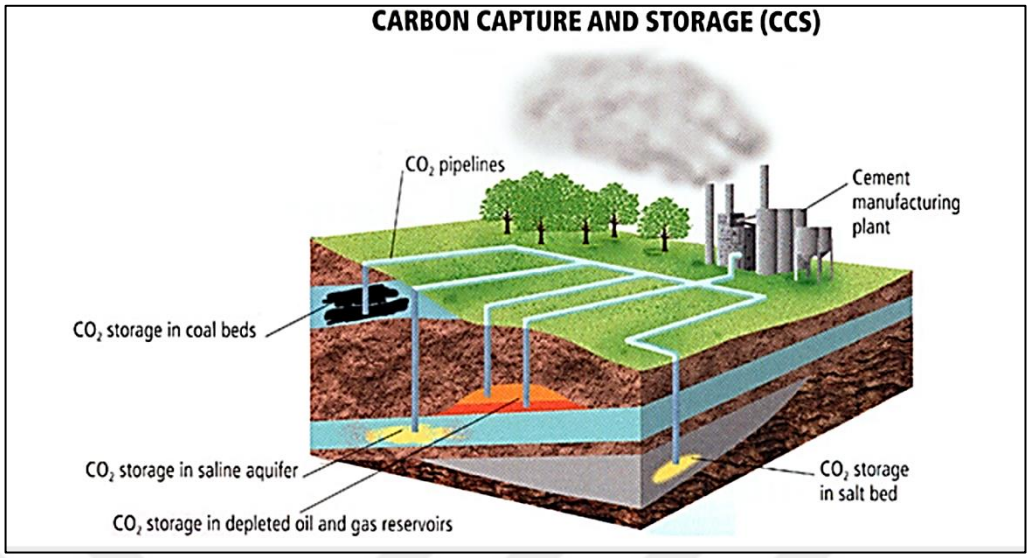


Figure 3.7. CCUS [55]

In order to solve the issue of climate change, greenhouse gas mitigation must be prioritized. We must take action to lessen or halt the production of these gases in order to assist in reducing the severity of global warming and its effects on the environment and society. To put it another way, we can make a big difference in the fight against climate change and its negative impacts by taking steps to avoid or reduce greenhouse gas emissions [52,54].

3.4. CCUS (CARBON CAPTURE, UTILIZATION AND STORAGE)

Carbon capture, utilization, and storage (CCUS) refers to a group of technologies and procedures created to address the problem of lowering greenhouse gas emissions, primarily carbon dioxide (CO_2), and lessening the effects of climate change. The main goal of CCUS is to collect CO_2 from industrial sources, stop it from being released into the environment, store it safely underground, or use it for a variety of advantageous uses. We may be able to significantly lower CO_2 emissions while sustaining economic growth and promoting sustainable development by utilizing CCUS technology [56].

Carbon capture, which entails taking CO_2 from emission sources including power plants, cement plants, and industrial facilities, is an essential initial step in the CCUS procedure. Figure 3.8 shows the global greenhouse gas emissions by sector. There are several capture systems used, each adapted to certain emission sources and environmental factors. Post-combustion capture, which involves capturing CO_2 from flue gases after the fuel has burnt,

is one extensively utilized technique. Before CO_2 is separated and captured, synthesis gas (syngas) is created from fossil fuels as part of pre-combustion capture. Another strategy is oxy-fuel combustion, which involves burning fuel in an oxygen-rich atmosphere to produce a stream of flue gas that is primarily made up of CO_2. These capture systems make it possible to separate CO_2 from other flue gases, making it easier to store or use it later [56].

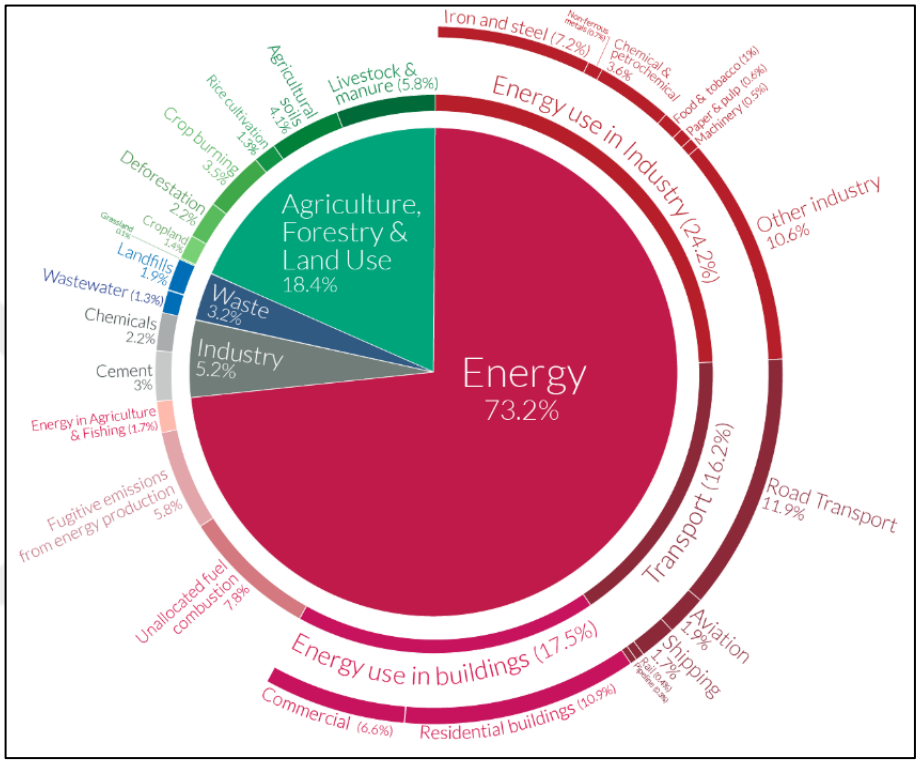


Figure 3.8. The global greenhouse gas emissions by sector (2020) [57]

The process of using collected CO_2 after it has been caught involves either turning it into useful goods or using it in a variety of industrial activities. Utilizing CO_2 offers a chance to increase economic value while lowering emissions. Enhanced oil recovery (EOR), where collected CO_2 is injected into oil reservoirs to boost oil output, is one typical use of CO_2 usage. In this procedure, the CO_2 is pumped into the oil, mixing with it to reduce its viscosity and aid in its extraction. EOR not only aids in boosting oil production but also offers a way to permanently store the CO_2 that is caught below. EOR is a desirable choice for CCUS deployment because it offers the twin advantages of higher oil production and CO_2 storage [56].

There are other ways to use CO_2 in addition to EOR. Chemicals, polymers, and construction materials may all be made using CO_2. As an example, CO_2 may be chemically changed into

methanol, a flexible fuel and feedstock for several chemical processes. Additionally, CO_2 may be utilized as a starting point for the synthesis of carbonates, which are used to make cement, concrete, and other building materials. We cut emissions while also advancing the idea of carbon capture and usage as a sustainable strategy by adding CO_2 into these items [56].

Carbon storage, also known as carbon sequestration, is the last phase in the CCUS process. In order to permanently store the CO_2 that has been extracted, it is necessary to inject it far down into geological formations. Saline aquifers, exhausted oil, and gas fields, and unmineable coal seams are a few examples of these formations. These geological reserves firmly hold the injected CO_2, limiting its escape into the atmosphere. To guarantee the integrity and safety of the storage locations, careful site selection, monitoring, and verification protocols are essential. This lessens the chance of leakage and any possible negative effects on the environment [58].

Particularly in industries that are difficult to totally decarbonize, such heavy industry and fossil fuel-based power generation, CCUS technologies hold tremendous promise for reducing climate change. By collecting and storing CO_2 emissions or using them, CCUS offers a method to significantly reduce emissions while promoting economic expansion and employment development. It also provides flexibility in regulating emissions from existing infrastructure and aids in the transition to a low-carbon energy system [58,59].

3.4.1. Carbon capture methods

Post-combustion capture (Figure 3.9) is one common approach for capturing carbon. This method involves capturing CO_2 from the flue gases released after the burning of fossil fuels in power plants or industrial sites. Once reaching a suitable storage location, such as deep underground geological formations, the captured CO_2 is compressed and transferred there to be kept there permanently. Technologies for post-combustion capture have been widely used, particularly in coal-fired power stations, and have demonstrated a great potential to lower CO_2 emissions [60,61].

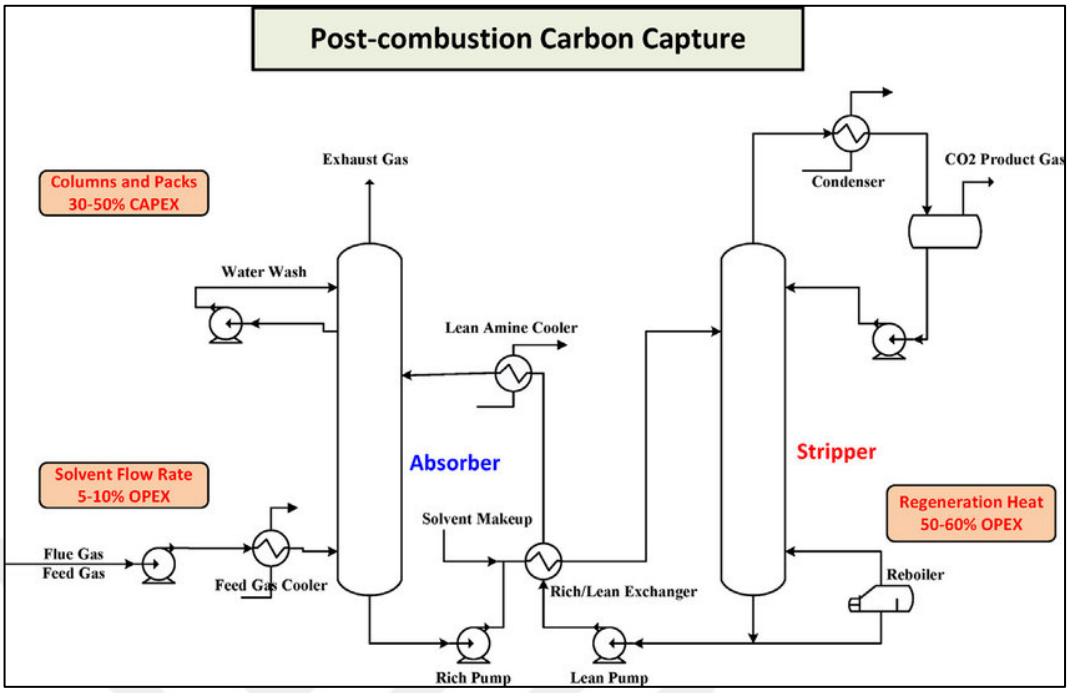


Figure 3.9. Post combustion carbon capture [62]

In a separate strategy known as pre-combustion capture (Figure 3.10), fossil fuels are gasified or reformatted to produce a mixture of CO_2 and hydrogen. Following hydrogen separation, the CO_2 is collected for usage or storage. Pre-combustion capture offers the advantage of providing a fuel rich in hydrogen that may be used for a range of applications, such as transportation or power generation, while simultaneously capturing CO_2 emissions before they are released into the environment [63,64].

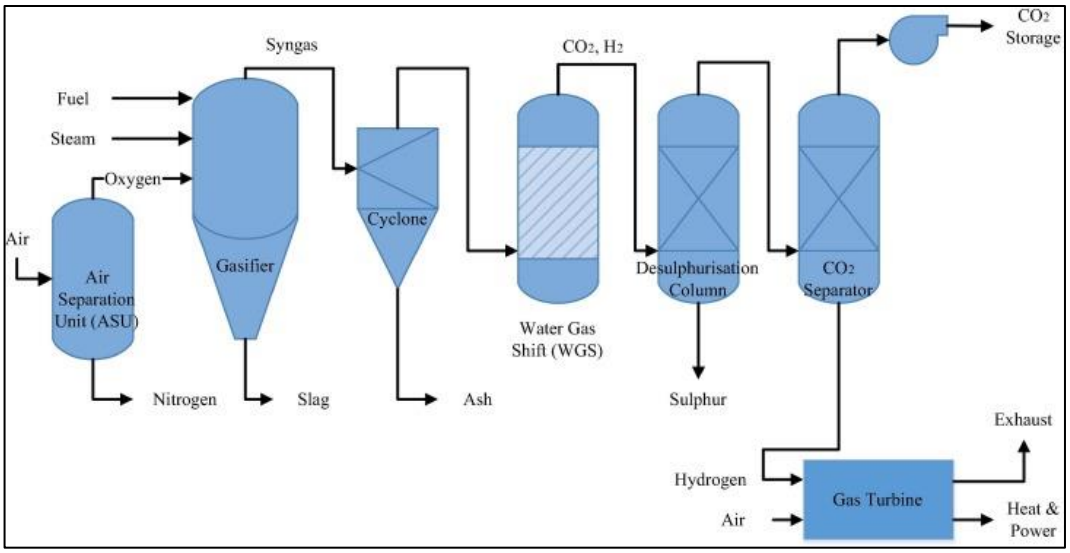


Figure 3.10. Pre-combustion carbon capture [65]

Another method of carbon capture uses oxy-fuel combustion (Figure 3.11), which burns fossil fuels in an environment of just pure oxygen as opposed to air. This produces a flue gas stream that is predominantly made up of CO_2 and water vapor, which makes the collection process easier. The CO_2 that has been caught can be compressed, moved, and stored underground or employed in commercial operations like improved oil recovery. Particularly useful for industrial and power plant retrofits are oxy-fuel combustion systems [58,63].

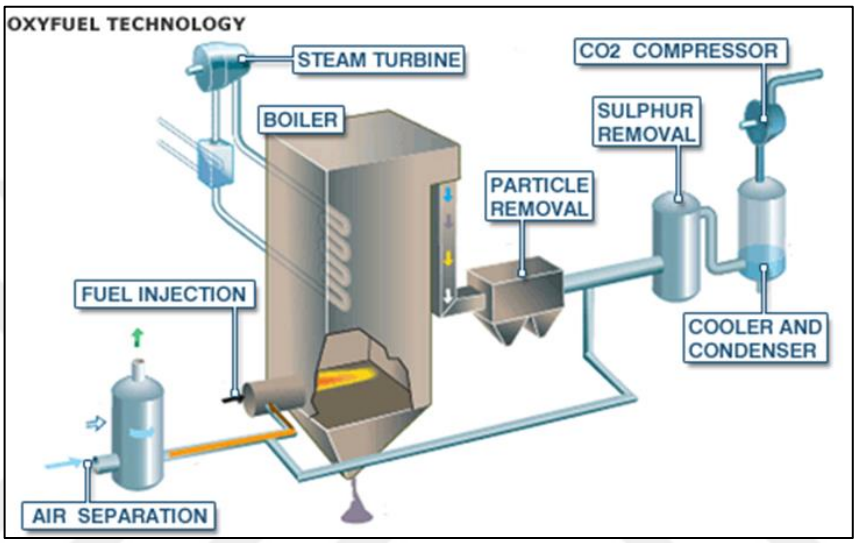


Figure 3.11. Oxyfuel-Combustion process [66]

Using specialized technology, direct air capture (DAC) (Figure 3.12) is a technique for taking CO_2 straight out of the air. These systems use physical adsorption or chemical processes to capture CO_2 that can then be used, stored, or both. Its ability to absorb CO_2 from a variety of sources, including diffuse emissions, makes DAC a potentially useful instrument for reaching negative emissions [58,63].

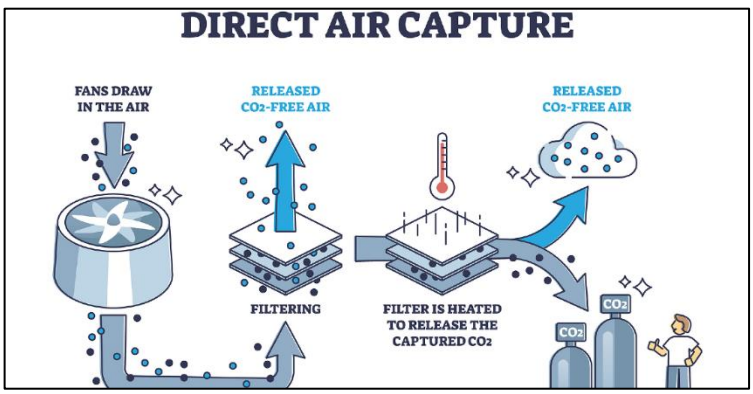


Figure 3.12.: Direct air capture [67]

In order to collect CO_2 from the atmosphere and store it in biomass or biochar, biological carbon capture (Figure 3.13) relies on natural processes like photosynthesis in plants and algae. Initiatives for planting and replanting trees, as well as the adoption of sustainable agriculture methods, support biological carbon capture. By improving soil fertility and conserving biodiversity, this strategy not only collects CO_2 but also offers other environmental advantages [58,63,68].

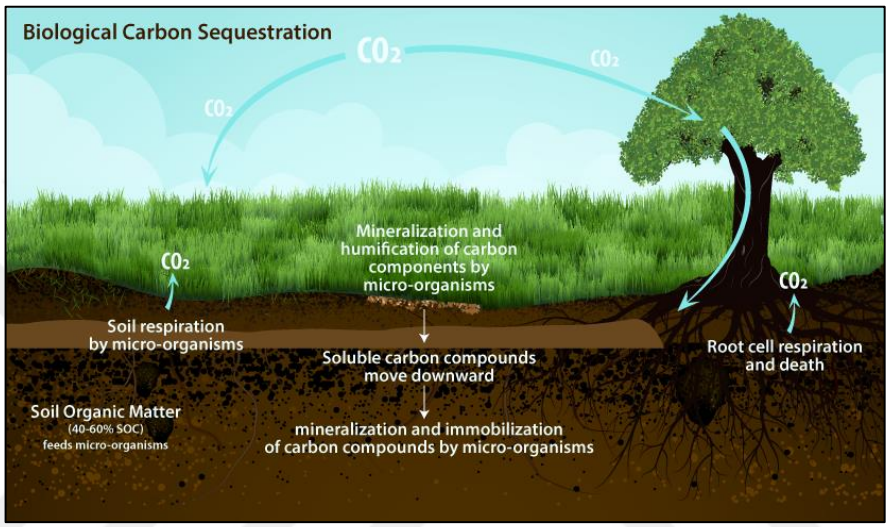


Figure 3.13. Biological carbon sequestration [69]

Another interesting technique is mineral carbonation (Figure 3.14), in which CO_2 is trapped and chemically interacts with certain minerals like olivine or serpentine to create stable carbonates. Although it happens naturally, this process may be hastened in artificial systems. The carbonation of minerals may provide long-term and geologically stable CO_2 storage. However, further study is required to maximize the effectiveness and scalability of this strategy [58,63].

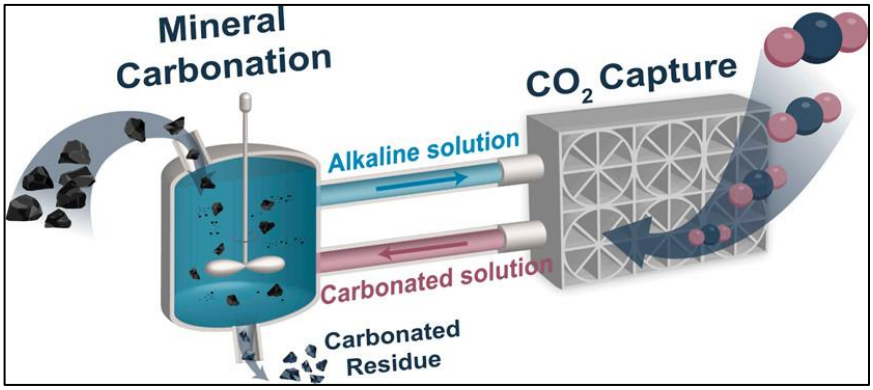


Figure 3.14. Mineral carbonation [70]

It is essential to remember that, despite their effectiveness in lowering CO_2 emissions, carbon capture techniques have drawbacks. High energy needs, high capital and operating expenditures, and the necessity for adequate storage locations are a few of these. In order to make these technologies more broadly available and efficient, ongoing research and development efforts are concentrated on enhancing these factors [58,63].

In addition, carbon capture technologies provide workable alternatives for reducing greenhouse gas emissions and halting climate change. The options include post-combustion capture, pre-combustion capture, oxy-fuel combustion, direct air capture, biological carbon capture, and mineral carbonation. By dramatically reducing CO_2 emissions from multiple sources and promoting the growth of low-carbon enterprises, these techniques may assist accomplish sustainable development goals [60,63].

3.4.1.1. Post combustion carbon capture by using high temperature sorbents

An important strategy for reducing greenhouse gas emissions from factories and power plants is post-combustion carbon capture utilizing high-temperature sorbents. This technique entails removing carbon dioxide (CO_2) after the burning of fossil fuels like coal or natural gas from the flue gas produced after combustion. CO_2 may be separated from the flue gas stream and then stored or utilized by using high-temperature sorbents to selectively adsorb it [60].

Solid sorbents based on metal oxides, such magnesium oxide (MgO) or calcium oxide (CaO), are one type of frequently used high-temperature sorbent. At high temperatures, usually exceeding 500 degrees Celsius, these sorbents may collect CO_2. The sorbent material combines with the CO_2 in the flue gas to create stable carbonate compounds throughout the capture process. The CO_2 trapped can then be released at high temperatures to renew the carbonated sorbent, which enables its further use or storage [71].

Since they are unaffected by water vapor, high-temperature sorbents have the benefit of being able to collect CO_2 from flue gases with high moisture content. Their suitability for post-combustion capture in power plants, where the flue gas frequently contains significant volumes of water vapor, is a result of this. The flue gas drying process uses the least amount of extra energy possible thanks to the high-temperature capture method, which can increase the carbon capture system's overall effectiveness [60].

Furthermore, the incorporation of carbon capture technology into current power plants is possible without substantially altering the combustion process because of the use of high-temperature sorbents. As a result, upgrading older facilities that might not have been built with carbon capture in mind becomes a realistic alternative. High-temperature sorbent-based carbon capture systems may be retrofitted into existing facilities to dramatically cut CO_2 emissions, increase operational longevity, and help mitigate climate change [63].

Enhancing the effectiveness and performance of high-temperature sorbents for carbon capture applications is the focus of research and development activities. To improve the selectivity and capacity of CO_2 collection, this entails adjusting the sorbent's composition, structure, and surface area. Research is also being done to create energy-efficient regeneration procedures that increase the stability and longevity of the sorbent materials [63].

In conclusion, employing high-temperature sorbents to collect carbon dioxide after combustion is a potential strategy for lowering CO_2 emissions from factories and power plants. Metal oxide-based solid sorbents, such as calcium oxide and magnesium oxide, have demonstrated promise for CO_2 capture at high temperatures. Incorporating high-temperature sorbents into an existing plant infrastructure and being compatible with high-moisture flue gases are only two benefits of doing so. The performance and effectiveness of high-temperature sorbents are being further improved via ongoing research and development in order to effectively collect carbon [63].

3.4.2. Carbon capture of concrete

In order to lessen the effect of climate change, carbon dioxide (CO_2) emissions from the manufacturing of concrete or from the atmosphere are captured and stored. Due to the calcination of limestone during the manufacture of cement and the use of fossil fuels as an energy source, the manufacturing of concrete contributes significantly to CO_2 emissions. In order to lessen their negative effects on the environment, carbon capture technologies seek to catch and either use or store these CO_2 emissions [72,73].

In the case of concrete, there are many methods for carbon capture. Direct carbon capture during the manufacture of cement is one approach (Figure 3.15). This entails removing and

purifying the CO_2 for later usage or storage once it has been separated and released straight from the cement kiln or flue gas. The collected CO_2 may be used in a variety of processes, including the creation of chemicals and materials or improved oil recovery [72,73].

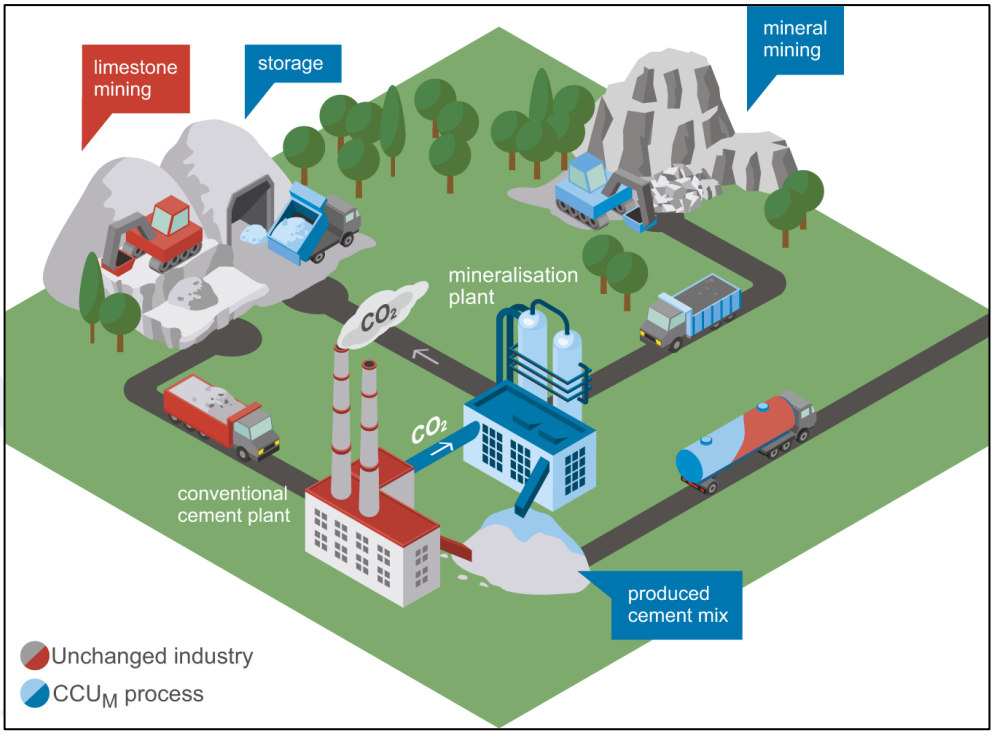


Figure 3.15. Direct carbon capture during manufacture of concrete [74]

Indirect carbon capture is a different strategy that involves adding ingredients to concrete that can absorb and store CO_2. These substances, often referred to as mineralizers or carbon capture additives, interact with CO_2 during the curing of concrete to transform it into stable carbonates. As a result, the concrete structure helps permanently store CO_2, lowering the material's carbon impact [72,73].

To create and improve carbon capture systems for concrete, research is continuing. The possibility for carbon capture in a variety of additives and mineralizers, including synthetic compounds or industrial byproducts, is being investigated. Concrete may benefit from these materials' improved sustainability and performance while actively capturing CO_2. Finding scalable, affordable solutions that may be included into manufacturing processes for concrete is a difficulty [72,73].

A further choice besides direct carbon capture and mineralization is the concept of carbon capture and use (CCU) in concrete. In this instance, CO_2 emissions are absorbed and used

as a feedstock for the production of chemicals or high-value goods. For example, CO_2 may be converted into carbonates or polymers that can be added to concrete, providing a technique to reduce emissions without sacrificing the substance's valuable properties [72,73].

It's crucial to remember that although carbon capture technologies for concrete appear promising, they are still in the planning and research stages. These technologies require more investigation and optimization in terms of their scalability, affordability, and long-term performance. But they have a lot of promise to make concrete a more environmentally friendly building material by lowering its carbon footprint [75].

4. FUNDAMENTALS FOR LEACHING AND DEHYDRATION

4.1. BASICS OF LEACHING

Leaching is a vital step in the study of materials and refers to the process of removing soluble components from solid materials using a liquid medium. Metallurgy, environmental science, and materials engineering are just a few of the scientific fields where this approach is frequently employed. A fundamental knowledge of leaching is required in order to research material behavior, examine compositions, and evaluate interactions between materials and their environments [76].

A solid substance known as the substrate or matrix is in contact with a liquid known as the leachant during the leaching process. Depending on the application, the leachant may be water, an organic solvent, or a combination of chemicals. Leaching's goal is the selective dissolution of certain components from the solid matrix while preserving the desired material or isolating valuable components from the substrate [76].

Several important parameters have an impact on the leaching process. The composition, porosity, and surface area of the solid material are important factors in affecting the pace and degree of leaching. The effectiveness and selectivity of leaching are also influenced by the leachant's characteristics, such as its pH, temperature, and chemical makeup [76].

Depending on the material and leachant involved, several methods can control the leaching process. Diffusion-controlled leaching is one typical method, in which the leachant permeates the solid matrix and the solute molecules migrate from the material's core to its surface, where they dissolve into the leachant. Another technique is chemically reaction-controlled leaching, in which the components of the solid material and the leachant undergo chemical reactions to cause the solid to dissolve [76].

Leaching is utilized in a variety of ways in materials science. It is routinely used to painstakingly remove certain chemicals or components in order to clarify the makeup and properties of materials. Leaching studies are essential for comprehending how materials behave in a range of conditions, such as the release of toxins from dangerous soils or the leaching of minerals from ores, to name just a couple of instances. Additionally, it is employed in the pharmaceutical industry for the manufacture of drugs and the separation of

active substances, as well as for the metallurgical purification process and the extraction of precious metals from industrial waste [76,77].

Multiple aspects need to be taken into account in order to improve leaching processes. These comprise the choice of leachant, the properties of the substance, the intended result, and any potential environmental effects. To guarantee effective and sustainable procedures, factors including leaching kinetics, equilibrium conditions, and the disposal or treatment of leachate should be carefully considered [76,77].

In conclusion, the extraction of soluble components from solid materials using a liquid media is known as leaching, and it is a crucial procedure in the study of materials. It is a flexible approach with uses in a range of industries and scientific disciplines. Leaching fundamentals must be understood in order to investigate material behavior, examine compositions, and improve processes in materials science and engineering [76,77].

4.1.1. Acidic leaching

In materials science and metallurgy, a method known as acidic leaching is frequently used to extract desired elements or compounds from solid materials by using acidic solutions as leaching agents. In order to separate certain components from the rest of the material during this procedure, particular components from the solid matrix must be dissolved into the acidic solution. Numerous sectors, including mining, mineral processing, and environmental cleanup, frequently use acidic leaching. Figure 4.1 shows the acidic leaching flowsheet [78,79].

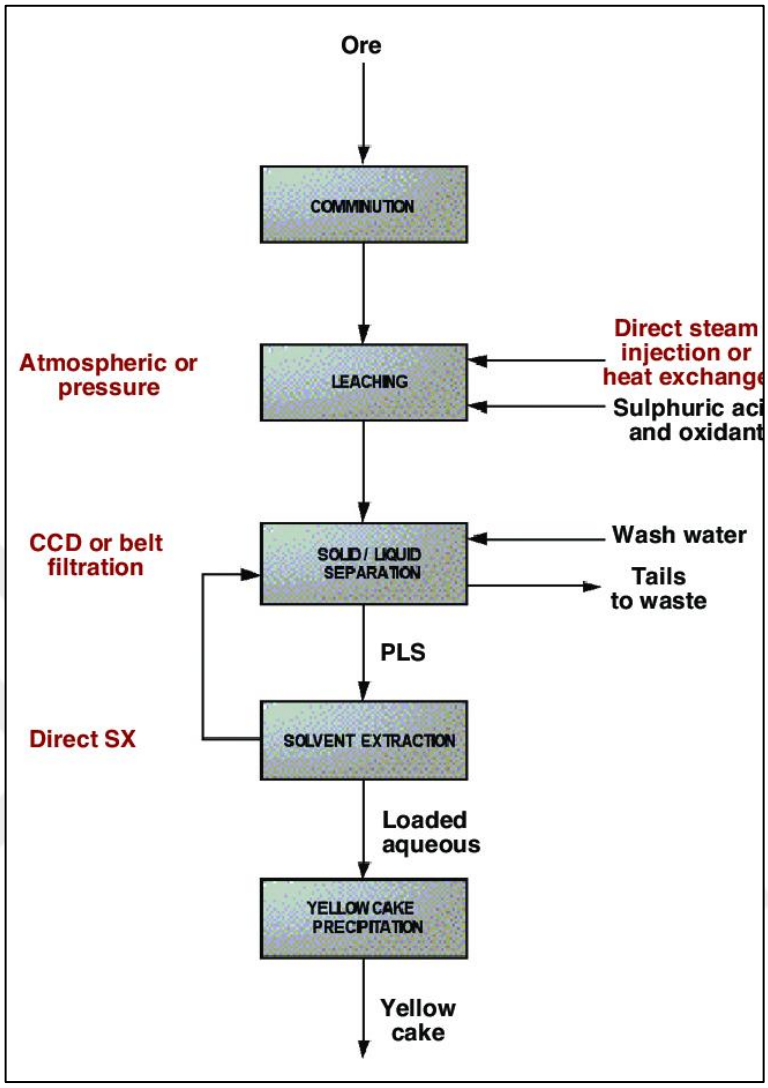


Figure 4.1. Acidic leaching flowsheet [80]

The kind of target material and the required components to be extracted determine which acid is employed in acidic leaching. Acids like hydrofluoric acid (HF), nitric acid (HNO_3), sulfuric acid (H_2SO_4), and hydrochloric acid (HCl) are often utilized. These acids provide a very acidic environment that helps certain minerals, metals, or chemical compounds dissolve from the solid substance [78,79,81].

Several variables affect the efficiency of acidic leaching. The leaching process depends heavily on the acid content, temperature, contact duration, and agitation. As more acid molecules are available to dissolve the target components, increasing the acid concentration typically improves the leaching efficiency. By enhancing solubility and reaction rates, higher temperatures can hasten the leaching process [81].

Based on the particular conditions and process goals, acidic leaching may be divided into a variety of modes. For instance, in heap leaching, crushed ore is stacked in heaps and acid solution is applied through irrigation systems. This technique is frequently applied to the extraction of precious metals from inferior ores. Contrarily, in situ leaching entails pumping acid into the subsurface to dissolve minerals where they naturally occur, enabling resource extraction without physically digging the ore [78,79].

Acidic leaching may be used by many industries. In the mining sector, it is used to extract metals like gold, uranium, and copper from ores. Valuable components can also be recovered from industrial waste and byproducts via acidic leaching. It can be used, for example, to recover rare earth elements from used catalysts or to extract metals from electronic waste [78,79].

While using acidic leaching to extract desired components might be efficient, it's crucial to take the environment's possible effects into account and put in place the necessary protections. Large amounts of acidic leachate are produced during acidic leaching operations, and this leachate may contain pollutants such dissolved metals. Leachate must be properly handled and disposed of in order to avoid environmental damage and to comply with rules [78,79].

In conclusion, acidic leaching is a common method in materials science and metallurgy for removing desired components from solid materials while employing acidic solutions as the leaching agents. It has uses in a number of sectors, including mining, processing minerals, and environmental cleanup. Acid content, temperature, and contact duration are only a few variables that affect how effectively the leaching process works. It is essential to take environmental effects into account and use appropriate waste management techniques while applying acidic leaching[78,79,82] .

4.1.2. Alkaline leaching

In materials science and metallurgy, a method called alkaline leaching—also referred to as alkaline extraction or alkaline dissolution—is used to remove desirable components from solid materials by utilizing alkaline solutions as leaching agents. Alkaline leaching depends on alkaline chemicals to dissolve certain compounds or components from the solid matrix,

as opposed to acidic leaching, which employs acidic solutions. Figure 4.2 shows the flowchart of the two-stage alkali leaching process [83].

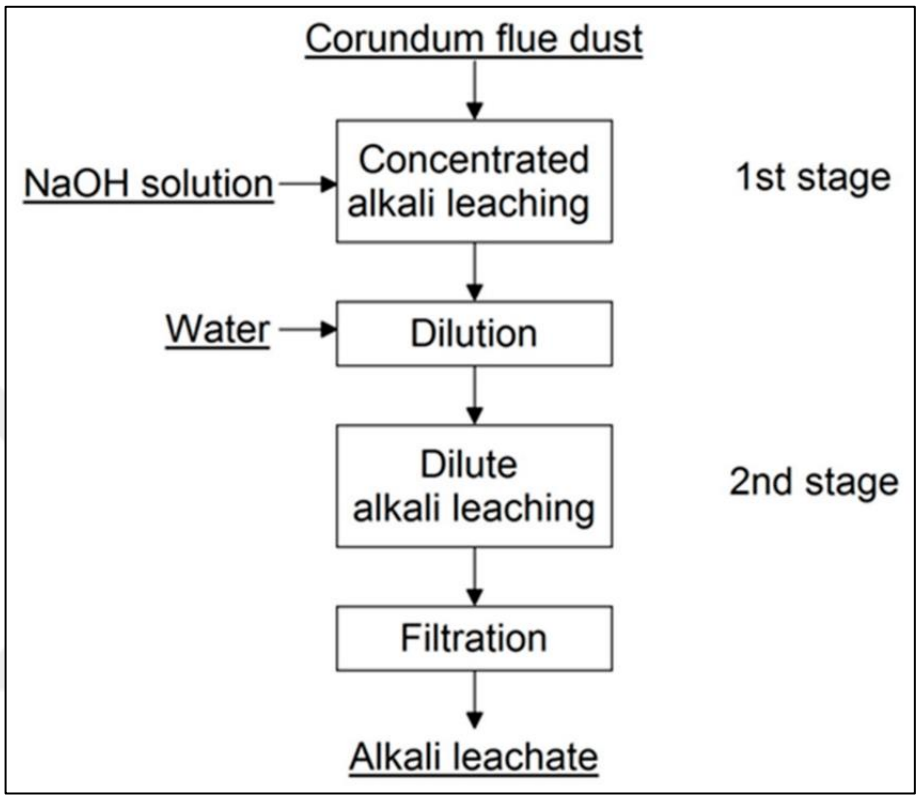


Figure 4.2. The flowchart of the two-stage alkali leaching process [84]

In the mining, metallurgical, and hydrometallurgical sectors, alkaline leaching is a widely used process. Extraction from their ores may be quite successful for essential metals like copper, nickel, zinc, and cobalt. Priceless components may also be recovered with this method from a number of waste materials, such as industrial trash and electronic waste [83].

The exact material being treated and the required components to be removed will determine the best alkaline solution to use for leaching. Sodium hydroxide (NaOH), potassium hydroxide (KOH), ammonium hydroxide (NH_4OH), and sodium carbonate (Na_2CO_3) are examples of commonly used alkaline agents. These alkaline solutions provide a high pH environment that helps some minerals or chemicals dissolve from the solid substance [83].

The concentration of the alkaline solution, temperature, the length of the leaching process, and agitation are some of the variables that affect how effective alkaline leaching is. By

delivering more alkaline ions for the process of dissolving, increasing the alkaline solution's concentration often improves the leaching efficiency. Elevated temperatures can also make the target components more soluble and hasten the leaching kinetics [83].

A variety of methods, including in situ leaching, heap leaching, and agitation leaching, can be used to carry out alkaline leaching. Agitation leaching includes maintaining ideal conditions for the leaching process while mixing the solid material with an alkaline solution in a tank or reactor. To extract the necessary components, heap leaching entails piling up the material and irrigating it with an alkaline solution. To dissolve minerals in their natural environment, in situ leaching requires injecting an alkaline solution directly into the subsurface [83].

Beyond only removing metals, alkaline leaching is employed. It is also used to desilt minerals, remove pollutants, and leach out specific elements in addition to these purposes. As an illustration, sodium hydroxide causes aluminum hydroxide to dissolve, allowing alumina to be extracted from bauxite ore through the process of alkaline leaching [83].

When using alkaline leaching, it is crucial to take adequate waste management and environmental factors into account. Alkaline leachate produced during the process may contain dissolved metals and other pollutants that need to be properly treated and disposed of to avoid contaminating the environment and to meet legal requirements [83].

In conclusion, alkaline leaching is a commonly used technique in materials science and metallurgy for removing desired components from solid materials while employing alkaline solutions as the leaching agents. It has uses in the mining, metallurgical, and hydrometallurgical sectors. The effectiveness of the procedure is influenced by variables including alkaline content, temperature, and leaching duration. Alkaline leaching is particularly effective for recovering valuable elements from a variety of materials and extracting base metals from ore. When adopting alkaline leaching procedures, proper environmental concerns and waste management techniques are crucial [83].

4.2. BASICS OF DEHYDRATION

Dehydration is an important process within the field of materials science that involves the removal of water molecules from a material. It is a fundamental step in various

manufacturing and research processes, enabling the modification of material properties and the synthesis of new materials. Dehydration can be achieved through different techniques depending on the specific requirements and characteristics of the material [85].

Thermal dehydration is a typical technique for dehydration in materials science. In order to do this, the material must be heated under control so that the water molecules may escape from the substance. Vacuum drying, oven drying, and even high-temperature treatments are examples of ways to apply heat. Thermal dehydration is a common technique for removing moisture from coatings, films, and fibers as well as solvents from materials including ceramics, powders, and composites [85].

In materials science, freeze-drying or lyophilization is another method of dehydration. Sensitive or heat-sensitive materials benefit greatly from this procedure. It entails freezing the substance to a solid state and putting it into a vacuum atmosphere so that the frozen water may instantly transition from the solid to the vapor phase. As it helps preserve the material's structure and qualities by reducing damage brought on by ice crystal formation, freeze-drying is frequently employed in the preservation of biological samples, medicines, and food goods [85,86,87].

In the field of materials science, desiccation is another technique for dehydration. It entails subjecting the material to a desiccant, a chemical with a high affinity for water molecules that can efficiently absorb moisture from the material. Desiccants can be either liquids like strong sulfuric acid or solids like silica gel or molecular sieves. For materials that are sensitive to moisture or in controlled situations where low humidity is necessary, desiccation is frequently used [88].

Dehydration is vital to the synthesis and processing of many materials, according to materials science. It enables the elimination of water or solvents, changing the material's structure, content, and characteristics. Dehydration can be used to speed up reactions or phase transitions while also regulating the porosity, density, and mechanical strength of materials. Furthermore, it is crucial for the characterization of materials when it is necessary to remove moisture or water in order to undertake precise measurements or tests [87].

Overall, dehydration is a fundamental process in materials science that involves the removal of water from materials through various techniques such as thermal dehydration, freeze-drying, and desiccation. It enables the modification, synthesis, and characterization of

materials, playing a critical role in achieving desired properties and advancing research and development in the field of materials science [85,86,87].

4.2.1. Dehydration of calcium hydroxide

When calcium hydroxide—also referred to as lime or hydrated lime—is dehydrated, calcium oxide (quicklime) is created as a result of the removal of water from the chemical. Here are some details on calcium hydroxide's dehydration:

Calcium oxide is transformed into $CaCO_3$ to produce calcium hydroxide, a white, crystalline powder. Due of water's strong attraction for calcium, it joins the crystal structure of calcium hydroxide. This occurs when calcium hydroxide is exposed to moisture in the air [10,89].

When calcium hydroxide is dehydrated, a chemical reaction occurs that results in the release of water molecules and the formation of calcium oxide. It releases heat since this process is exothermic. Calcium hydroxide may be dehydrated using a variety of techniques, including heating, air exposure, and vacuum drying [10,89].

Thermal treatment is one approach that is frequently used to dehydrate calcium hydroxide. Calcination is the process that occurs when calcium hydroxide is heated to temperatures more than 500 °C. The water molecules bonded to the calcium hydroxide crystals are released during calcination, and calcium oxide is produced instead. The response may be modeled as follows:

$Ca(OH)_2 \rightarrow CaO + H_2O$

The resultant calcium oxide, sometimes referred to as quicklime or burned lime, is a highly reactive and caustic substance that has a variety of uses in the building, farming, and chemical manufacturing sectors [10,89].

An essential stage in the creation of goods based on lime is the dehydration of calcium hydroxide. The elimination of water improves the cleanliness and reactivity of the calcium oxide, making it appropriate for uses such soil stabilization, water treatment, cement manufacture, and steel production. Depending on the particular needs of the application, the dehydrated lime can be further processed and used in several forms, such as hydrated lime (calcium hydroxide), lime putty, or lime slurry [10,89].

It is significant to highlight that the dehydration of calcium hydroxide is a reversible process. Calcium oxide immediately turns back into calcium hydroxide when it comes into touch with moisture or water by absorbing the water molecules. This property is widely utilized in calcium hydroxide due to its chemical reactivity or as a drying agent [10,89].

In conclusion, calcium hydroxide is dehydrated, or stripped of its water molecules, to create calcium oxide. This procedure, which is often carried out via heat processing, results in quicklime. Dehydrated lime is employed in a variety of industries and has improved reactivity [10,89].

5. LAND RESTORATION

5.1. TECHNICAL ASPECTS OF LAND RESTORATION

A deteriorated or damaged land area is being restored when it is brought back to its original, natural state. Figure 5.1 shows the results of land degradation. It entails putting numerous strategies into action in order to boost biodiversity, restore biological processes, and improve soil quality. In order to support the recovery and sustainability of the ecosystem, land restoration aims to mitigate the negative effects left behind by human activity or natural disasters [90,91].

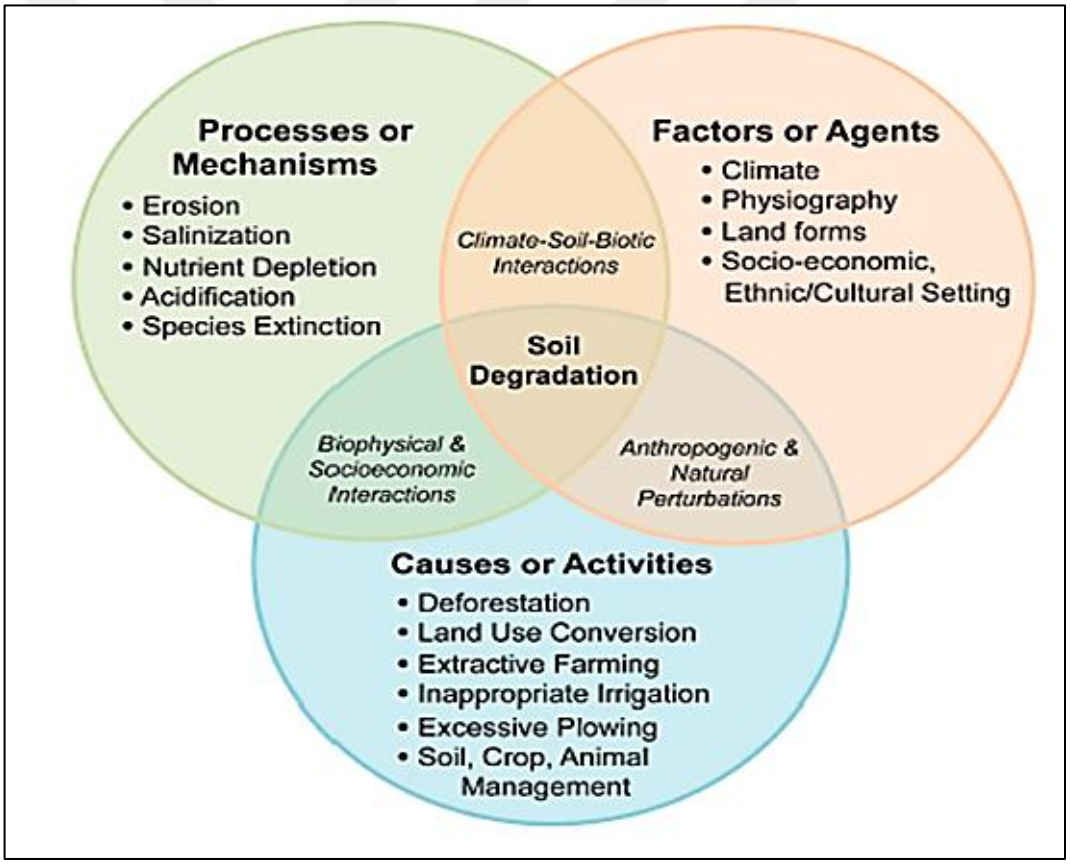


Figure 5.1. Results of land degradation [92]

Typically, restoring a piece of land entails several crucial processes. In order to comprehend the scope and causes of land degradation, an evaluation is first carried out. The proper restoration methods and tactics are determined by this assessment. Deforestation, soil

erosion, desertification, mining operations, and pollution are common examples of land degradation [90,91].

Activities for restoration can be started when the assessment is finished. Reforestation or afforestation to restore tree cover, the introduction of native plant species, the rehabilitation of wetlands or water bodies, and the restoration of natural habitats for animals are a few examples of these efforts. To increase biodiversity, restoring land in certain circumstances may also entail reintroducing endangered or vulnerable species [90,91].

Projects involving the restoration of land sometimes need a mix of biological, chemical, and physical treatments. For instance, soil supplements can be utilized to enhance the structure and fertility of the soil, while erosion control methods like contour plowing or vegetative barriers can assist stop future soil erosion. Remediation procedures may be used to eliminate or neutralize pollutants in regions that have been contaminated or subject to pollution [90,91].

The availability of suitable plant species, access to water resources, long-term management strategies, and community engagement are just a few of the variables that affect how well land restoration operations are accomplished. The sustainability of land restoration programs depends on community involvement and support, which may assist assure local buy-in, knowledge exchange, and the long-term upkeep of recovered regions [90,91].

The benefits of restoring land are numerous. It promotes the fertility and health of the soil, helps to mitigate climate change by capturing carbon dioxide through reforestation efforts, and boosts the general resilience of ecosystems. By giving plants and animals a place to live, it also helps to preserve biodiversity. Rehabilitated sites could also provide opportunities for sustainable land uses including forestry, agriculture, ecotourism, and recreation [90,91].

Land restoration is an intricate and drawn-out process that calls for careful planning, observation, and adaptive management. The precise methods and procedures employed for land restoration differ according to the regional context, the degree of land degradation, and the targeted results. For land restoration efforts to be effective and sustainable, it is frequently necessary for local people, environmental groups, and scientific professionals to work together [90].

5.1.1. The use of demolition concrete for land restoration

An inventive and environmentally friendly method of restoring damaged or disturbed land areas is to employ demolition concrete. The dismantling or destruction of old concrete structures yields demolition concrete, commonly referred to as recycled concrete aggregate (RCA). This material may be reused and applied in various land restoration initiatives rather of being thrown away in landfills (Figure 5.2) [27,93].

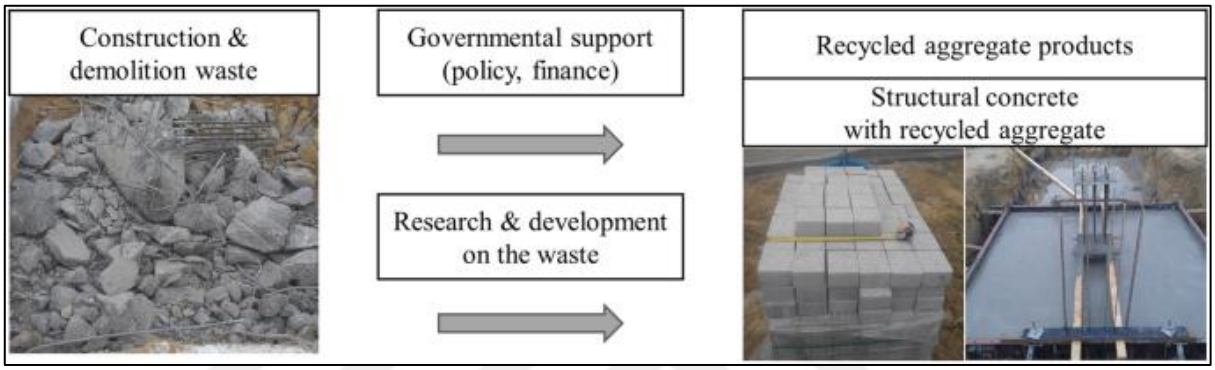


Figure 5.2. RCA [94]

The main use of demolition concrete in land restoration is to build roads, paths, and foundation layers instead of using conventional aggregates. It decreases the need for virgin aggregates and protects natural resources by utilizing RCA as the basis material. This strategy avoids the need for massive quarrying and decreases trash output, making it both economical and ecologically benign [95].

In addition to being used for demolition, demolition concrete may also be used to restore eroded or mine-affected portions of the landscape. With the help of the crushed concrete, slopes may be made more stable, erosion can be stopped, and a firm base for the growth of plants can be created. With these uses, it aids in restoring the land's structural integrity, halting additional soil erosion, and encouraging the growth of plants [96].

The use of demolition concrete in land restoration, in addition to its structural advantages, also promotes sustainable waste management techniques. It lessens the strain on disposal facilities and lessens the environmental effects associated with waste transportation and disposal by diverting concrete trash from landfills and recycling it in restoration projects [93].

Additionally, using demolition concrete for land restoration can improve how well an ecosystem functions. In addition to providing a good foundation for plant development, crumbled concrete may improve soil fertility and water retention. The establishment of plants on recovered areas improves biodiversity, habitat formation, and ecosystem resilience [96].

It should be noted that careful planning and consideration of site-specific elements are necessary for the successful application of demolition concrete in land restoration projects. This entails evaluating the caliber and usability of the recycled concrete aggregate, choosing the best application strategies, and taking into account any potential ecological or environmental concerns [93,95].

Using demolition concrete, or recycled concrete aggregate, in land restoration projects has several benefits, to sum up. It offers a greener substitute for conventional aggregates, lowers waste production, encourages efficient use of resources, and aids in the regeneration of ravaged land. The issues of waste management can be addressed while also assisting in the sustainable and appropriate use of resources in land restoration projects by integrating demolition concrete into restoration operations [97].

5.2. LAND RESTORATION EXAMPLES IN THE WORLD

Degraded land areas are intended to be resurrected and regenerated via the application of restoration techniques. Successful land restoration programs all across the world can serve as examples of the potential for ecosystem recovery and sustainable land management techniques. Think about the following circumstances.

The Loess Plateau, China: Because of massive soil erosion and unsustainable land practices, the Loess Plateau in northern China has been badly deteriorated. Large-scale initiatives at terracing, soil protection, and afforestation were made possible by the "Grain for Green" program. Figure 5.3 shows the grain of green project results. Millions of trees and bushes were planted as part of the initiative, turning the desolate area into a fruitful and biologically varied territory. This project has improved the soil's quality, decreased erosion, boosted water availability, and improved local populations' standard of living [98].

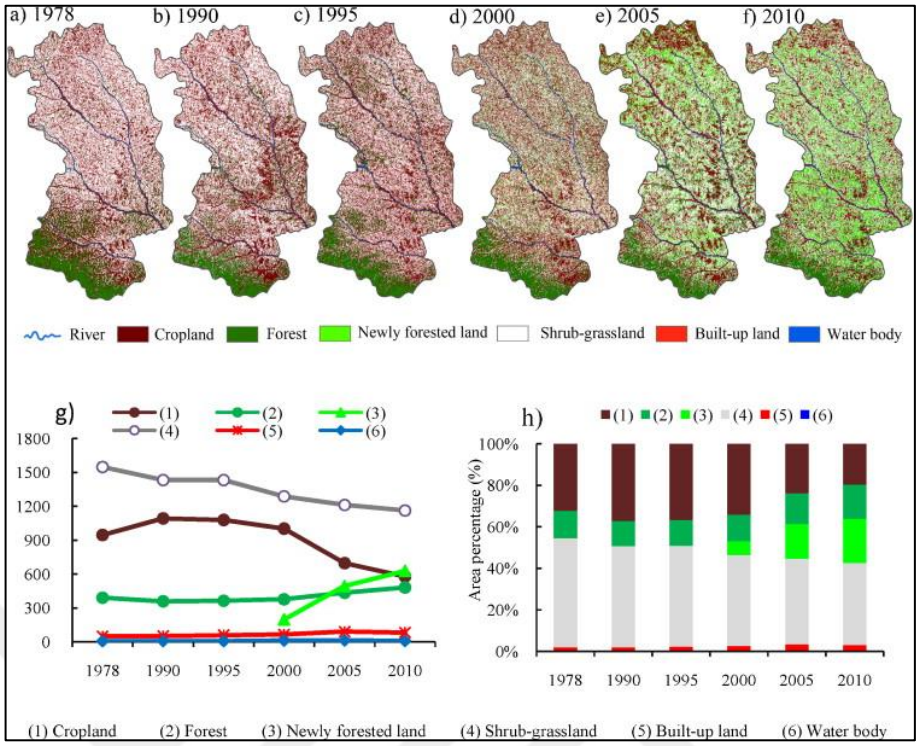


Figure 5.3. Grain of green [99]

Tanzania's Yaeda Valley is a vital environment for the native Hadzabe people and is home to a wide variety of wildlife. Significant deterioration has been brought on by unsustainable land use practices including overgrazing and deforestation. The Carbon Tanzania initiative prioritizes sustainable land management and forest protection in conjunction with local populations. The project seeks to enhance ecosystem health, support livelihoods, and reduce climate change through carbon sequestration through community-led efforts, such as land restoration, forest conservation, and tree planting [100].

The Aral Sea area, in Central Asia: Water diversion for irrigation projects caused the Aral Sea, formerly one of the biggest inland lakes in the world, to suffer significant environmental deterioration. The building of dams and canals to channel water from the Amu Darya and Syr Darya rivers back into the surviving Aral Sea is part of the restoration efforts in this area. The water body has partially recovered as a result, and the local ecosystems and fishing communities have also improved. Figure 5.4 shows the Aral Sea over the years [98].

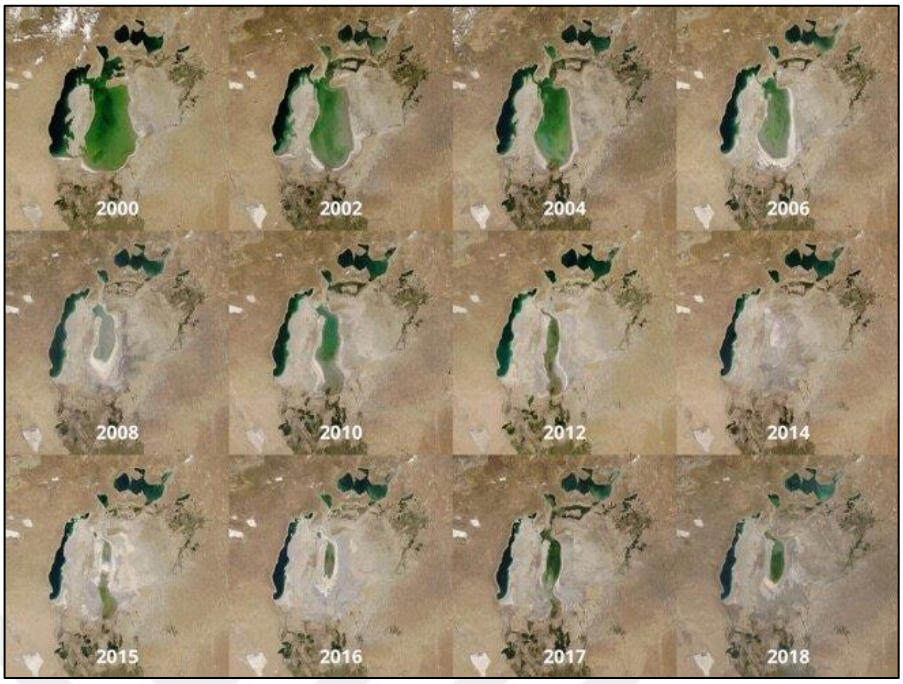


Figure 5.4. The Aral sea over the years [101]

Brazil's Atlantic Forest is one of the most biodiverse ecosystems in the world, but deforestation and land degradation have had a severe influence on it generally. The Brazilian government, non-governmental groups, and municipal governments have all launched various restoration efforts. These initiatives focus on protecting important ecosystems, growing new trees, and creating ecological corridors. Damaged forest portions are to be repaired, endangered species are to be protected, and ecosystem functions are to be improved through restoration activities. Figure 5.5 shows the results of land restoration [100,102].

Figure 5.5. Brazil's Atlantic forest land restoration [103]

The Great Green Wall project in Africa aims to halt land deterioration and desertification in the Sahel region. In order to repair harmed soil, provide food security, battle climate change, and support local livelihoods, the idea calls for the creation of a "green belt" of trees and plants throughout the continent. Figure 5.6 shows the Great Green Wall in Africa [100].

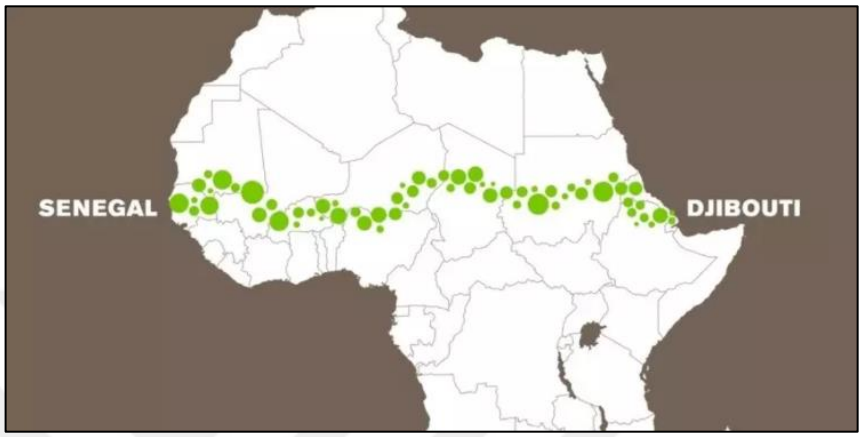


Figure 5.6. The greet green wall in Africa [104]

Examples including afforestation, reforestation, soil protection, and community involvement show the variety of methods used for land restoration. Collaboration between governments, local communities, nonprofits, and other stakeholders is necessary for projects to be successful, as is having a common understanding of sustainable land management and ecological restoration [105].

5.3. ENVIRONMENTAL EFFECTS OF LAND RESTORATION

The mitigation of environmental deterioration and the advancement of ecological sustainability depend heavily on land restoration. Initiatives for land restoration have the potential to have a variety of beneficial environmental consequences by addressing problems such soil erosion, deforestation, desertification, and habitat loss. The following are some significant environmental advantages of land restoration generally:

Conservation of biodiversity: Land restoration projects help to maintain and replenish biodiversity. Ecological equilibrium is bolstered by the habitat that restored ecosystems give for a variety of plant and animal species. Reforestation, the planting of native plants, and the creation of protected areas all contribute to the preservation of species and increase the resilience of the ecosystem as a whole generally [106,107].

Fertility and soil conservation are the main objectives of land restoration techniques. Techniques include terracing, reforestation, erosion control, and the addition of organic matter improves soil structure, lowers erosion rates, and encourage nutrient cycling. Better equipped to hold onto water, stop soil deterioration, and boost agricultural output are restored soils [106,107,108].

Water resource management: Land restoration initiatives have favorable effects on the availability of water. Restored landscapes contribute to improved groundwater recharge, reduced runoff, and flow regulation. This increases the amount of water available for ecosystems, farming, and human use. Additionally, by lowering sedimentation and filtering pollutants, restoration works in rivers, wetlands, and riparian zones improve water quality generally [106,107].

Climate change mitigation: Carbon sequestration through land restoration helps to reduce global warming. Ecosystems that have been restored, particularly forests, absorb and store carbon dioxide from the atmosphere, reducing greenhouse gas emissions. Because trees are so important in carbon fixation, reforestation and afforestation operations are extremely successful at storing carbon [106,107].

Agroforestry, conservation agriculture, and sustainable farming methods are just a few examples of the sustainable land use and agriculture that land restoration encourages. These techniques improve soil fertility, lower the demand for chemical inputs, increase water efficiency, and save natural resources. Agricultural production, food security, and rural livelihoods are all supported by sustainable land use over the long run generally [106,107].

Improved ecosystem services: Land restoration initiatives help to deliver crucial ecosystem services. Ecosystems that have been restored carry out tasks including nutrient cycling, soil creation, pollination, and water filtration. These services support a variety of economic, social, and cultural activities while enhancing both human well-being and ecological health [106,107,109].

It is essential to remember that the precise environmental consequences of land restoration might change depending on the situation, the scope, and the restoration methods used. Comprehensive planning, stakeholder involvement, and adaptive management are frequently needed for successful land restoration initiatives in order to produce long-term environmental benefits [109].

6. EXPERIMENTAL STUDIES

6.1. MATERIALS

In this study, demolished concrete (Istanbul, Turkey) was used as the starting material. It has been used for the reason of it having a high percentage of calcium-based and silicate-based content. Concrete powder was used after grinding. After leaching experiments there were four types of powders which are the original concrete powder, calcium enhanced concrete powder (retrieved from alkaline leaching), calcium hydroxide [$Ca(OH)_2$] powder (retrieved from acidic leaching) and dehydrated/calcinated $Ca(OH)_2$ (retrieved from acidic leaching). Phase analysis of the powders used in this study were carried out with X-ray diffractometer (Rigaku Miniflex) using Cu-Kα radiation at a scanning speed of 5°/min between 2θ=10-90.

6.2. METHODS

In this study, concrete samples were collected from a demolished building located at Merdivenkoy, Hamle Sk. No:13, Istanbul, Turkey. The concrete samples were subjected to various methods to investigate the leaching behavior and potential for CO_2 capture. The following steps were undertaken (Figure 6.1 shows the flow chart of the experimental process):

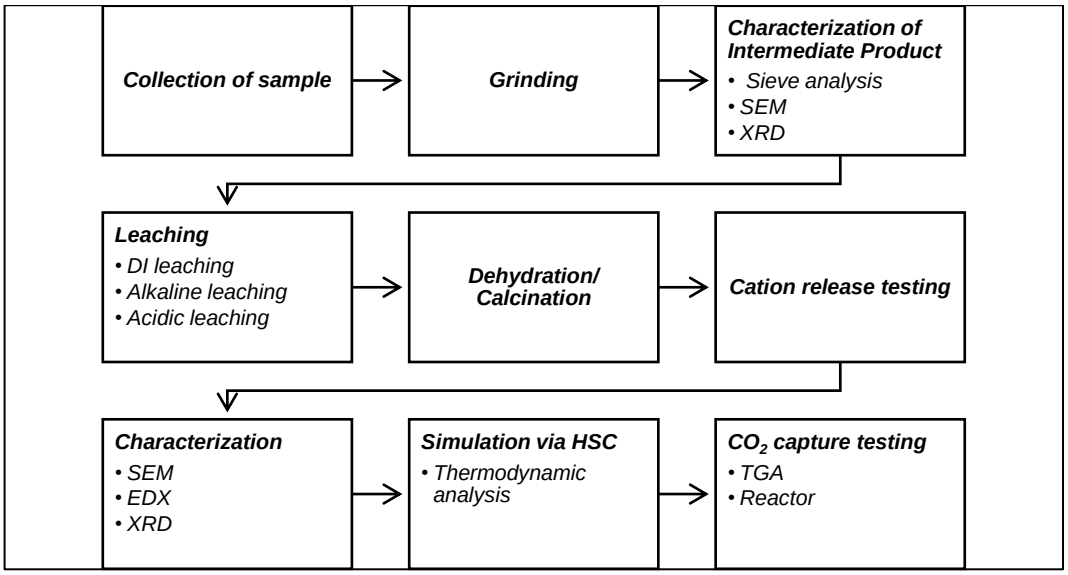


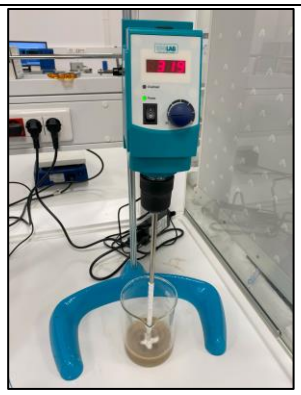
Figure 6.1. Flow chart of the experimental process

The collected concrete samples were grinded using a vibratory cup mill at ITU-Turkey. This process aimed to reduce the concrete into smaller particles for further analysis. After grinding, the intermediate product underwent characterization using sieve analysis, scanning electron microscopy (SEM), and X-ray diffraction (XRD) techniques. Sieve analysis provided information about the particle size distribution, while SEM and XRD analyses allowed for the examination of the microstructure and identification of the mineral phases present in the concrete. Three different leaching experiments were conducted to evaluate the leaching behavior of the concrete samples. The first experiment involved leaching with distilled water (DI Leaching), the second experiment used alkaline leaching with sodium hydroxide (NaOH), and the third experiment involved acidic leaching using hydrochloric acid (HCl). After the acidic leaching process, the resulting powder, which primarily consisted of calcium hydroxide [$Ca(OH)_2$], was subjected to dehydration/calcination. This process involved heating the powder to high temperatures, leading to the conversion of calcium hydroxide into calcium oxide (CaO). Cation release testing was performed on four different powders: the original concrete powder, the alkaline leached powder, the acidic leached powder ($Ca(OH)_2$), and the dehydrated powder (CaO). This testing aimed to determine the release of cations from these powders under specific conditions, providing insights into their potential for capturing CO_2. Following the cation release testing, another round of characterization analysis was conducted using SEM, XRD, and energy-dispersive X-ray spectroscopy (EDX). These techniques allowed for the examination of the microstructure, mineral composition, and elemental distribution within the powders. Thermodynamic analysis was performed using the HSC Chemistry program to simulate and analyze the chemical reactions and equilibrium conditions during the various processes. This analysis provided insights into the thermodynamic feasibility and stability of the reactions involved. Finally, CO_2 capture testing was conducted using a thermogravimetric analyzer (TGA) machine. This testing aimed to evaluate the CO_2 capture capacity of the powders, particularly focusing on the dehydrated powder (CaO) obtained from the concrete samples.

The described methods were employed to investigate the leaching behavior, chemical transformations, and CO_2 capture potential of the concrete samples. The combination of experimental techniques, characterization analyses, thermodynamic simulations, and CO_2 capture testing provides a comprehensive understanding of the material properties and potential applications for sustainable environmental purposes.

Figure 6.2 shows the devices used in this thesis.

(a) Retsch Octagon 200



(b) ISOLAB Laborgerate GmbH

(c) DAIHAN Scientific Oven

(d) PROTHERM Furnace

(e) IMS-CP used for cation release testing

(f) (NETZSCH STA 449F3) TGA

Figure 6.2. The devices used in the thesis

7. RESULTS AND DISCUSSION

7.1. RESULTS OF SIEVE ANALYSIS

In this study, the concrete samples collected from the demolition site were subjected to grinding. After grinding, sieve analysis was performed to determine the particle size distribution of the concrete powder. The average particle size of the concrete powder was found to be 211.09 μm. This information provides valuable insights into the size distribution and granularity of the ground concrete particles.

To further visualize the results, several Figures were generated. Figure 7.1 illustrates the relationship between the cumulative mass percent finer (%) and the sieve opening (μm). This graph showcases the distribution of particles across different sieve openings and demonstrates the gradation of the concrete powder.

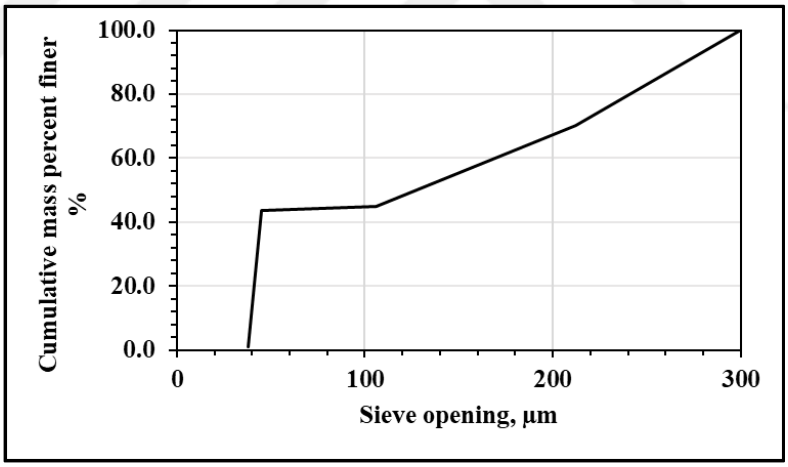


Figure 7.1. Sieve analysis

Additionally, Figure 7.2 presents the sieve analysis Histogram, which presents the frequency distribution of particles based on their size. This histogram provides a visual representation of the particle count within specific size ranges, highlighting the predominant particle sizes present in the concrete powder.

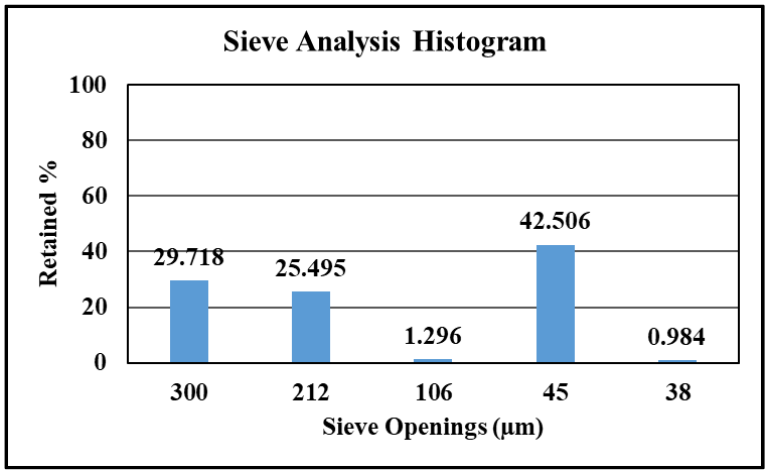


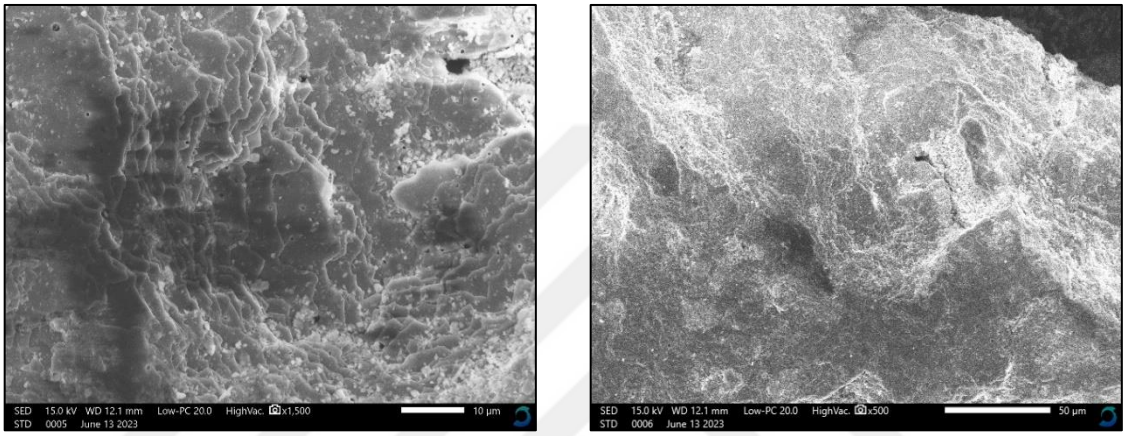
Figure 7.2. Sieve analysis histogram

These Figures aid in interpreting and visualizing the results of the sieve analysis, allowing for a comprehensive understanding of the particle size distribution of the ground concrete powder. The data presented in Table 1, along with the graphical representations in Figures 36 and 37, provide valuable information for characterizing the physical properties and particle size distribution of the concrete powder, which are crucial for further analysis and interpretation in the context of this study. The results of the sieve analysis are presented in Table 7.1.

Table 7.1. Concrete powder sieve analysis

Sieve	**Sieve opening, mm**	**Concrete, g**	**%**
(+300)	0.300	29.258	29.718
(-300+212)	0.212	25.100	25.495
(-212+106	0.106	1.276	1.296
(-106+45)	0.045	41.848	42.506
-45	0.045	0.969	0.984
	total	98.451	100.000

Furthermore, to gain further insights into the morphology and microstructure of the raw concrete powder, scanning electron microscopy (SEM) analysis was performed. Figures 7.3 showcase the SEM images of the raw concrete powder. These images provide a detailed view of the surface characteristics, particle shape, and internal structure of the concrete powder at a microscopic level. SEM analysis enables a closer examination of the particle morphology, aiding in the understanding of the physical properties and potential interactions within the concrete powder.



(a) **(b)**

Figure 7.3. Concrete SEM (a) 1500X, (b) 500X

The combination of sieve analysis and SEM imaging offers a comprehensive approach to characterizing the concrete powder obtained from the grinding process. While sieve analysis provides information about the particle size distribution, the SEM images provide visual evidence of the surface features and structural attributes of the particles. This multi-faceted characterization approach ensures a thorough understanding of the physical properties and microstructure of the concrete powder, contributing to a comprehensive analysis of its behavior and potential applications in further stages of the research. Table 7.2 shows the chemical analysis of the demolished concrete measured by means of atomic absorption spectrometry (AAS) and chemical analysis.

Table 7.2. Concrete chemical composition

Element	% by weight
SiO2	53.03
CaO	36.05
Al2O3	4.44
MgO	0.18
Fe2O3	3.39

These findings, along with the sieve analysis results and SEM images, serve as crucial components in the characterization and analysis of the concrete powder. They provide a foundation for understanding the particle size distribution, surface characteristics, and microstructure of the ground concrete, which are essential for subsequent experiments, simulations, and interpretations in the context of this study.

7.2. RESULTS OF LEACHING EXPERIMENTS

7.2.1. Distilled water leaching experiments

In the initial phase of the leaching experiments, distilled water was employed as the leaching agent to enhance the calcium-based content within the concrete. The procedure involved leaching 10 grams of the demolished concrete with 100 ml of distilled water, followed by drying and recording the new mass. This leaching series was performed for six different samples of the same demolished concrete, with varying leaching durations of 15 minutes, 30 minutes, 60 minutes, 180 minutes, and 360 minutes. The percentage remaining in mass is depicted in Figure 7.4, illustrating the variation in mass reduction across the different leaching durations. These results indicate the extent to which the calcium-based compounds present in the concrete are susceptible to leaching and dissolution in distilled water.

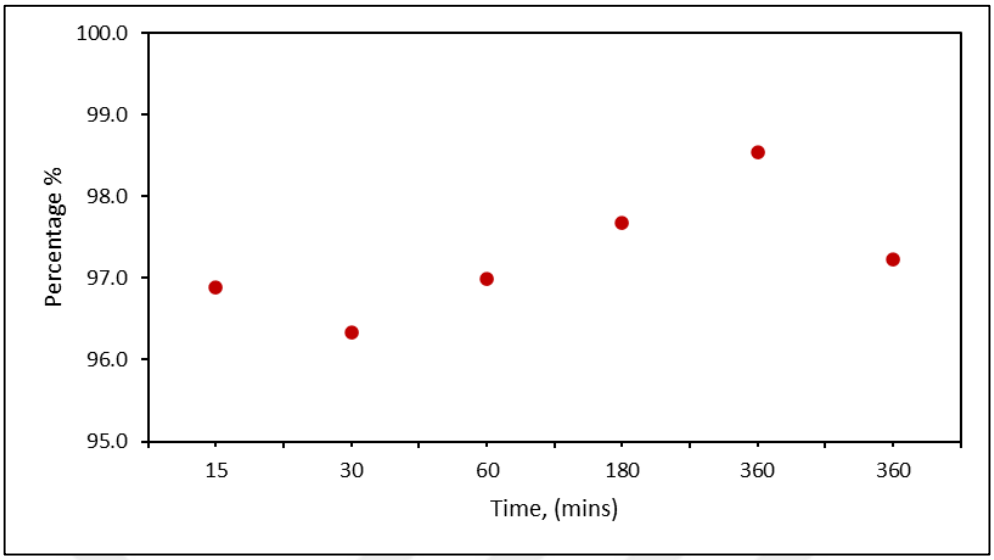


Figure 7.4. Samples % remaining

The leaching experiments with distilled water serve as a crucial step in assessing the leachability and potential release of calcium-based compounds from the concrete matrix. By subjecting the demolished concrete samples to controlled leaching durations, we can evaluate the impact of leaching time on the leachability of calcium-based compounds. The variations in mass reduction observed in Table 7.3 and Figure 7.4 offer valuable insights into the leaching behavior and provide a basis for understanding the leaching kinetics and effectiveness of distilled water as a leaching agent. The results of the distilled water leaching are presented in Table 7.3, highlighting the changes in the mass of the concrete samples.

Table 7.3. Concrete DI leaching

Duration (min)	15	30	60	180	360
sample masses (g)	5.1	10.0	10.0	10.0	10.0
amount of reduction in mass (g)	0.2	0.4	0.3	0.2	0.1
percent of reduction	3.1	3.7	3.0	2.3	1.5
remaining mass	96.9	96.3	97.0	97.7	98.5

These findings contribute to the understanding of the leaching characteristics of demolished concrete and provide insights into the release of calcium-based compounds under the

influence of distilled water. The results of the distilled water leaching series aid in the identification of optimal leaching durations for subsequent experiments and provide a foundation for further investigations on the leaching behavior of the concrete samples.

7.2.2. Alkaline leaching experiments

The second phase of the leaching experiments involved alkaline leaching using sodium hydroxide (NaOH) as the leaching agent. Alkaline leaching was employed to convert the calcium oxide-based (CaO) content within the demolished concrete into calcium hydroxide [$Ca(OH)_2$], which possesses a significant carbon capture capacity. Various leaching conditions were explored, including different molarities of NaOH and varying leaching durations.

The procedure for alkaline leaching was as follows: 10 grams of the demolished concrete sample was taken and mixed with 4 grams of NaOH in 100 ml of distilled water. The leaching process was conducted for different durations, including 15 minutes, 30 minutes, 60 minutes, 180 minutes, and 360 minutes. Additionally, different molarities of sodium hydroxide were used, 0.25 M, 0.50 M, and 1.00 M, to evaluate the influence of molarity on the leaching efficiency. The molarity (M) is defined by the equation $M = n/v$, where n represents the number of moles and v represents the volume in liters.

The results of the alkaline leaching experiments under different molarities are presented in Figures 7.5, 7.6, and 7.7, representing the outcomes for molarities of 0.25 M, 0.50 M, and 1.00 M, respectively. These Figures provide insights into the effect of NaOH concentration on the leaching efficiency and the resulting conversion of CaO into $Ca(OH)_2$. The data depicted in the Figures demonstrate the variation in leaching efficiency and the extent of CaO conversion achieved under different molarities and leaching durations.

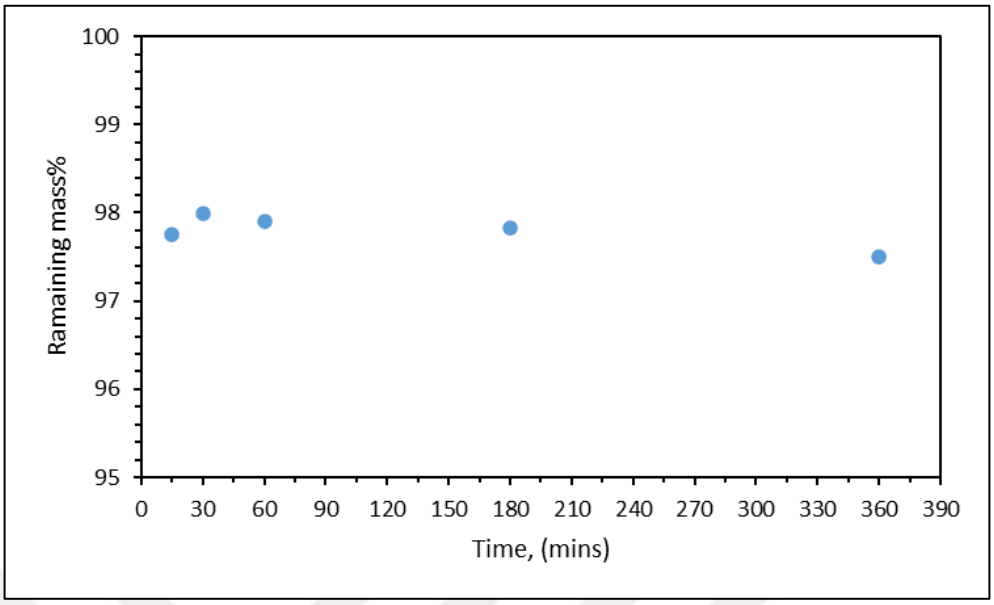


Figure 7.5. Alkaline leaching (M=0.25)

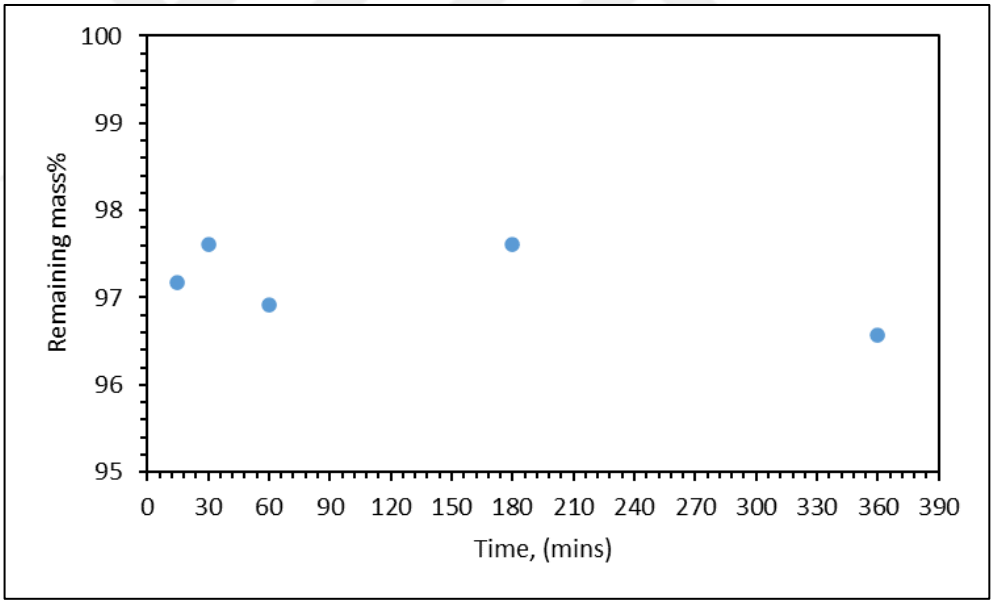


Figure 7.6. Alkaline leaching (M=0.50)

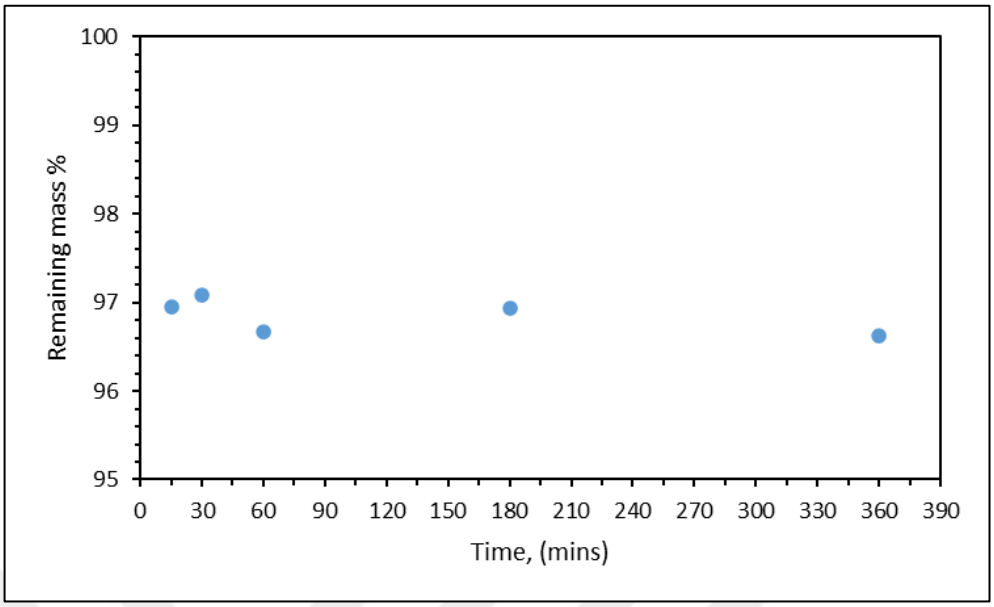


Figure 7.7. Alkaline leaching (M=1.0)

By altering the molarity of NaOH and the duration of leaching, it is possible to optimize the alkaline leaching process and enhance the carbon capture potential of the demolished concrete. The results of the alkaline leaching experiments help identify the most effective conditions for achieving higher levels of $Ca(OH)_2$ content, which is crucial for enhancing the carbon capture capacity of the concrete. These findings highlight the importance of alkaline leaching as a viable approach for transforming CaO-based compounds into $Ca(OH)_2$, which offers enhanced carbon capture potential. The results obtained from the alkaline leaching experiments provide valuable insights into the impact of molarity and leaching duration on the conversion efficiency. This information serves as a basis for further investigations on optimizing the alkaline leaching process and its application in carbon capture technologies.

Figure 7.8 shows the XRD results for normal DC and Alkaline leached DC.

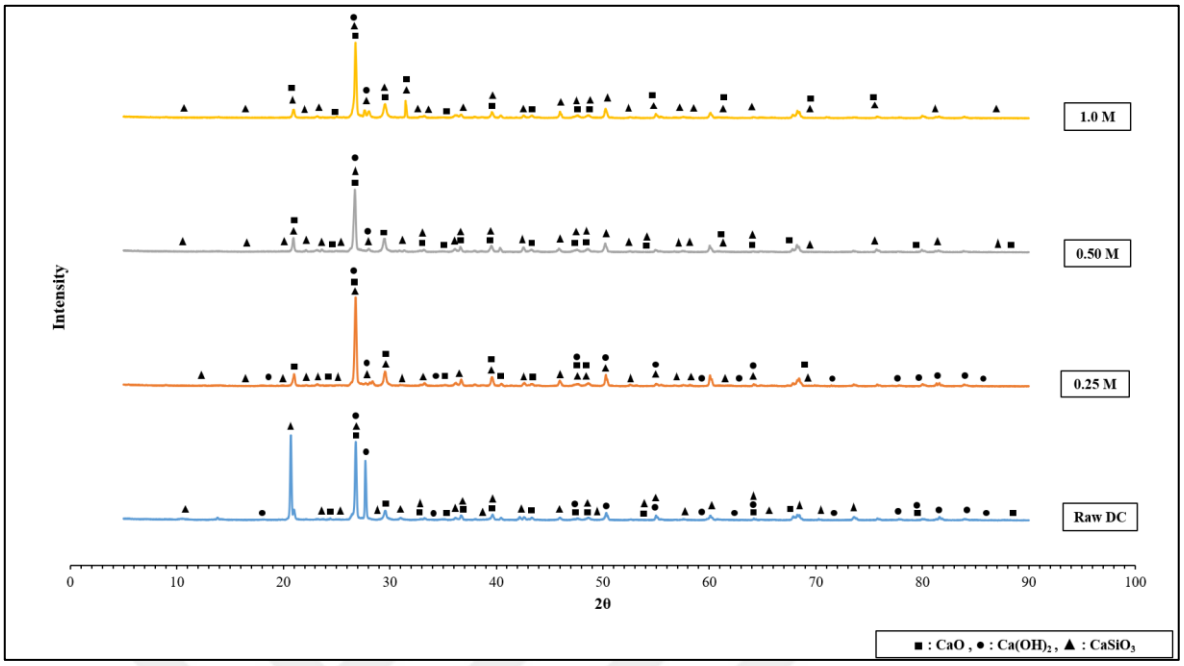
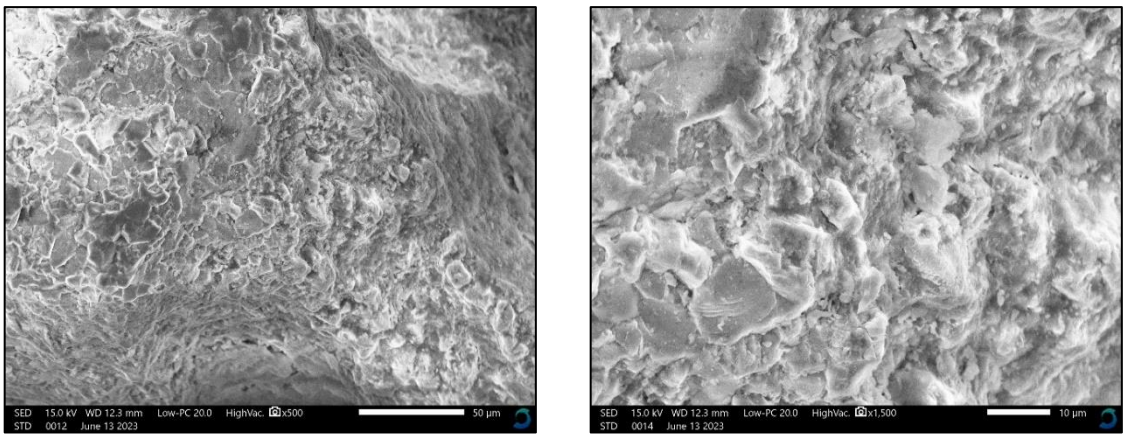


Figure 7.8. XRD results of Raw DC and Alkaline Leached DC

Figure 7.9 shows the SEM images of alkaline leached DC under the conditions of 0.5 M for 30 minutes.



(a) (b)

Figure 7.9. SEM images of alkaline leached samples (a) 500X, (b)1500X

7.2.3. Acidic leaching experiments

The third and final leaching series involved acidic leaching of the grinded demolished concrete. Acid leaching was conducted for two primary purposes: to extract all calcium-based components from the demolished concrete and to facilitate the precipitation of calcium

hydroxide [$Ca(OH)_2$] through the addition of sodium hydroxide (NaOH). Subsequently, the $Ca(OH)_2$ precipitates obtained were subjected to calcination/dehydration to convert them into calcium oxide (CaO) mixtures.

Multiple trials were conducted to explore the efficiency of acidic leaching. In the first trial (Figure 7.10), the samples were leached for various durations, including 15, 30, 60, 180, and 360 minutes. The procedure for acidic leaching was as follows: 10 grams of the ground demolished concrete powder were mixed with 8.3 ml of hydrochloric acid (HCl) for a specific time range. After the leaching process, the samples were filtered, and the resulting solution was retained. Sodium hydroxide (NaOH) droplets were then added in desired amounts at different molarities.

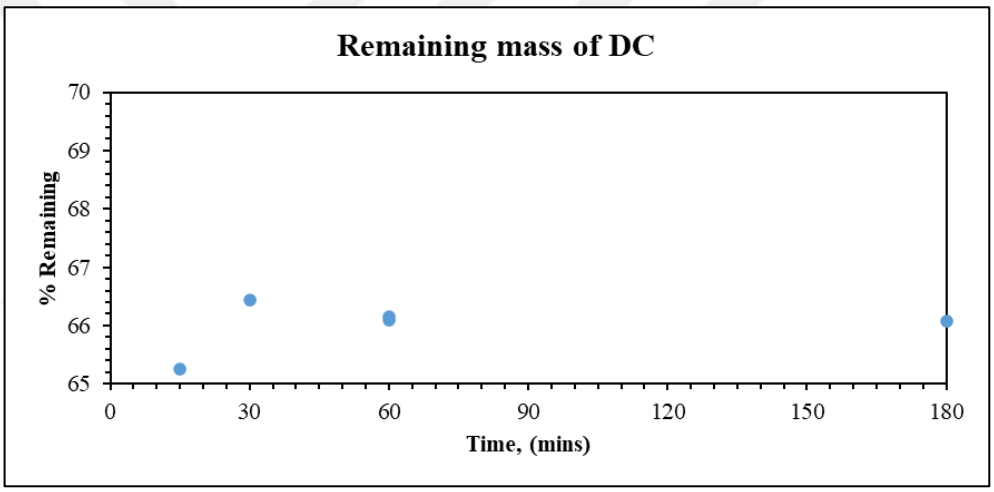


Figure 7.10. Trial 1 remaining mass %

Upon the addition of NaOH, $Ca(OH)_2$ precipitates were retrieved (Figure 7.11 depicts an example of precipitation from Trial 4). The solution containing the precipitates was allowed to rest for 24 hours to complete the precipitation process. Subsequently, the samples were filtered once again using filtering papers (FP 388 and FP 391). Following filtration, the samples underwent drying for 3 to 4 hours at 105°C using DAIHAN Scientific Oven. Once dry, the samples were ground and weighed.

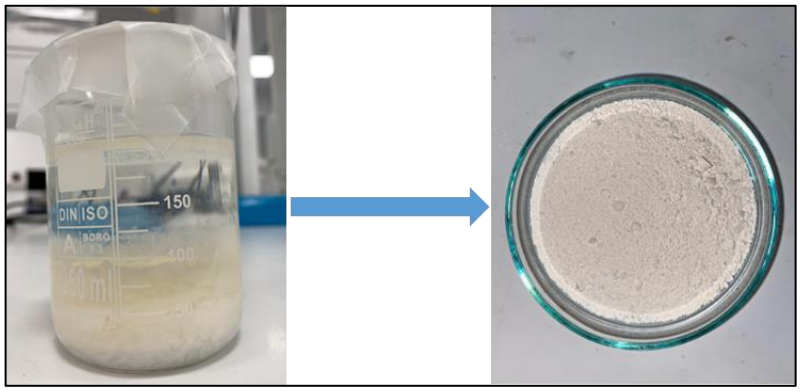
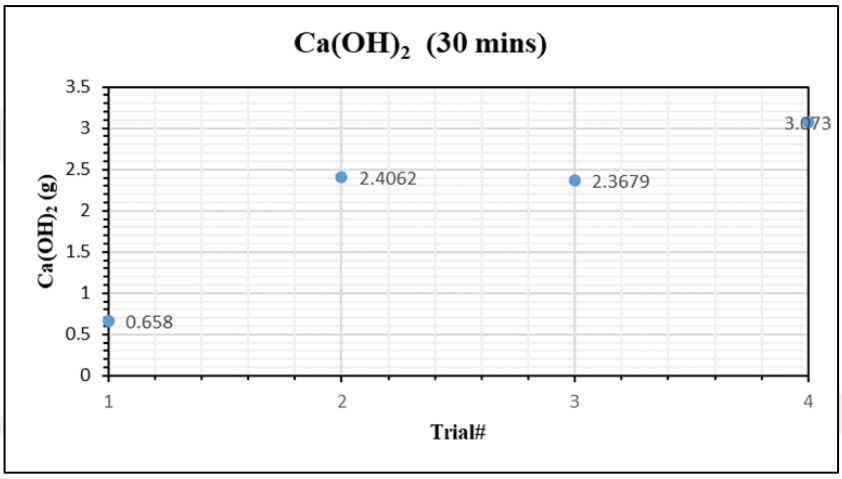
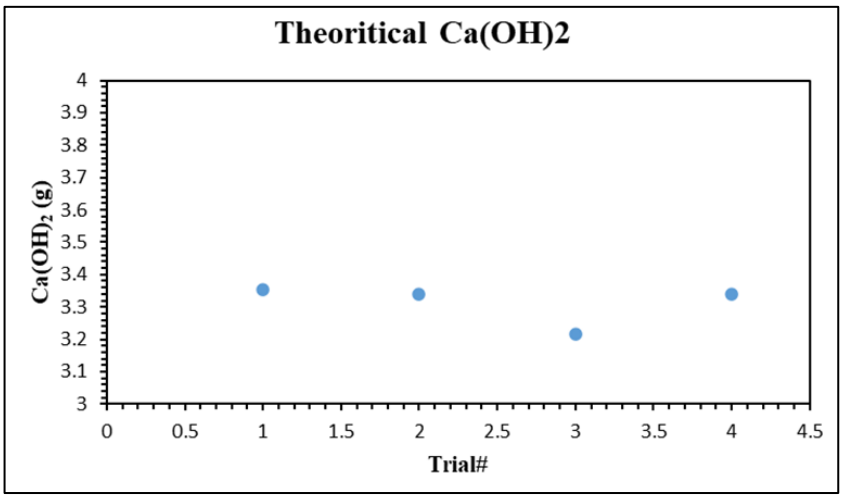


Figure 7.11. Precipitated Ca(OH)2



(a)



(b)

Figure 7.12. (a) Shows the retrieved Ca(OH)2 from 4 trials, the molarities of NaOH of the trials respectfully are 9.96 ml, 26.2 ml, 18.08 ml and 40 ml. It shows that the higher the molarity used, the more Ca(OH)2 we retrieve, (b) Shows the theoretically retrieved

Figure 7.12 presents the retrieved $Ca(OH)_2$ content for the four trials and the theoretical $Ca(OH)_2$ retrieved, with Trial 1 having the lowest molarity of NaOH added and Trial 4 having the highest molarity. The results demonstrate that higher molarities of NaOH lead to greater quantities of $Ca(OH)_2$ claimed/retrieved. Importantly, all trials exhibited a consistent pH range of 12.75 to 13.00.

These findings indicate the effectiveness of acidic leaching in extracting calcium-based components from demolished concrete. The addition of NaOH enables the precipitation of $Ca(OH)_2$, which can be further utilized in subsequent processes. The variation in molarity of NaOH allows for control over the amount of $Ca(OH)_2$ obtained, with higher molarities leading to increased yields. The pH range observed throughout the trials indicates the alkaline nature of the leaching process and the favorable conditions for $Ca(OH)_2$ precipitation.

These results provide valuable insights into the optimization of the acidic leaching process for the recovery of $Ca(OH)_2$ from demolished concrete. The data obtained from the leaching trials, precipitation, and subsequent analysis contribute to a comprehensive understanding of the efficiency and potential applications of the acid leaching approach in the context of carbon capture and utilization. Further investigations can explore the utilization of the obtained $Ca(OH)_2$ for carbon capture or other value-added applications in sustainable construction practices. Figure 7.13 shows the XRD of $Ca(OH)_2$ from acidic leaching.

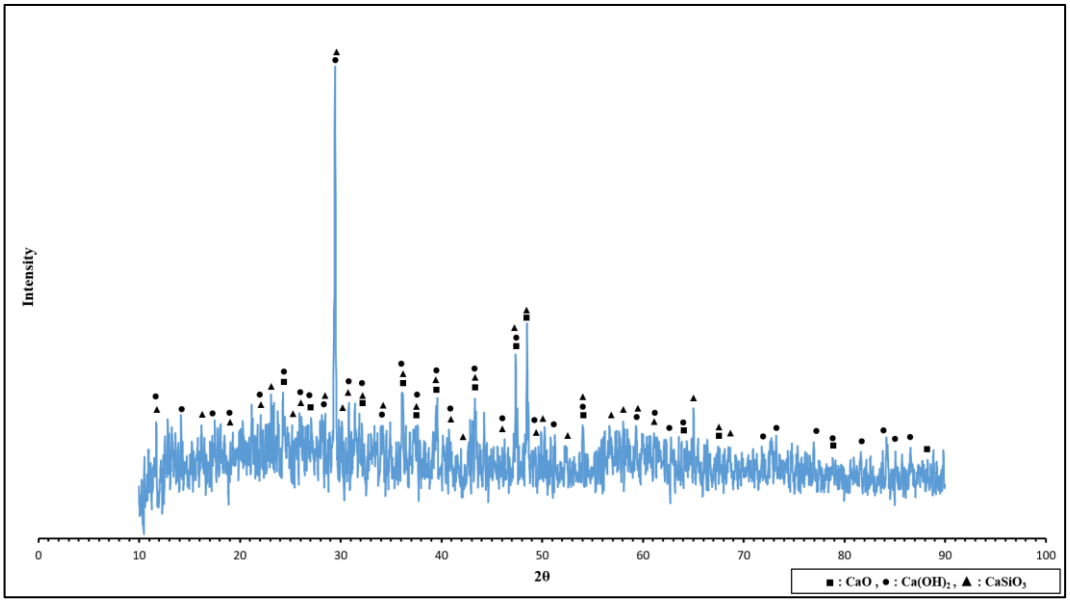
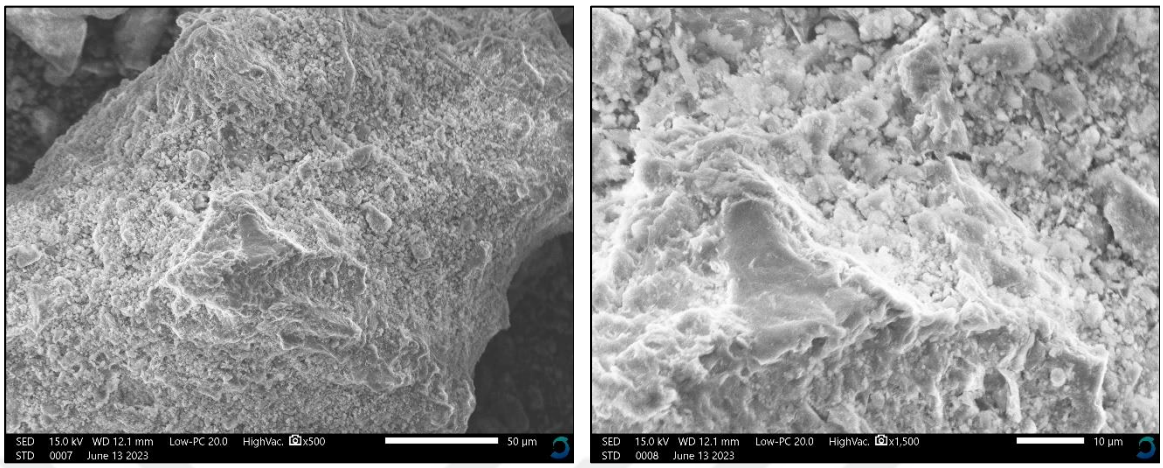


Figure 7.13. XRD of Ca(OH)2 precipitated form acidic leaching

Figure 7.14 shows the SEM images of $Ca(OH)_2$ retrieved from acidic leaching.



(a) (b)

Figure 7.14. SEM images of precipitated Ca(OH)2 phase (a) 500X, (b) 1500X

7.3. RESULTS OF DEHYDRATION

The calcium hydroxide [$Ca(OH)_2$] obtained from the acidic leaching process was subjected to dehydration. For the dehydration process, Trial 3 was selected as the representative sample. The procedure for dehydration was as follows: A mass of 1.1013 grams was taken from Trial 3, and the dehydration temperature was set at 700 degrees Celsius.

To gain further insights into the thermodynamics of the dehydration process, a dehydration TPP (temperature, pressure, phase) diagram was generated using HSC chemistry software (Figure 7.15), also probable phases were modelled by means of the same software (Figure 7.18-b). This diagram provides valuable information about the relationship between temperature, pressure, and the phase changes that occur during the dehydration process.

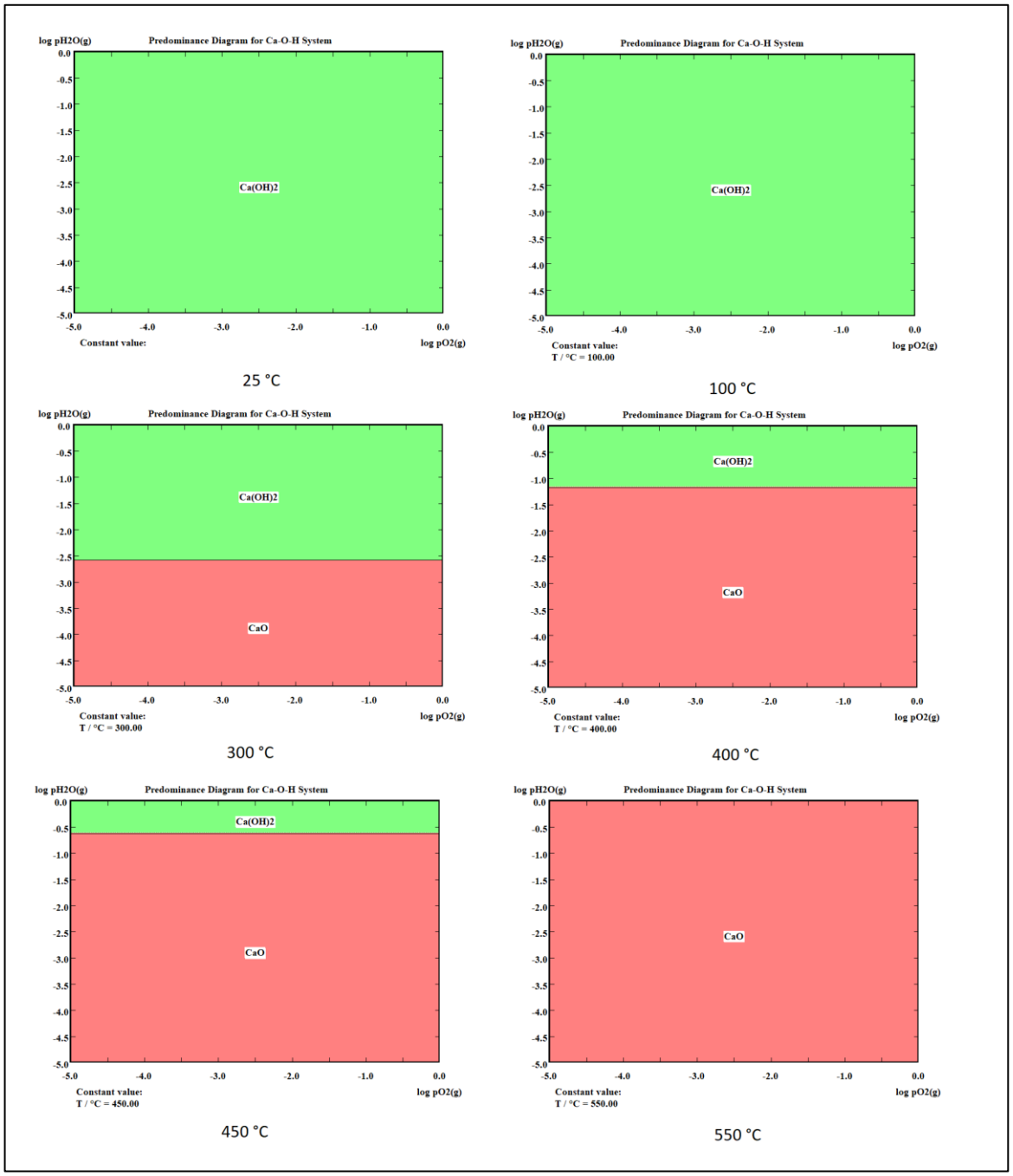


Figure 7.15. Ca(OH)2 dehydration TPP diagrams

To conduct the dehydration process, a furnace (PROTHERM furnaces) was utilized. The graph in Figure 7.16 illustrates the protocol of the dehydration process, showcasing the changes in temperature over time. The duration of dehydration was set at 30 minutes. Figure 7.17 presents the masses of $Ca(OH)_2$ before and after dehydration. In Trial 3, the mass reduction rate was around 37.17% after dehydration.

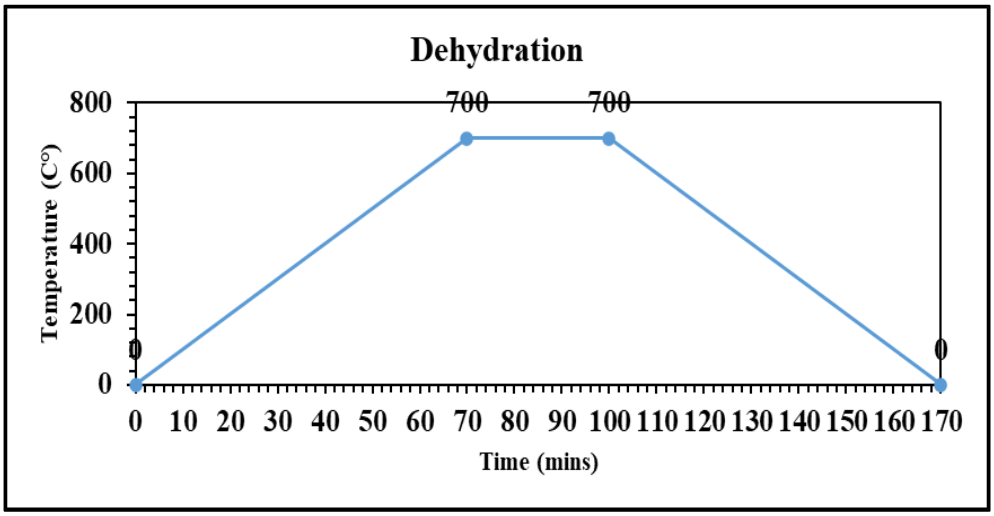


Figure 7.16. The protocol of the applied dehydration process

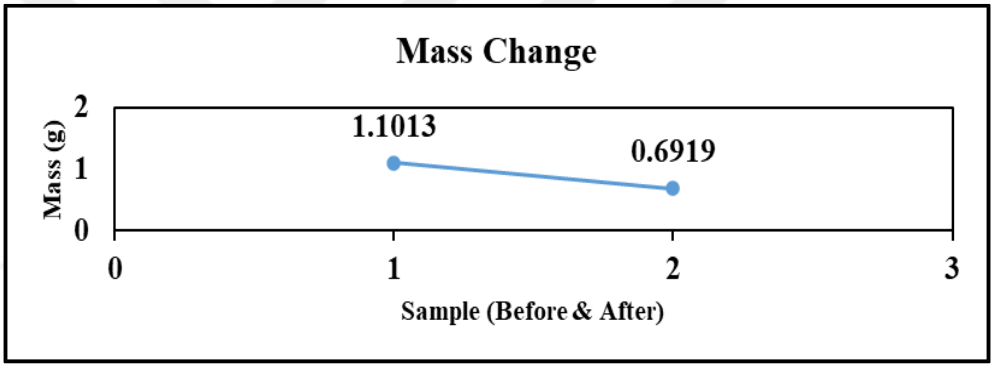
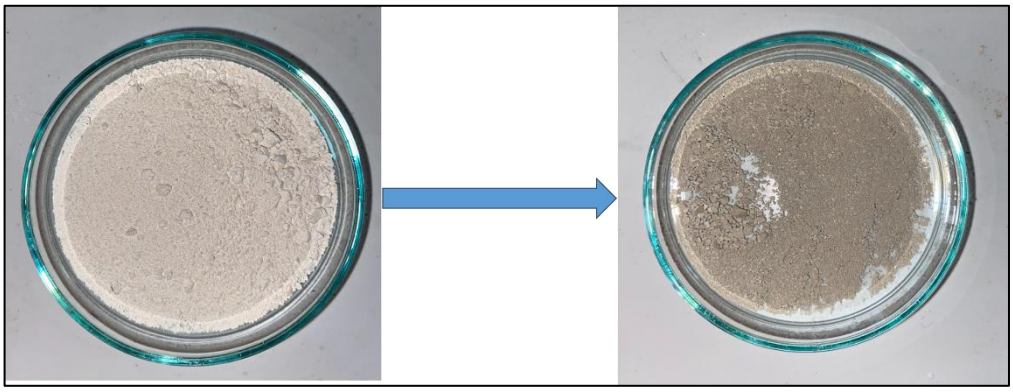


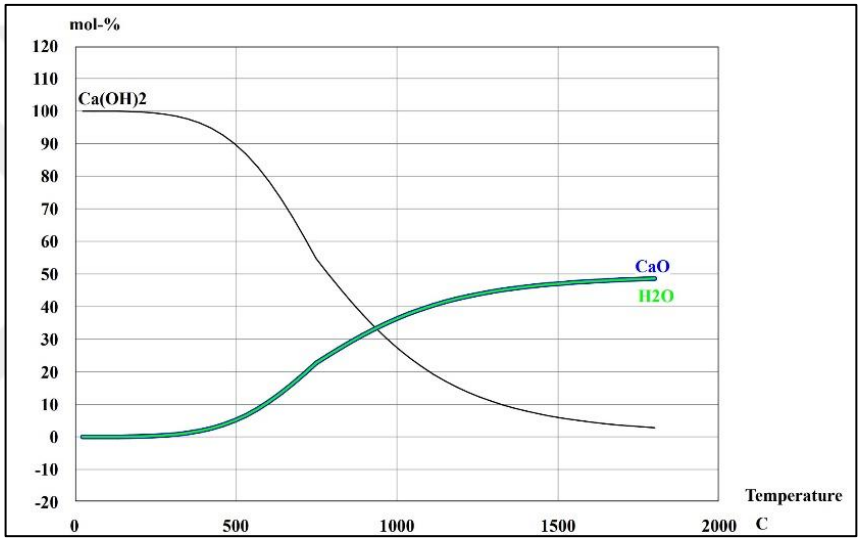
Figure 7.17. Trial#3 mass change after dehydration

The dehydration of $Ca(OH)_2$ is a critical step in the transformation of calcium-based compounds into calcium oxide (CaO). Figure 7.18 shows the $Ca(OH)_2$ before and after dehydration and shows the probable phases modelled by means of HSC Chemistry during dehydration.

Through dehydration, the water molecules bound within $Ca(OH)_2$ are eliminated, resulting in the formation of CaO. This conversion is essential for various applications, including carbon capture and utilization.



(a)



(b)

Figure 7.18. (a) Ca(OH)2 before and after dehydration, (b) probable phases in the dehydration simulated by using HSC Chemistry

The results obtained from the dehydration trials provide valuable insights into the efficiency of the dehydration process and the mass reduction achieved. The significant mass loss observed indicates the successful removal of water molecules from $Ca(OH)_2$, leading to the formation of CaO. The modelled diagram (Figure 7.18-b) aids in understanding the thermodynamic behavior of the dehydration process, enabling further optimization and control over the transformation of $Ca(OH)_2$ into CaO.

These findings contribute to the understanding of the transformation processes involved in the utilization of $Ca(OH)_2$ for carbon capture and utilization. The information obtained from the dehydration experiments and thermodynamic analysis provides a foundation for further

investigations and the development of sustainable approaches in materials science and engineering. Figure 7.19 shows the XRD pattern of the dehydrated $Ca(OH)_2$.

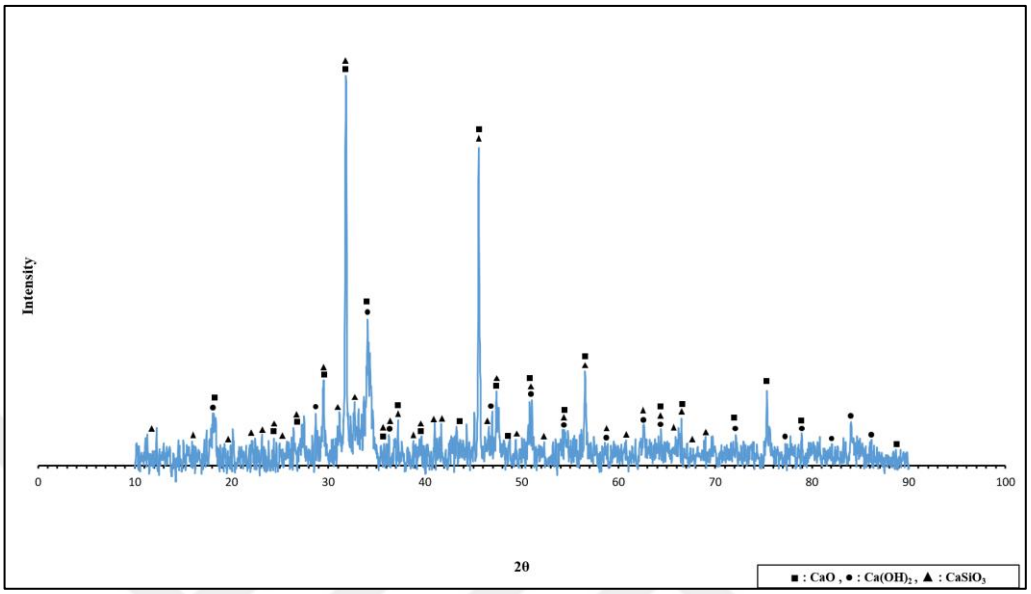
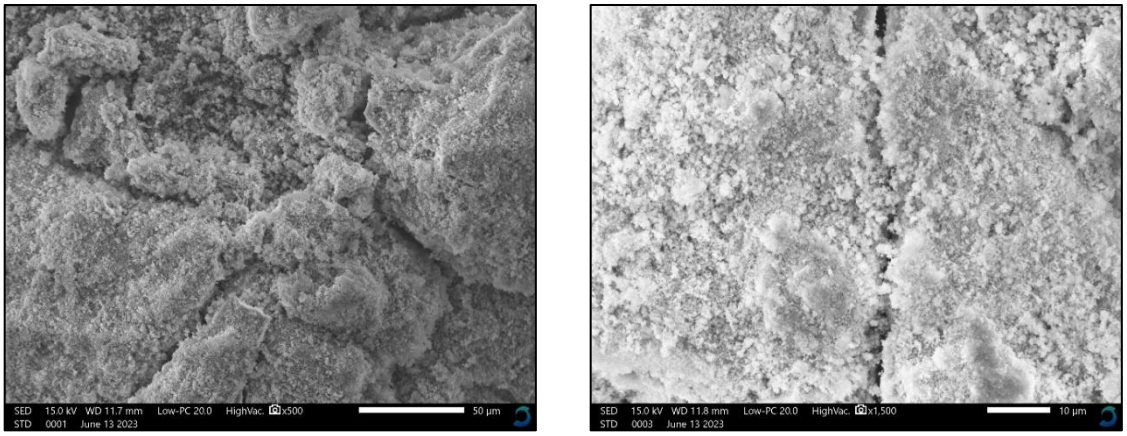


Figure 7.19. XRD of the dehydrated Ca(OH)2

Figure 7.20 shows the SEM images of dehydrated $Ca(OH)_2$.



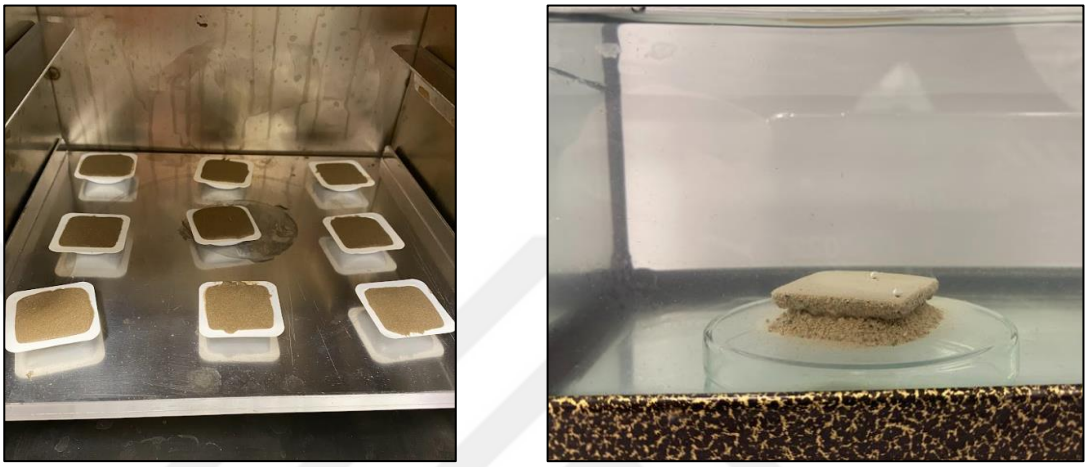
(a) (b)

Figure 7.20. Dehydrated Ca(OH)2 (a) 500X, (b) 1500X

7.4. RESULTS OF CATION RELEASE TESTS

In order to conduct the cation release tests, an ICP-MS (Inductively Coupled Plasma Mass Spectrometry) machine was utilized. Two series of concrete samples were tested, each with different compositions. The first series involved mixing concrete with Arabic gum to form

pallets, as depicted in Figure 7.21. The pallets were created using 14 grams of Arabic gum, 130 grams of DC powder, and 30 ml of distilled water. The second series comprised of raw concrete, where 130 grams of DC powder were submerged in 3 liters of seawater in a fish tank, as illustrated in Figure 7.22. The pH values of the DC powder were recorded and are presented in Table 7.4.



(a) (b)

Figure 7.21. (a) Shows the drying of pallets in the oven for 15 mins under the temperature of 60 °C, (b) Shows a pallet inside the fish tank

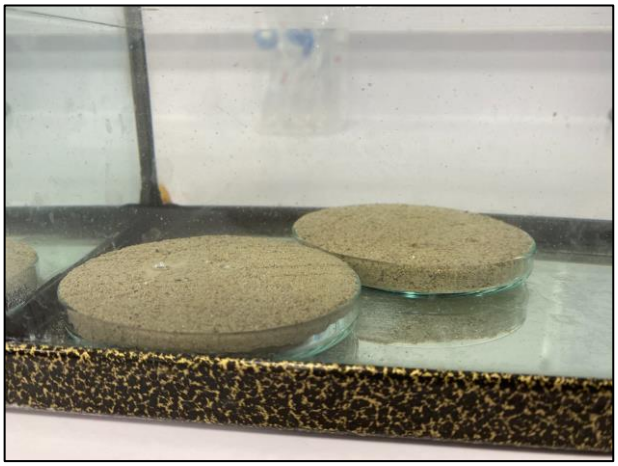


Figure 7.22. Raw DC under sea water for cation release testing

Table 7.4. DC powder PH under sea water for 7 days

Days	PH
1	7.68
2	8.37
3	8.26
4	8.26
5	8.24
6	8.2
7	8.17

Both series were placed in the fish tank filled with seawater for a duration of 7 to 8 days. During this period, water samples were collected daily to assess cation release. The procedure for collecting the water samples involved taking 5 ml of seawater and combining it with 5 ml of an HCl solution containing 5% HCl (5 ml of HCl + 95 ml of distilled water) in a 10 ml tube. These resulting samples were then subjected to analysis using the ICP-MS system, yielding the outcomes presented in Table 7.5. A1 to A7 represent the Arabic gum samples while R1 to R7 represent the Raw DC samples, for both series the number specifies the day of sample collection.

The cation release tests were conducted to determine the extent of leaching and release of various cations from the concrete samples. The ICP-MS analysis provided quantitative data on the concentration of cations present in the collected water samples. This data was crucial in evaluating the leaching behavior of the concrete samples and assessing the potential environmental impact of cation release.

By analyzing the results from the ICP-MS analysis, valuable insights were gained regarding the cation release profiles of the concrete samples. The concentrations of different cations, such as calcium (Ca_2+), sodium (Na+), iron (Fe+), and aluminum (Al+), were measured and recorded. These findings offered important information on the mobility and leaching characteristics of these cations from the concrete samples.

The cation release profiles provided a comprehensive understanding of the potential environmental implications associated with the concrete materials. The data obtained through the ICP-MS analysis helped in assessing the overall environmental impact of the concrete samples, particularly in terms of cation release and the potential contamination of surrounding ecosystems.

Table 7.5. Cation release results using ICP-MS

Day	Chemical Element	Type	Results (ppm)	Day	Chemical Element	Type	Results (ppm)
1	Sodium (Na)	R	3747	2	Sodium (Na)	R	3727
		A	3674			A	3426
	Aluminum (Al)	R	0.097		Aluminum (Al)	R	0.087
		A	0.07			A	0.078
	Calcium (Ca)	R	99		Calcium (Ca)	R	122
		A	103			A	86
	Iron (Fe)	R	0.488		Iron (Fe)	R	0.519
		A	0.451			A	0.466
3	Sodium (Na)	R	3755	4	Sodium (Na)	R	3755
		A	3618			A	3509
	Aluminum (Al)	R	0.082		Aluminum (Al)	R	0.079
		A	0.081			A	0.079
	Calcium (Ca)	R	116		Calcium (Ca)	R	129
		A	83			A	76
	Iron (Fe)	R	0.519		Iron (Fe)	R	0.555
		A	0.479			A	0.491
5	Sodium (Na)	R	3594	6	Sodium (Na)	R	3569
		A	3737			A	3427
	Aluminum (Al)	R	0.076		Aluminum (Al)	R	0.075
		A	0.078			A	0.079
	Calcium (Ca)	R	117		Calcium (Ca)	R	122
		A	106			A	121
	Iron (Fe)	R	0.5722		Iron (Fe)	R	0.578
		A	0.494			A	0.518
7	Sodium (Na)	R	3383				
		A	3736				
	Aluminum (Al)	R	0.074				
		A	0.079				
	Calcium (Ca)	R	119				
		A	103				
	Iron (Fe)	R	0.605				
		A	0.519				

In conclusion, the cation release tests conducted using the ICP-MS technique allowed for a detailed evaluation of the leaching behavior and cation release profiles of the concrete samples. The results obtained through this analysis provided valuable insights into the environmental impact of the concrete materials and their potential effects on surrounding ecosystems. These findings contribute to the broader understanding of concrete's behavior

and its environmental implications, aiding in the development of sustainable and environmentally friendly construction practices.

7.5. RESULTS OF CARBON CAPTURE TESTS

In order to analyze the carbon capture capacity of the concrete samples, Thermogravimetric Analysis (TGA) was employed. Three samples were selected for testing: raw demolished concrete (DC), alkaline leached DC (0.5 M NaOH), and $Ca(OH)_2$ obtained after the acidic leaching of DC using 18.08ml NaOH for 30 minutes. The CO_2 uptake values (80% CO_2 by volume) of these samples were recorded at varying temperatures and over increasing time intervals. Figure 7.23 illustrates the changes in CO_2 uptake for raw DC, alkaline leached DC, and $Ca(OH)_2$. The samples were heated under N_2 atmosphere from the room temperature up to 700 °C and, when the samples reached at 700 °C, the gas, which was introduced into the system, was switched to a gas mixture containing 80% CO_2 and remaining N_2 by volume.

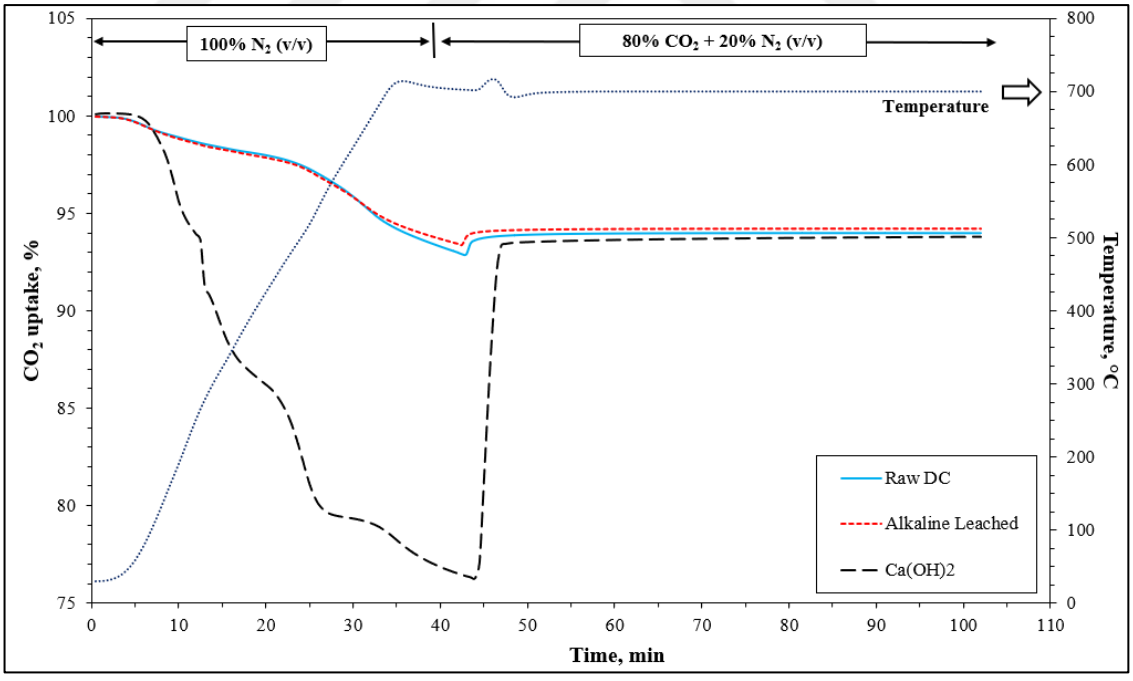


Figure 7.23. CO2 uptake values (80% CO2 by vol.) of raw DC, alkaline leached (0.5 M) and Ca(OH)2 with increasing time and changing temperature.

To further evaluate the carbon capture behavior, the normalized CO_2 uptake values (80% CO_2 by volume) of raw DC, alkaline leached DC (0.5 M NaOH), and $Ca(OH)_2$ were plotted

against time, as depicted in Figure 7.24. The corresponding normalized CO_2 uptake values were presented in Table 7.6.

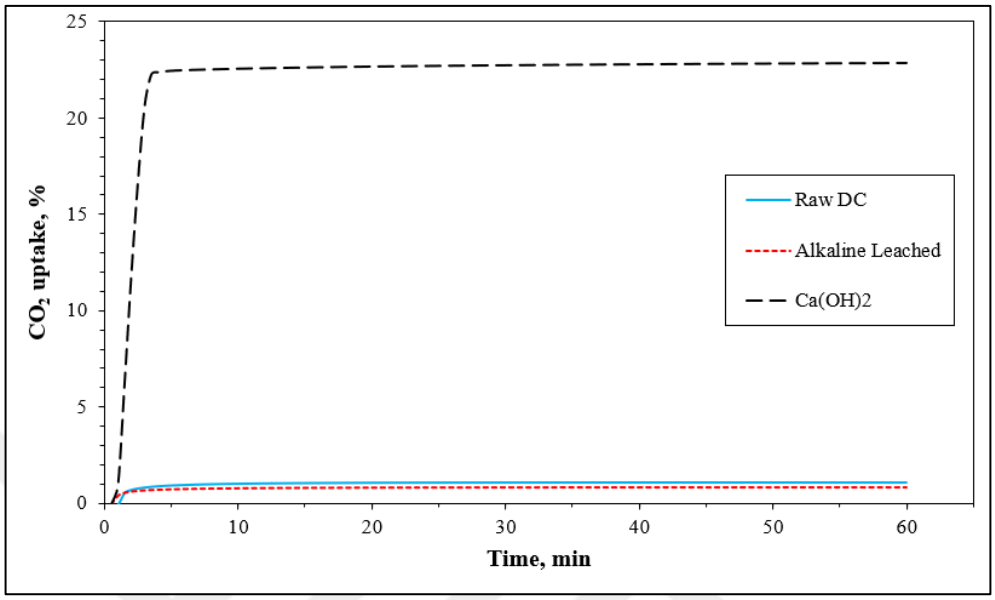


Figure 7.24. Normalized CO2 uptake values (80% CO2 by vol.) of raw DC, alkaline leached (0.5 M) and Ca(OH)2 with increasing time at 700 °C.

Table 7.6. Normalized CO2 uptake values by wt.% (80% CO2 by vol.) of raw DC, alkaline leached (0.5 M) and Ca(OH)2 with respect to time and at 700 °C.

Time, min	**Raw DC**	**Alkaline Leached**	**$Ca(OH)_2$**
10	1.00	0.78	22.57
20	1.05	0.81	22.68
30	1.06	0.83	22.75
40	1.07	0.83	22.80
50	1.07	0.83	22.84
60	1.06	0.83	22.87

The obtained results indicated that the carbon capture performance was not as high as initially anticipated for alkaline leached samples. Several factors could contribute to this outcome. Firstly, the limited solubility of calcium hydroxide may have influenced its carbon capture capacity. It is possible that during the alkaline leaching process, a small portion of calcium hydroxide was lost, which subsequently affected the carbon capture results. Therefore, it is crucial to investigate the solubility of calcium hydroxide in water and its potential impact on carbon capture efficiency.

Understanding the factors that influence carbon capture performance is essential for optimizing the efficiency of concrete materials in mitigating CO_2 emissions. By evaluating the CO_2 uptake behavior of the different samples, valuable insights can be gained into the effectiveness of the carbon capture process. These findings contribute to the broader understanding of sustainable construction practices and provide valuable information for the development of concrete materials with enhanced carbon capture capabilities.

On the other hand, a remarkable carbon uptake capacity was measured for the sorbent which were produced through acidic leaching (22.87wt.% after 60 minutes of carbonation). Acidic leaching and following precipitation can be a promising way to produce CO_2 capture sorbents from demolishing concretes.

In conclusion, the TGA analysis provided valuable insights into the carbon capture capacity of the concrete samples. The recorded CO_2 uptake values and their variations over time and temperature provided a comprehensive understanding of the carbon capture behavior. The study highlighted the need to address factors such as solubility limitations and potential losses during the leaching process to further enhance the carbon capture efficiency of concrete materials. These findings contribute to the ongoing efforts to develop sustainable construction practices and mitigate the environmental impact of concrete production.

8. CONCLUSION

In conclusion, this thesis aimed to explore the potential of demolition concrete (DC) as a new material for carbon capture, considering its abundance and the significant amount of waste generated. The DC was processed by grinding, resulting in an average particle size of 211.09 μm, making it suitable for further analysis and testing.

Leaching experiments were conducted using three different methods: (1) distilled water (DI) leaching, (2) alkaline leaching with NaOH and, (3) acidic leaching with HCl and precipitation of $Ca(OH)_2$-based sorbents through NaOH addition. DI and alkaline leaching were employed to enhance the content of free calcium oxide-based materials within the DC powder, while acidic leaching aimed to recover calcium hydroxide [$Ca(OH)_2$]. X-ray diffraction (XRD) analysis confirmed the presence of a substantial amount of calcium-based materials in the samples, validating the effectiveness of the leaching processes.

Dehydration of the obtained $Ca(OH)_2$ from acidic leaching was carried out at a temperature of 700 °C, transforming it into calcium oxide (CaO). This step further demonstrated the versatility and potential applications of DC in different forms.

Cation release tests were conducted on both the raw DC powder and the DC powder mixed with arabic gum over a period of 7 days in sea water in a fish tank. The purpose was to assess the leaching behavior and potential release of cations from the samples. The results provided insights into the mobility and leaching characteristics of various cations, contributing to a better understanding of the environmental impact of DC materials.

Carbon capture experiments were performed by means of a thermogravimetric analyzer (TGA). Three samples, namely raw DC, alkaline-leached DC and $Ca(OH)_2$ from acidic leaching, were tested for their carbon capture capabilities. The results revealed that both raw DC and alkaline-leached DC exhibited similar abilities to capture carbon, although the efficiency was not significantly high (around 1 wt.%). However, $Ca(OH)_2$ showed the highest potential for carbon capture (up to 22.87 wt.%). It should be noted that the carbon capture efficiency of $Ca(OH)_2$ did not reach the theoretical values, which can be attributed to various factors such as the dissolution of calcium-based materials during leaching. Nevertheless, this study presents promising prospects for utilizing DC in carbon capture applications, opening avenues for further research and exploration in the field.

Overall, this project sheds light on the potential of demolition concrete as a viable material for carbon capture. The findings emphasize the importance of innovative approaches in sustainable construction practices and highlight the need for continued research and development in this area. By utilizing DC as a carbon capture material, significant strides can be made towards mitigating carbon emissions and promoting environmental sustainability in the construction industry. For further studies in this field, it is recommended to apply cation release tests (in sea water) to carbon captured samples in order to benchmark their cation release performances with that of original samples which were conducted in this thesis. Thus, through this way, environmental effects of carbon captured samples from demolition concrete can be evaluated for possible offshore sea filling applications.

REFERENCES

1. Pacheco-Torgal F, Castro-Gomes J, Jalali S. Alkali-activated binders: A review. Part 1. Historical background, terminology, reaction mechanisms and hydration products. *Constr Build Mater*. 2008;22(7):1305–14.

2. Pacheco-Torgal F, Castro-Gomes J, Jalali S. Alkali-activated binders: A review. Part 2. About materials and binders manufacture. *Constr Build Mater*. 2008;22(7):1315–22.

3. Song X, Xiaoyu C, Lin Q, Yanna L. A Review of Mineral Carbonation from Industrial Waste. *IOP Conf Ser Earth Environ Sci*. 2019;401(1).

4. Mehta K, J. M. Montreiro P. Concrete microstructure, properties, and materials fourth edition. 4th ed. *McGrawHill*;

5. American Concrete Institute. Building Code Requirements for Structural Concrete (ACI 318-14). *American Concrete Institute*. 2014. 1–524 p.

6. A.M. Neville, J.J. Brooks. *Civil_Engineering_Materials*.Pdf. 1987.

7. Steven H. Kosmatka, Beatrix Kerkhoff and WCP, Kosmatka SH, Kerkhoff B, Panarese WC. *Design and Control Design and Control of*. 2002. 105–118 p.

8. Edition F, Member H, Society C. properties of concrete. Vol. 199, *Notes and Queries*. 1954. 131 p.

9. Taylor HFW. *Cement chemistry*. Cem Chem. 1997;

10. ACI Committee 116. Cement and Concrete Terminology. *Am Concr Inst* [Internet]. 2000;58. Available from: http://dl.mycivil.ir/dozanani/ACI/ACI 116R-00 Cement and Concrete Terminology_MyCivil.ir.pdf

11. *Based on Purpose Concrete* [Internet]. Available from: https://www.youtube.com/watch?v=qLW-MOd_n_c

12. Mehta PK. High-performance, high-volume fly ash concrete for sustainable development. *Int Work Sustain Dev Concr Technol*. 2004;3–14.

13. Weil M, Jeske U, Dombrowski K, Buchwald A. Sustainable design of geopolymers - Evaluation of raw materials by the integration of economic and environmental aspects in the early phases of material development. *Adv Life Cycle Eng Sustain Manuf Businesses - Proc 14th CIRP Conf Life Cycle Eng*. 2007;(January):279–83.

14. Erdem S. Synthesis and characterization of calcium phosphate cement based macroporous scaffolds. *Thesis*. 2012;(July):1–332.

15. Nejad FM, Tolouei M, Nazari H, Naderan A. Effects of calcium carbonate nanoparticles and fly ash on mechanical and permeability properties of concrete. *Adv Civ Eng Mater*. 2018;7(1):651–68.

16. Wang D, Shi C, Farzadnia N, Shi Z, Jia H, Ou Z. A review on use of limestone powder in cement-based materials: Mechanism, hydration and microstructures. *Constr Build Mater*. 2018;181:659–72.

17. Liu H, Zhao J, Wang Y, Yi N, Cui C. Strength performance and microstructure of calcium sulfoaluminate cement-stabilized soft soil. *Sustain*. 2021;13(4):1–12.

18. Andrew RM. Global CO 2 emissions from cement production , 1928 – 2018. 2019;1675–710.

19. Farooq M, Pisante M. Innovations in sustainable agriculture. *Innovations in Sustainable Agriculture*. 2019. 1–627 p.

20. FISCHER G, WANG S, LI VC. Design of Engineered Cementitious Composites (Ecc) for Processing and Workability Requirements. *Brittle Matrix Composites 7*. 2003. p. 29–36.

21. Basavaraj AS, Gettu R. Life Cycle Assessment As a Tool in Sustainability Assessment of Concrete Systems: Why and How? *Indian Concr J*. 2022;96(4):8–27.

22. Noyce P, Grevello G. Durability of reinforced concrete. *Struct Mag*. 2016;(January):10–3.

23. *Concrete Dumps* [Internet]. Available from: https://moretonbayrecycling.com.au/concrete-disposal-recycling-methods/

24. Silva R V., De Brito J, Dhir RK. The influence of the use of recycled aggregates on

the compressive strength of concrete: A review. *Eur J Environ Civ Eng*. 2015;19(7):825–49.

25. Ding Z, Wang Y, Zou PXW. An agent based environmental impact assessment of building demolition waste management: Conventional versus green management. *J Clean Prod*. 2016;133:1136–53.

26. Pada Bose B. State-of-the-art on Recycling of Construction and Demolition Waste in a Circular Economy: An Approach Towards Sustainable Development. *Int J Earth Sci Knowl Appl J homepage B P Bose Int J Earth Sci Knowl Appl* [Internet]. 2022;4(3):516–23. Available from: http://www.ijeska.com/index.php/ijeska

27. Kabirifar K, Mojtahedi M, Wang C, Tam VWY. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *J Clean Prod*. 2020;263(April).

28. Tam VWY. Economic comparison of concrete recycling: *A case study approach. Resour Conserv Recycl*. 2008;52(5):821–8.

29. Potgieter JH. An Overview of Cement production: How “green” and sustainable is the industry? *Environ Manag Sustain Dev*. 2012;1(2).

30. Shen LY, Li Hao J, Tam VWY, Yao H. A checklist for assessing sustainability performance of construction projects. *J Civ Eng Manag*. 2007;13(4):273–81.

31. *zion market revenue* [Internet]. Available from: https://www.zionmarketresearch.com/report/cellular-concrete-market

32. Mehta PK. Greening of the Concrete Industry for Sustainable Development. *Concr Int*. 2002;24(7):23–8.

33. *global concrete market*.

34. Dou Y, Xue X, Zhao Z, Luo X. Factors influence China’s off-site construction technology innovation diffusion. *Sustain*. 2019;11(7).

35. *china cement consumption*. Available from: https://carboncounter.wordpress.com/2015/02/09/chinas-cement-consumption-grew-more-this-century-than-the-rest-of-planets-has-since-the-invention-of-cement/

36. SUN TK. A Dissertation Submitted To the Faculty of Architecture in Candidacy for the Degree of Bachelor of Science in Surveying By. 2004;140.

37. Mathur Vs, Farouq Mm, Labaran Yh. The carbon footprint of construction industry: A review of direct and indirect emission. *J Sustain Constr Mater Technol*. 2021;6(3):101–15.

38. Tran NP. Strategic progress in foam stabilisation towards high-performance. 2022;

39. Hood R. Global Warming of 1.5°C. *A Companion to Appl Ethics*. 2007;674–84.

40. (PUBLIC USEPA DOMAIN). *Energy and the environment explained Greenhouse gases* [Internet]. 2022. Available from: https://www.eia.gov/energyexplained/energy-and-the-environment/greenhouse-gases.php

41. Cook J, Oreskes N, Doran PT, Anderegg WRL, Verheggen B, Maibach EW, et al. Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environ Res Lett*. 2016;11(4).

42. 1.5 *c. Available from: https://www.smth.jp/english/sustainability/Initiatives_achievements/climate-change/strategy-1

43. Mann ME, Rahmstorf S, Kornhuber K, Steinman BA, Miller SK, Coumou D. Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. *Sci Rep*. 2017;7(March).

44. *global sea level*. Available from: https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

45. Delbeke J, Runge-Metzger A, Slingenberg Y, Werksman J. *The paris agreement*. Towar a Clim Eur Curbing Trend. 2019;24–45.

46. Jarraud M, Steiner A. Summary for policymakers. Vol. 9781107025, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: *Special Report of the Intergovernmental Panel on Climate Change*. 2012. 3–22 p.

47. *paris agreement goals* [Internet]. Available from: https://www.treeaid.org/blogs-updates/paris-climate-agreement/

48. Roy J, Harnisch J, Tanaka K, Worrell E. Climate change 2007: mitigation of climate change: contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Choice Rev Online.* 2008;45(09):45-5006-45–5006.

49. Yu X, Ye X, Lin H, Feng N, Gao S, Zhang X, et al. Knockdown of long non-coding RNA LCPAT1 inhibits autophagy in lung cancer. *Cancer Biol Med.* 2018;15(3):228–37.

50. *CO2 emissions* [Internet]. Available from: https://ourworldindata.org/co2-emissions

51. Venterea RT. Climate Change 2007: Mitigation of Climate Change. *J Environ Qual.* 2009;38(2):837–837.

52. Bhattacharyya P, Pathak H, Pal S. Mitigation of Greenhouse Gases Emission and Low Carbon Technologies. *Green Energy Technol*. 2020;129–53.

53. Negative Emissions Technologies and Reliable Sequestration. *Negative Emissions Technologies and Reliable Sequestration*. 2019.

54. *CCS* [Internet]. Available from: https://www.e-education.psu.edu/meteo469/book/export/html/223

55. Wang X, Zhang F, Li L, Zhang H, Deng S. Carbon dioxide capture. Vol. 58, *Advances in Chemical Engineering*. 2021. 297–348 p.

56. *A Global Breakdown Of Greenhouse Gas Emissions By Sector*. Available from: https://www.visualcapitalist.com/a-global-breakdown-of-greenhouse-gas-emissions-by-sector/

57. *Carbon Capture and Sequestration (CCS) in the United States*. 2022;

58. United Nations Framework Convention on Climate Change [UNFCCC]. *United Nations Climate Change Annual Report 2019* [Internet]. 2019. 56 p. Available from: https://unfccc.int/sites/default/files/resource/unfccc_annual_report_2019.pdf

59. Samanta A, Zhao A, Shimizu GKH, Sarkar P, Gupta R. Post-combustion CO 2 capture using solid sorbents: A review. *Ind Eng Chem Res*. 2012;51(4):1438–63.

60. Energy Technology Perspectives 2020 - Special Report on Carbon Capture Utilisation and Storage. Energy Technol Perspect 2020 - *Spec Rep Carbon Capture Util Storage*. 2020;

61. Liang Z (Henry), Rongwong W, Liu H, Fu K, Gao H, Cao F, et al. Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents. *Int J Greenh Gas Control* [Internet]. 2015;40(January):26–54. Available from: http://dx.doi.org/10.1016/j.ijggc.2015.06.017

62. Rubin ES. The Outlook for Improved Carbon Capture Technology Outline of Today ' s Talk Two Principal Measures of Improved Capture Technology. 2015;1–16.

63. Page B, Turan G, Zapantis A, Burrows J, Consoli C. *The Global Status of CCS 2020: Vital to Achieve Net Zero.* 2020; Available from: https://www.h2knowledgecentre.com/content/researchpaper1679

64. Theo WL, Lim JS, Hashim H, Mustaffa AA, Ho WS. Review of pre-combustion capture and ionic liquid in carbon capture and storage. *Appl Energy* [Internet]. 2016;183:1633–63. Available from: http://dx.doi.org/10.1016/j.apenergy.2016.09.103

65. *oxyfuel* [Internet]. Available from: https://www.icb.csic.es/en/gi/co2-capture-oxy-fuel-combustion/

66. *direct air capture* [Internet]. Available from: https://www.proximoinfra.com/articles/8105/proximo-weekly-direct-air-capture-direct-to-market

67. Kätelhön A, Meys R, Deutz S, Suh S, Bardow A. Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proc Natl Acad Sci U S A*. 2019;166(23):11187–94.

68. *biological carbon sequestation* [Internet]. Available from: https://calrecycle.ca.gov/organics/compostmulch/toolbox/carbonsequest/

69. *Mineral carbonation.* Available from: https://pubs.acs.org/doi/10.1021/acssuschemeng.1c07867

70. Akiti TT, Constant KP, Doraiswamy LK, Wheelock TD. Development of an advanced calcium-based sorbent for desulfurizing hot coal gas. *Adv Environ Res*. 2001;5(1):31–8.

71. Ravikumar D, Zhang D, Keoleian G, Miller S, Sick V, Li V. Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. *Nat Commun* [Internet]. 2021;12(1):1–13. Available from: http://dx.doi.org/10.1038/s41467-021-21148-w

72. Şanal İ. Significance of Concrete Production in Terms of Carbondioxide Emissions: Social and Environmental Impacts. *J Polytech*. 2018;0900(2):369–78.

73. Strunge T, Renforth P, Van der Spek M. Towards a business case for CO2 mineralisation in the cement industry. *Commun Earth Environ*. 2022;3(1):1–14.

74. Schuldt SJ, Jagoda JA, Hoisington AJ, Delorit JD. A systematic review and analysis of the viability of 3D-printed construction in remote environments. *Autom Constr*. 2021;125(February).

75. Derg S. Bulletin of the Mineral Research and Exploration. 2014;85–106.

76. Nriagu JO, Jozef M. Pacyna. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. *Tropics* [Internet]. 2016;10(1):10. Available from: https://www.infodesign.org.br/infodesign/article/view/355%0Ahttp://www.abergo.org.br/revista/index.php/ae/article/view/731%0Ahttp://www.abergo.org.br/revista/index.php/ae/article/view/269%0Ahttp://www.abergo.org.br/revista/index.php/ae/article/view/106

77. Senanayake G. Acid leaching of metals from deep-sea manganese nodules - A critical review of fundamentals and applications. *Miner Eng* [Internet]. 2011;24(13):1379–96. Available from: http://dx.doi.org/10.1016/j.mineng.2011.06.003

78. Aaltonen M, Peng C, Wilson BP, Lundström M. Leaching of metals from spent lithium-ion batteries. *Recycling*. 2017;2(4).

79. Lunt D, Boshoff P, Boylett M, El-Ansary Z. Uranium extraction: The key process drivers. *J South African Inst Min Metall*. 2007;107(7):419–26.

80. Ghorbani Y, Franzidis JP, Petersen J. Heap leaching technology - Current State, innovations, and future directions: A review. *Miner Process Extr Metall Rev*. 2016;37(2):73–119.

81. Zarib NSM, Abdullah* SA, Jamil NH. Extraction Of Silica From Rice Husk Via Acid Leaching Treatment. 2019;175–83.

82. Jha MK, Kumari A, Panda R, Rajesh Kumar J, Yoo K, Lee JY. Review on hydrometallurgical recovery of rare earth metals. *Hydrometallurgy* [Internet]. 2016;165:2–26. Available from: http://dx.doi.org/10.1016/j.hydromet.2016.01.035

83. Wen K, Jiang F, Zhou X, Sun Z. Recovery of gallium from corundum flue dust by two-stage alkali leaching, carbonation, acid leaching and solvent extraction process. *Metals (Basel)*. 2018;8(7):10–2.

84. Parikh DM. Vacuum Drying: Basics and application. *Chem Eng (United States)*. 2015;122(4):48–54.

85. Rattanadecho P, Makul N. Microwave-Assisted Drying: A Review of the State-of-the-Art. *Dry Technol.* 2016;34(1):1–38.

86. S. Nur Dirim* GÇ. Determination of the Effect of Freeze Drying Process on the Production of Pumpkin (Cucúrbita Moschatä) Puree Powder and the Powder Properties Dondurarak Kurutma Í § Lemínín Balkabagi. *Gida*. 2012;37(4):203–10.

87. Orthous-daunay FRÉ. Loss on ignition: estimation method for organic matter in particulate matter loss on ignition: estimating organic matter in PM. *Origins. 2013*;(November):1–25.

88. Introduction AN, Callister WD, Rethwisch DG. *Materials Science and Engineering.*

89. Zomer RJ, Trabucco A, Bossio DA, Verchot L V. Climate Change Mitigation : A Spatial Analysis of Global Land Suitability for Climate change mitigation : *A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation*. 2008;(December 2017).

90. Lett ER, Chazdon RL, Lindenmayer D, Guariguata MR, Crouzeilles R. Corrigendum : Fostering natural forest regeneration on former agricultural land through economic

and policy interventions Fostering natural forest regeneration on former agricultural land through economic and policy interventions. *Environ Res Lett* [Internet]. 2020;15(4):43002. Available from: http://dx.doi.org/10.1088/1748-9326/ab79e6

91. Lal R. Restoring soil quality to mitigate soil degradation. *Sustain*. 2015;7(5):5875–95.

92. Xu X, Sreeram A, Cheng S. Potential use of recycled concrete aggregate (RCA) for sustainable asphalt pavements of the future: *A state-of-the-art review*. 2022;(February).

93. Kim J. Construction and demolition waste management in Korea: recycled aggregate and its application. *Clean Technol Environ Policy* [Internet]. 2021;23(8):2223–34. Available from: https://doi.org/10.1007/s10098-021-02177-x

94. Poon CS, Chan D. Paving blocks made with recycled concrete aggregate and crushed clay brick. 2006;20:569–77.

95. Profile SEE, Profile SEE. Recycled aggregate concrete – sustainable use of construction and demolition waste and reduction of energy consumption Recycled aggregate concrete – *sustainable use of construction and demolition waste and reduction of energy consumption*. 2016;(January).

96. Alengaram UJ, Rahman M. use of recycled concrete aggregate in concrete: a review. 2013;(August 2016).

97. Reed MS, Kenter J, Bonn A, Broad K, Burt TP, Fazey IR, et al. Participatory scenario development for environmental management : A methodological framework illustrated with experience from the UK uplands. *J Environ Manage* [Internet]. 2013;128:345–62. Available from: http://dx.doi.org/10.1016/j.jenvman.2013.05.016

98. Zhou D, Zhao S, Zhu C. The grain for green project induced land cover change in the Loess Plateau: A case study with Ansai County, Shanxi Province, China. *Ecol Indic* [Internet]. 2012;23:88–94. Available from: http://dx.doi.org/10.1016/j.ecolind.2012.03.021

99. Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, et al. Systems integration for global sustainability. 2015;

100. *aral sea* [Internet]. Available from: https://www.youtube.com/watch?v=UZwLTJroLpE

101. The NOF. *The great green wall Initiative of the sahara and the sahel*.

102. *brazil* [Internet]. Available from: https://www.brightvibes.com/the-brazilian-photographer-and-the-20-year-reforestation-project-of-over-2-7-million-trees/

103. *Great Green Wall* [Internet]. Available from: https://www.weforum.org/agenda/2021/06/how-a-great-green-wall-could-help-africa-combat-climate-change/

104. Pa RWO. *Opportunities Assessment*.

105. Chazdon RL. Beyond Deforestation : *Restoring Degraded Lands*. 2008;1458.

106. Global Dialogue *EXPO 2000*. 2000.

107. Rica C. Land cover dynamics following a deforestation ban in northern Costa Rica. 2020;

108. Reed Ms, Buenemann M, Atlhopheng J, Bachmann F, Bastin G, Bigas H, Et Al. Cross-Scale Monitoring And Assessment Of Land Degradation And Sustainable Land Management : *A Methodological Framework For Knowledge Management*. 2011;271(January):261–71.

109. To The United Nations Convention To Combat Desertification In Those Countries Experiencing Serious Drought And / Or Desertification , Particularly africa and the council of the global environment facility. 2018;