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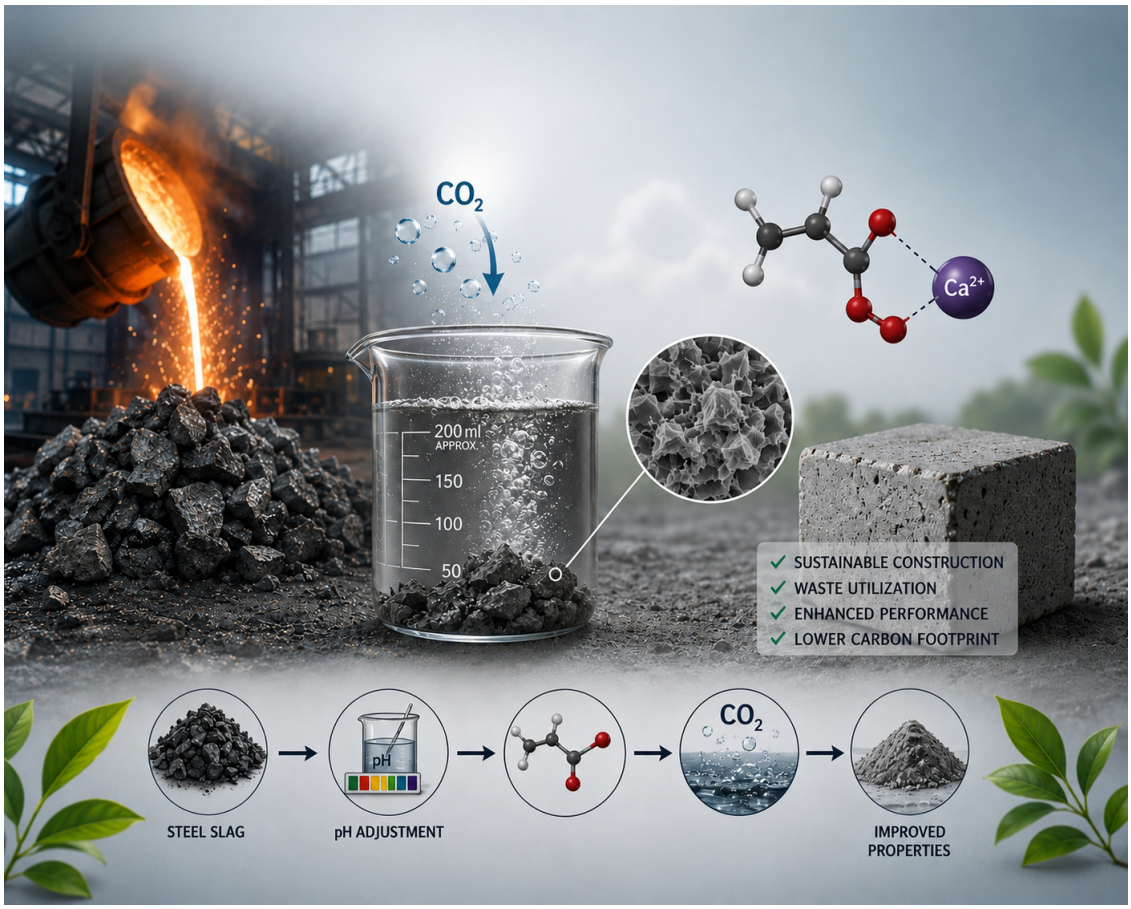

Optimization of Mineralized Steel Slag: Pre-Treatment and pH Adjustment

Master's thesis in the Master's Programme Structural Engineering and Building Technology

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

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MASTER'S THESIS ACEX30

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Conceptual Demonstration of the optimazation of slag through Pre-Treatment and pH Adjustment for Sustainable Cementitious Material
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ABSTRACT

The growing demand for sustainable construction materials created a need to investigate and identify alternative Supplementary Cementitious Materials (SCMs) that not only can reduce cement consumption but also promote the utilization of industrial by-products. Among them, steel slag is a calcium and silicate-rich by-product from the steel industry that was considered as potential to be used as SCM; however, due to its low reactivity and presence of unstable mineral phase prohibits it from direct application. So, this study investigates the optimization of the steel slag with mechanical and chemical treatment methods followed by pH adjustment and carbonation particularly empahsis on Electric Arc Furnace Slag and Basic Oxygen Furnace Slag. The main objective was to analyse how different treatment conditions affect mineral dissolution, carbonate formation, and the potential performance of the treated slag as a partial cement replacement.

Both of the slags were mechanically treated by drying, grinding, and sieving them through 63 μm before the chemical treatment with 2.5%, 5%, and 10% acetic acid concentration. The influence was then evaluated through pH monitoring and characterization techniques, including ICP-MS, XRD, TGA, SEM, and compressive strength testing. Subsequent carbonation studies focused mainly on EAF slag under different carbonation conditions such as 80°C for 4 hours, 105°C for 4 hours and 2 hours.

The results demonstrated that increasing the concentration of acid enhances the dissolution of mineral phases, but XRD analysis indicates the stronger acid treatment also caused a greater reduction in calcium silicate phases, demonstrating a trade-off between calcium extraction and preservation of potentially cementitious minerals. Carbonation results in the formation of crystalline carbonated phases, primarily calcite and aragonite, which is confirmed by XRD and SEM. TGA showed that the sample carbonated at 80 °C for 4 hours showed a greater carbonation-related mass loss among the different investigated conditions.

Compressive Strength testing with 20% cement replacement further showed that the sample carbonated at 80 °C for 4 hours gained the best 28-day performance among others, reaching approximately 47 MPa, equivalent to 90% of the reference cement strength. Overall, the study demonstrates that controlled pre-treatment and mineral carbonation can improve the potential of EAF slag as SCM. The results also emphasize that optimum treatment conditions depend on achieving an appropriate balance between calcium extraction, carbonate formation, preservation of reactive phase, and mechanical performance.

Key words:
Supplementary Cementitious Materials, Steel Slags, EAF Slag, BOF Slag, Treatment, Mechanical Treatment, Chemical Treatment, pH Adjustment, Carbonation

Optimization of Mineralized Steel Slag: Pre-Treatment and pH Adjustment

Examensarbete inom masterprogrammet Konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

Den ökande efterfrågan på hållbara byggmaterial har skapat ett behov av alternativa kompletterande cementmaterial (SCM) som kan minska cementförbrukningen och samtidigt främja användningen av industriella biprodukter. Stålslagg är en kalcium- och silikatrik biprodukt från stålindustrin med potential att användas som SCM, men dess låga reaktivitet och förekomsten av instabila mineralfaser begränsar direkt användning. Denna studie undersöker därför optimering av ljusbågsugnsslagg (EAF) och syrgaskonverterslagg (BOF) genom mekanisk och kemisk behandling, följt av pH-justering och karbonatisering. Syftet var att utvärdera hur olika behandlingsförhållanden påverkar mineralupplösning, karbonatbildning och slaggets potential som partiell cementersättning.

Slaggerna torkades, maldes och siktades till under 63 μm och behandlades därefter med 2,5 %, 5 % och 10 % ättiksyra. Effekterna utvärderades genom pH-mätning samt ICP-MS, XRD, TGA, SEM och tryckhållfasthetsprovning. Karbonatiseringsförsöken fokuserade främst på EAF-slagg vid 80 °C och 105 °C under olika behandlingstider.

Resultaten visade att högre syrakoncentration ökade mineralupplösningen, men XRD-analysen visade samtidigt en större minskning av kalciumsilikatfaser vid starkare syrabehandling. Detta visar på en avvägning mellan kalciumextraktion och bevarandet av potentiellt cementreaktiva faser. Karbonatiseringen ledde främst till bildning av kalcit och aragonit, vilket bekräftades genom XRD och SEM. TGA visade att provet karbonatiserat vid 80 °C i 4 timmar uppvisade den största karbonatrelaterade massförlusten.

Vid 20 % cementersättning uppnådde samma prov även den bästa tryckhållfastheten efter 28 dagar, cirka 47 MPa, motsvarande ungefär 90 % av referenscementets hållfasthet. Sammantaget visar studien att kontrollerad förbehandling och mineralkarbonatisering kan förbättra EAF-slaggens potential som SCM. Optimala behandlingsförhållanden kräver dock en balans mellan kalciumextraktion, karbonatbildning, bevarande av reaktiva mineralfaser och mekanisk prestanda.

Nyckelord:
Kompletterande cementmaterial, stålslagg, EAF-slagg, BOF-slagg, behandling, mekanisk behandling, kemisk behandling, pH-justering, karbonatisering.

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Preface

This master's thesis was carried out as a part of the Master's Programme at Chalmers University of Technology and carried out from January 2026 to August 2026.. The thesis work primarily focused on the optimization of mineralized steel slag through different mechanical and chemical pre-treatments, followed by pH adjustment and carbonation, with particular emphasis on improving the potential for use as a supplementary cementitious material (SCM).

I would like to express my sincere gratitude to my supervisor, Baodong Li, for his continuous guidance, valuable feedback, encouragement, and support throughout the planning and development of this thesis. His suggestions and guidance were highly valuable in shaping the experimental work and improving the overall quality of the study.

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Notations

Abbreviations

BOF	Basic Oxygen Furnace
EAF	Electric Arc Furnace
GGBFS	Ground Granulated Blast Furnace Slag
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
SCM	Supplementary Cementitious Material
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
XRD	X-ray Diffraction

Chemical formulas and mineral phases

Al	Aluminium
Ca	Calcium
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide (Portlandite)
Ca_2SiO_4	Dicalcium silicate
CH_3COOH	Acetic acid
CO_2	Carbon dioxide
Cr	Chromium
Fe	Iron
H_2O	Water
HNO_3	Nitric acid
Mg	Magnesium
MgO	Magnesium oxide
Mn	Manganese
SiO_2	Silicon dioxide
C–S–H	Calcium silicate hydrate

Symbols

C_{original}	Element concentration in the original leachate
C_{ICP}	Element concentration measured by ICP-MS
d	Interplanar spacing
n	Order of diffraction
λ	Wavelength of incident X-ray
θ	Bragg angle

Units and experimental notation

°C	Degree Celsius
μm	Micrometre
MPa	Megapascal

rpm	Revolutions per minute
%	Percentage
h	Hour
min	Minute

Sample designations

CS80/4h	Carbonated steel slag treated at 80°C for 4 hours
CS105/2h	Carbonated steel slag treated at 105°C for 2 hours
CS105/4h	Carbonated steel slag treated at 105°C for 4 hours
C+CS80/4h	Cement containing steel slag carbonated at 80°C for 4 hours
C+CS105/4h	Cement containing steel slag carbonated at 105°C for 4 hours
C+CS105/2h	Cement containing steel slag carbonated at 105°C for 2 hours

1 Introduction

The construction industry has a very significant role in development as it provides infrastructure, the industrial sector, transport networks, as well as residential buildings. With the continuous growth of this sector, demand for cement and concrete has increased significantly, making the cement industry one of the top contributors to global carbon emissions. So the concern towards the environment and greenhouse has attracted many researchers towards more sustainable construction materials that can reduce emissions and helps to reduce the impact of it. So, this study also focuses on the experimentation of the materials, i.e., steel slags, for viability to be used as supplementary cementitious materials(SCMs), thereby reducing cement consumption with the motive of establishing the sustainable construction industry.

1.1 Background

Climate change and the increase in the concentration of the CO_2 in the atmosphere have become a serious issue worldwide in today's situation.[1]. Various sources emit the CO_2 in the atmosphere, such as fossil fuel consumption, waste, landfills, industrial processes, and many more [2]. Among them, the cement industry plays a significant role in the emission of CO_2 , which is about 8% of the global CO_2 emission[3]. A large proportion of emissions is due to the production of cement clinker, especially for Portland cement[1, 4], which requires high temperatures and the decomposition of limestone[1, 4]. In the production of clinker, limestone($CaCO_3$) and other materials are heated in a rotary kiln at a very high temperature of around 1450 °C [5]. During this process, $CaCO_3$ undergoes a chemical reaction known as Calcination, where $CaCO_3$ decomposes into Calcium Oxide (CaO) and CO_2[4]. The equation is given below.

$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2} \uparrow \tag{1.1}$$

In addition to this, to maintain the high temperature of the kiln, a large quantity of fossil fuels is consumed that also contributes in CO_2 emissions in the cement industry[6, 1]. Not only this, fossil fuels are widely consumed in various forms such as electricity or heat production, transportation, and other industrial sectors[7] that makes it as one of the highest contributor to global CO_2 emission.It accounted for approximately 70% of cumulative anthropogenic CO_2 emissions between 1850 and 2021[8].
To address these challenges and their consequences, many researchers are interested in finding and developing sustainable alternative materials[9]. Reducing the usage of conventional cement and improving the efficiency of Raw materials in cement production are major approaches towards minimizing CO_2 emissions in the cement industry[4]. Furthermore, effective utilization of the industrial by-product can also promote environmental conservation and promoting sustainable construction practices[9]. One of the promising approaches is the partial replacement of Ordinary Portland cement with SCMs.

1.2 Supplementary Cementitious Materials (SCMs)

SCMs are materials that have some cementitious properties and show hydraulic or pozzolanic behaviour, or a combination of both*[10]*, and are used alongside Portland cement to partially replace the clinker in the concrete or mortar[10, 4]. SCMs are mostly

industrial by-products or naturally occurring materials, due to which they are considered more sustainable than traditional cement[11]. Some of the commonly known SCMs are fly ash, Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume, Calcined Clay, Limestone Powder, and Steel Slag[12]. Among these, fly ash and GGBFS are commonly used in practice commercially[13]. Fly ash is the by-product of the coal-fired plant, whereas GGBFS is the by-product of the iron manufacturing[14]. Fly ash is further categorized into two types, Class F and Class C, depending on its properties, and can typically replace about 15-30% of the binder. During the cement hydration process, it produces calcium hydroxide, which then reacts with these SCMs to form a compound known as Calcium Silicate Hydrate (C-S-H).[10, 15]. This compound helps to improve the strength and durability of the cement or concrete[16]. On the other hand, some studies show that GGBFS can replace up to 70% of the binder in some cases, but typically it replaces about 30-50% of the binder[17, 18]. Also, the chemical, mineralogical characteristics, and cementitious behaviour are considerably different between these two. As it has high latent hydraulic reactivity, it is widely used as an SCM.
As the world is moving towards sustainability and many countries are making certain rules and regulations to reduce carbon emissions, they are mostly shutting down the coal plants, as burning coal emits carbon[19]. Fly ash now has less availability than before[20]. The European Union has made climate and emissions laws that are restricting coal power plants, reducing fossil fuel use, and promoting the use of renewable sources of energy such as wind, solar, and hydro. They are aiming for climate neutrality by 2050[21]. Even Sweden shut down its last coal-fired power plant in 2020[22]. Not only that, but the legislative body of Sweden has also banned the new project to extract coal, oil, and natural gas since 2022[23]. Because of this, there is no production of fly ash in most of the European countries which makes it limited and unreliable. Not only this, the steel manufacturing industries are also moving towards the electric arc furnace instead of the blast furnace because of the low carbon dioxide emissions[24]. The blast furnace emits about 1.8 to 2.2 t CO_2 per ton of steel, whereas the electric arc furnace emits about 0.3 to 0.6 t CO_2 per ton of Steel[25]. So, there is also limited production and availability of GGBFS[26].
For this reason, there is always a need for more sustainable alternative materials, and steel slag is one of the prominent areas of study [27, 28].

1.3 Steel Slags

Steel Slag is an industrial by-product generated during the steel manufacturing process[29]. It is formed when impurities of molten metal react with fluxing agents such as lime or dolomite at high temperatures[30]. These fluxes facilitate the removal of impurities[31] such as silicon, phosphorus, and sulphur, which react with lime or dolomite to form a separate molten slag layer, which is subsequently separated and cooled as slag[32, 33]. If we talk about the chemical composition of this kind of slag, then it contains calcium oxides(CaO), magnesium oxides(MgO), silicon oxides(SiO_2), aluminium oxides(Al_2O_3), or iron oxides (Fe_2O_3)[34] along with various crystalline phases. One of the most important components is the RO phase, which is a solid solution mainly composed of FeO, MgO, and MnO in varying proportions. Due to its relatively low hydraulic reactivity, a higher proportion of this phase limits its direct utilization as SCM.
Global production of steel slag is estimated at around 160-300 million tonnes every year[35], with significant quantities remaining stockpiled.[27]. Many researchers are

studying the physical, chemical and mechanical properties of these kind of slag to be used as the SCMs, as it contains potential cementitious minerals[36]. However, their limited reactivity and the presence of expansive phases often require mechanical or chemical treatment before utilization[37]. Based on the process of the manufacturing of the steel, the slags are also classified into three categorizes which is known as Basic Oxygen Furnace Slag (BOF Slag), Electric Arc Furnace Slag (EAF Slag) and Ladle Furnace Slag (LF Slag)[38].

1.3.1 Electric Arc Furnace Slag (EAF Slag)

EAF Slag is an industrial by-product generated during the steel manufacturing process in an electric furnace, primarily through the melting of scrap steel. Compared to other conventional basic furnace routes, this method generally produces less CO_2 emission due to its fewer emissions on fossil fuels.[39] The EAF shows similar behaviour to the natural rocks as it has very high mineral contents[40, 34]. EAF show very strong characteristics in respect to the strength and durability due to which it can be considered as the suitable material for the construction sector[41, 40]. Recently, it was mostly used as the aggregate in road construction sector as it has better skid resistance due to the rough texture[42, 37]. As EAF steel-making holds roughly 25-30% of the total steel-making production, the EAF slag is produced with the estimation of the 65-90 million tons every year anually[35]. As the world is shifting towards the sustainability or green steel, the world is moving for the EAF steelmaking process which can increase the quantity of the EAF slag in the future[39, 24].

1.3.2 Basic Oxygen Furnace Slag (BOF Slag)

BOF Slag is an industrial by-product generated during the conversion of molten pig iron into steel. During this process, high-purity oxygen is blown into the molten metal in a basic oxygen furnace, promoting the oxidation of impurities, which react with fluxes such as lime and dolomite to form slag[43, 31]. This kind of slag contains calcium, silicate, iron oxide, magnesium oxide, and residual free lime[44, 34]. Physically, BOF are hard and dense in structure and possess good mechanical properties[44, 34].

Limitation of BOF and EAF Slag

Both EAF and BOF slags generally exhibit low hydraulic reactivity despite containing the calcium silicate phase with cementitious potential [37]. In EAF slag, the presence of relatively stable crystalline phases and iron-rich compounds limits its hydraulic activity. It reduces its contribution to the formation of the calcium silicate hydrate (C-S-H) compound[36]. Similarly, BOF slag contains calcium silicate phases such as dicalcium silicate(C_2S), which react with water to form the C-S-H compound. However, the slow hydration of these phases limits the formation of binding compounds and reduces their contribution to strength development[37, 45, 36].
Furthermore, the presence of free CaO and MgO in both slags, particularly in BOF slag, may cause additional durability problems. These oxides can react with water even after concrete is hardened, resulting in delayed hydration and volumetric expansion[28]. Such expansion may generate internal stresses and cause cracking, which can negatively affect the dimensional stability and durability of cement-based mate-

rials[46]. Therefore, appropriate pre-treatment methods are necessary to improve the hydraulic reactivity and reduce the potential expansion associated with both slags.

1.4 Mineralization

Mineralization is a chemical process in which CO_2 reacts with calcium and magnesium-bearing phases to form stable carbonate minerals. Steel slags are generally alkaline in nature and contain various reactive phases, such as free CaO, portlandite, and calcium silicates, which can react with CO_2 to form stable carbonate products, mainly $CaCO_3$. Therefore, mineralization provides a potential route for permanent CO_2 sequestration while also promoting the utilization of steel slag as an industrial by-product[47, 48]. The mineralization behaviour of steel slag depends on its mineralogical composition and treatment conditions, including particle size, temperature, CO_2 pressure, reaction time, and pH. Mineralization can also reduce unstable free CaO and modify the mineralogical composition and reactivity of the slag, potentially improving its volumetric stability and suitability for cement-based applications [48, 49]. Mineralization can generally be classified into two methods: Direct and Indirect Mineralization.

1.4.1 Direct Mineralization

Direct Mineralization is the process in which CO_2 reacts directly with calcium- and magnesium-bearing phases present in the steel slag without a separate chemical extraction step. This process can be carried out through gas-solid or aqueous carbonation. In gas-solid carbonation, CO_2 reacts with solid slag particles directly, whereas in aqueous carbonation, calcium and magnesium ions dissolve into the water and subsequently react with dissolved CO_2 to form stable carbonate minerals. The efficiency of this process depends on the particle size, temperature, pressure, and reaction time. However, the formation of carbonate layers on the slag surface may restrict further reactions and reduce the carbonation efficiency[49]. Therefore, different pre-treatment methods can help to increase the efficiency of mineralization of steel slag.

1.4.2 Indirect Mineralization

Indirect Mineralization involves extraction of the free CaO and MgO from steel slag before the mineralization process. In contrast to direct mineralization, the dissolution of the ions and the carbonation are done separately. Different chemical agents, such as acetic acid, can be used to dissolve the calcium-bearing phase and release the calcium ions into the solution, where the calcium acetate may be formed. The extraction efficiency depends on acid concentration, treatment time, particle size, and the mineralogical composition of slag[47, 50]. Also, pH plays a very important role in controlling the dissolution and carbonate formation. Acidic conditions favor the dissolution of the calcium phase, whereas the pH conditions promote carbonation when sufficient dissolved inorganic carbon is available. Therefore, these two parameters play a significant role in improving the calcium extraction and the subsequent mineralization potential of steel slag[47, 50]

1.5 Pre-Treatment

The first initial process that prepares the materials for further processing can be defined as pre-treatment. For the slag, it has various demerits if it is used as it is or raw. Raw slag exhibits low reactivity and contains free CaO and MgO phases, which increases the chances of volumetric instability. So, it should be pre-treated before being used as a SCM, to improve its dimensional stability and reactivity. There are various methods of pre-treatment, which are briefly described below:

1.5.1 Mechanical Pre-Treatment

The physical processing of the steel slag that includes changing of the physical characteristics can be termed as the mechanical pre-treatment. The raw steel slag sometimes comes in a wet state containing some portion of the solution inside it. These are then dried in an oven at $105°$C for 24 hours[37]. The dried slag is in the form of chunks, which are to be crushed into small particles. These particles are then further crushed into powder form[36]. It helps to increase the surface area, boosts the chemical reaction, and provides better bonding when used in the construction industry[51, 52]. The mechanical pre-treatment includes.: Grinding and Seiving. The ball mill or other grinding device can effectively crush the steel slag into powder form. For this, a certain ratio of steel balls to slag is taken in the holder of the ball mill, which is then fixed into the machine with the holder's counterweight. It is then rotated inside the machine at a pre-fixed or custom rotation per minute (RPM) for a certain time, depending on how fine the particles you need, without overheating the system[53, 51]. From this, we can extract the powder form of the steel slag[51].
Sieving is the mechanism of separating the different particle sizes of the steel slag[54]. There are various sieve sizes available in the market, such as 1mm, 2mm, 75 μm, 63 μm, 25 μm, etc. The powdered slag from the ball mill is then allowed to pass through the desired size of the sieve to get the desired particle size[37].

1.5.2 Chemical Pre-Treatment

The chemical pre-treatment involves the addition of various additives to the steel slag to stabilize and change the nature of the chemical composition of the slag[37, 36]. Usually, slag contains several free ions that are quite unstable and can react with water, which ultimately can cause expansion[28, 55]. It might result in the formation of cracks. So, the chemical pre-treatment could be very beneficial to improve the performance of the steel slag if used as a construction material and also for the CO_2 capture and sustainability[56, 57].
The main objective of chemical activation of steel slag is to modify its mineralogical and chemical properties to improve its reactivity and potential application as a SCM. Chemical activation involves treating the slag with different chemical agents, such as acids (phosphoric acid (H_3PO_4)), alkalis(Potassium Hydroxide(KOH)), and salts(Zinc Chloride($ZnCl_2$)), to promote the dissolution or activation of reactive mineral phases [58]. These treatments can modify the surface characteristics and chemical composition of the slag, which ultimately improves the adsorption properties[58, 51] that may influence its hydraulic and pozzolanic activity.
Chemical extraction is a pre-treatment process in which steel slag is treated with water or a chemical solution to dissolve reactive mineral phases and release elements such as

calcium and magnesium into the solution[56, 59]. In steel slag, acid extraction can promote the dissolution of calcium-bearing phases, increasing the availability of calcium ions for subsequent mineralization reactions. Organic acids, such as acetic acid, can react with calcium-bearing compounds present in steel slag and form soluble calcium salts[60]. For example, CaO reacts with acetic acid to form calcium acetate and water, as shown in the following equation:

$$\mathrm{CaO} + 2\mathrm{CH_3COOH} \rightarrow \mathrm{Ca(CH_3COO)_2} + \mathrm{H_2O} \tag{1.2}$$

1.5.3 Ageing or weathering pre-treatment

Ageing and weathering are natural or semi-natural pre-treatment methods used to improve the volumetric stability of steel slag before its application in construction materials[34]. Aging involves storing steel slag for an extended period under suitable environmental conditions, allowing free CaO and MgO to react gradually with moisture through hydration reactions [44]. These reactions can reduce the amount of unhydrated free oxides and thereby lower the risk of delayed volumetric expansion when the slag is used in cement-based materials. In contrast, weathering involves exposing steel slag to atmospheric conditions such as rainfall, moisture, temperature variations, and atmospheric CO_2. During this process, hydration and natural carbonation reactions may occur, while rainwater can also promote the leaching of soluble salts and certain metal ions[28, 34]. Both methods can contribute to stabilizing steel slag, although their effectiveness depends on exposure conditions, treatment duration, and the slag's mineralogical composition.

1.6 Aims and Objectives

The main aim of this research is to optimize the steel slag with different pre-treatment methods and adjust the pH to increase its performance so that it can be used as an SCM. To achieve this aim and divide the work into different subcategories, it is classified into different objectives, which are listed below;

- Characterize the various properties of the steel slags, especially BOF and EAF Slags.
- To examine the morphology and chemical composition of the treated steel slag, especially BOF and EAF Slags.
- To evaluate the influence of pH adjustment in the carbonation/ mineralization.
- Study the influence of the treated and pH-adjusted slag on the hydration behaviour and chemical activation potential when used as an SCM.

To complete my aims and objectives, the workflow diagram is as follows:

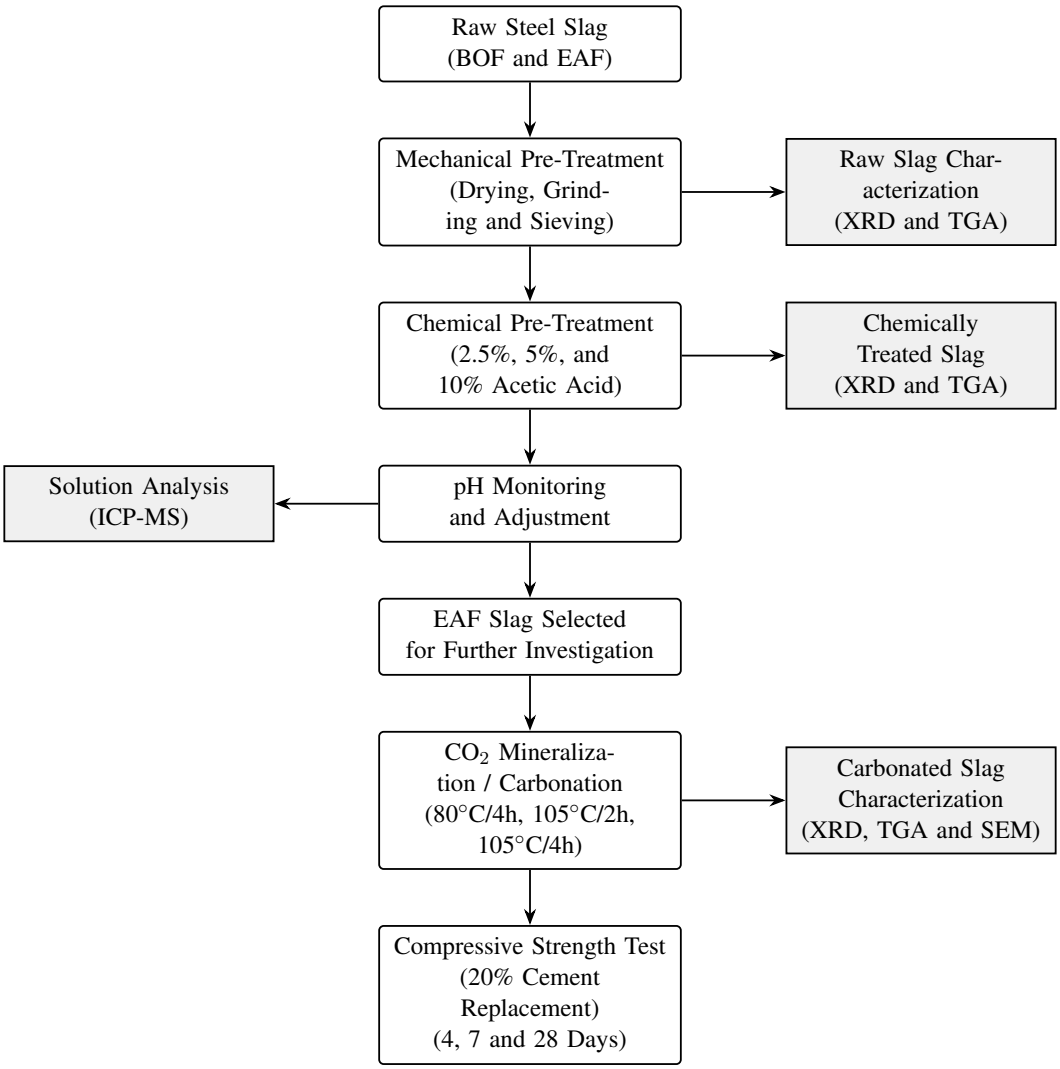


Figure 1.1: Overall experimental workflow for the pre-treatment, characterization, carbonation, and mechanical performance evaluation of steel slag.

1.7 Research Questions

The increasing demand for sustainable construction materials and the growing generation of steel slag highlight the importance of exploring its potential as a SCM. This study focuses on improving the properties of steel slag through mechanical and chemical pre-treatment, pH adjustment, and carbonation. The main objective is to investigate how these treatments influence the reactivity, mineralogical composition, and mineralization potential of steel slag for its possible use as SCM. To achieve this objective, the following research questions are addressed:

1. How does the optimization of the steel slag, i.e., pre-treatment and adjustment of the pH, affect the CO_2 extraction efficiency?
2. How does CO_2 mineralization and pH-adjusted pre-treatment of steel slag influence its hydration behavior and chemical activation potential when used as a supplementary cementitious material?
3. How does the mineralized steel slag affect the properties of the cement-based structure if it is used as a supplementary cementitious material?

2 Materials and Methods

2.1 Materials

The primary materials used in this experimental study were BOF slag and EAF slag. Both of them are by-products of the steelmaking process.

Table 2.1: Chemical composition of BOF and EAF slags (wt.%)

Slag	**CaO**	**Fe_2O_3**	**SiO_2**	**MgO**	**Al_2O_3**	**MnO**	**Cr_2O_3**	**TiO_2**	**P_2O_5**
BOF slag	51.55	21.39	13.96	0.76	4.45	2.83	0.54	1.03	0.77
EAF slag	29.10	37.70	9.71	6.32	4.92	6.20	2.24	0.40	0.30

Table 2.1 gives the chemical composition of the both BOF and EAF slag. It is clear that the BOF slag is rich with the calcium phases (51.44%) which could be of great potentiality of being used as SCM if properly treated. The material is primarily composed of CaO followed by Fe_2O_3(21.39%). The other composition includes SiO_2 , MgO ,Al_2O_3 and so on. The relatively high percentage of calcium oxide indicates the presence of the calcium-bearing phase that could participate in the dissolution during the treatment procedure, which increases mineralization the potentiality of the slag.
.Although EAF slag is rich in Fe_2O_3(37.70%), CaO(29.10%) is also present as the second-highest percentage. So, we can estimate that there is also the presence of the calcium-bearing phases. With the proper treatment, it might also be a potential SCM. The other materials are SiO_2, MgO, Al_2O_3, MnO and so on. These compositional differences are expected to influence the dissolution behaviour, pH response, mineralization as well as overall reactivity of the slag during the treatment procedure as well.
Besides this, the study includes the use of various reagents and laboratory materials that are involved in the mechanical and chemical treatment as well as the mineralisation. The major materials, chemicals, and their purposes are summarized in the tables below: The materials that were used for the entire work are tabulated below:

Table 2.2: Materials used in the experimental study

Material	**Grade/Purity**	**Supplier**	**Purpose**
BOF Steel Slag	Industrial by-product	-	Raw material for SCM study
EAF Steel Slag	Industrial by-product	-	Raw material for SCM study
Acetic Acid glacial	99.7%	Fisher Scientific	Calcium extraction
Calcium Hydroxide	95%	Alfa Aesar	pH adjustment
Distilled Water	Laboratory Grade	Laboratory	Solution preparation
Carbon Dioxide (CO_2)	99.9%	Gas Supplier	Mineral carbonation

2.2 Preparation Method

Prior to the experimental analysis, all the machines and equipment that were needed for the preparation of the samples, treatment, adjustment of the pH, and mineral carbonation were assembled, checked, and calibrated according to the laboratory procedures. The preparation of the samples includes reducing the size using mechanical grinding methods, sieving it to the appropriate size, pre-treatment, and carbonation under laboratory conditions. Appropriate instruments were used for the entire study to achieve accurate preparation and obtain reliable experimental parameters.
The instruments and equipment that were used for this research, with brief information, are in Table 2.3.

Table 2.3: Equipment and instruments used in the experimental study

Equipment/Instrument	**Model / Manufacturer**	**Purpose**
Ball Mill	PM 100 / Retsch	Grinding steel slag into fine powder prior to chemical treatment.
Jaw Crusher	Retsch	Reducing the size of dried steel slag before grinding.
Drying Oven	Heratherm Thermo Scientific	Drying raw and treated samples at 105°C.
Sieve Shaker	AS 200 / Retsch	Separating particles using a 63 μm sieve.
63 μm Test Sieve	ISO 3310 / Retsch	Obtaining uniformly sized slag particles.
pH Meter	SevenCompact S220 / Mettler Toledo	Monitoring and adjusting solution pH.
Vacuum Filtration Unit	-	Separating solid residues from the leachate.
Carbonation Reactor	Laboratory-built	Carbonating calcium-rich solution using CO_2.

2.3 Methods

2.3.1 Characterization

For the evaluation of physical, chemical, and mineralogical changes that might occur in the steel slag, different characterizations were performed before and after the pre-treatment and carbonation process. Different samples were analyzed in various stages of the work, such as raw slag, chemically treated slag and carbonated slag to examine the effectiveness of the work.
For the samples, BOF slags and EAF slags were used. These slags were heated in the oven at 105 °C for about 24 hours to let them dry. The big lumps of the slag were then crushed in the crusher to get the small particles, which were then ground in the ball mills to get the powder form. The powder is then sieved through 63 μm to get evenly fine particles, which were the raw slag that was used for the chemical pre-treatment.
The raw slag was then chemically treated. Acetic acid is used for the treatment of the steel slag. Three different concentrations of acid, i.e 2.5%, 5%, and 10%, were used for the proper examination of the effectiveness of the treatment. The steel slag was immersed in the solution with proper monitoring of the pH and stirring it properly to ensure the proper occurrence of the neutralization reaction.

After the treatment, more focus is given to EAF slag for further analysis. The carbonation was done with the filtered solution after the pre-treatment as well as the solution along with the slag. The later carbonated solution was filtered, and the sedimented steel slag particles were used for the various characterization methods. The listed characterization techniques provide information regarding the phase, composition, and morphology of the materials.

2.3.1.1 Inductively Coupled Plasma Mass Spectrometry

This test is commonly known as the ICP-MS test. For the pre-treatment, different mini samples were made to collect the solution for different days. The liquid is then extracted from the samples and acidified with nitric acid (HNO_3) for the stabilization of the dissolved metal ions and also to prevent further precipitation. The solution is then diluted 1000 times or within the calibration range of the instrument with deionized water and is tested to get the resulting value for the different elemental composition.
Therefore, the values obtained directly from the test represent the concentration in the 1000-times diluted sample. To estimate the elemental composition in the original leachate, the measured ICP-MS concentration should be multiplied by the dilution factor:

$$C_{\text{original}} = C_{\text{ICP}} \times 1000 \tag{2.1}$$

2.3.1.2 X-Ray Diffraction Test

It is commonly known as XRD Test and is the mostly use techniques to identify the mineral composition of minerals. The slag samples were prepared in powdered form for the identification of crystalline phases. The analysis was performed on raw, chemically pre-treated, and carbonated slag samples to evaluate the changes in mineralogical composition at different treatment stages. The crystalline phases were identified by comparing the characteristic diffraction peaks with reference patterns. Particular attention was given to calcium-bearing phases, such as CaO, portlandite, and Ca-Si, as well as the RO phase, while the formation of $CaCO_3$ polymorphs, including calcite, aragonite, was examined following carbonation. The XRD analysis was performed using a Bruker D8 DISCOVER diffractometer with Cu Kα radiation ($\lambda = 1.5406$ Å). The measurements were conducted over a 2θ range of $5°$–$60°$, with a step size of $0.02°$. The crystalline phases were identified by comparing the characteristic diffraction peaks with reference patterns. The analysis was used to evaluate changes in the mineralogical composition of the slag following chemical pre-treatment and carbonation.

2.3.1.3 Thermogravimetric Analysis

It is commonly known as the TGA test, and the samples are analysed by measuring the change in mass with the increase in temperature. A sample with a mass of 8- 12 mg was taken in a cube and placed in the machine, from which the machine's lever arm takes it into its inner chamber, where the temperature is gradually increased at the speed of 10 °C per minute up to 1000 °C. So the mass will change eventually with the decomposition of different compounds at different temperatures.
The main purpose of the TGA analysis is to determine the carbonates decomposed and

evaluate the carbonation efficiency.

2.3.1.4 Scanning Electron Microscope Test

It is commonly known as the SEM test and helps to analyze the surface morphology of the materials. The magnification of the SEM is generally much higher than the normal optical microscope, so it gives the full potential to gain the information related to the morphology of the material. It can magnify the sample from 100x to 10000x depending upon the necessity. The prepared samples are mounted on an aluminium specimen holder. For the improvement of the electrical conductivity and minimizing the charging effect, the samples were coated with gold. The samples are then kept inside the chamber for analysis under vacuum conditions.

2.3.1.5 Compressive Strength Test

It is a mechanical characterization technique and helps to determine the strength of the materials after the treatment is done. After the carbonation, the liquid is then filtered out, and the sediment is then dried in the oven at 105 °C for about 24 hours. The dried treated slag is then ground with the help of a hand grinder and sieved through a standard 75 μm sieve, and the particles are then used to replace the cement by 20% and then cast into a mortar cube, which is then demolded and cured for compressive strength tests for 4 days, 7 days, and 28 days.

3 Results

This chapter includes the experimental data and results obtained from different characterization techniques for the different samples. The results are organized sequentially, with the methodology followed by pH analysis, elemental composition, mineralogical characterization, morphological analysis, and mechanical performance. The findings are presented with figures and tables, and quantitative analysis is done along with the interpretation of the data; its implications are discussed in this chapter.

3.1 pH Analysis

During the chemical pre-treatment, three different concentrations of acetic acid (2.5%, 5%, and 10%) were used, and the pH value was monitored and evaluated on a timely basis. On plotting the data, the pH of both BOF and EAF slag increased rapidly during the initial stage of the reaction, followed by gradual stabilization. This is an indication that the dissolution of the alkaline minerals takes place prominently in the first place. The reason for the increment in the pH value is due to the dissolution of CaO, $Ca(OH)_2$, and other calcium-bearing phases that release OH^- ions into the solution.

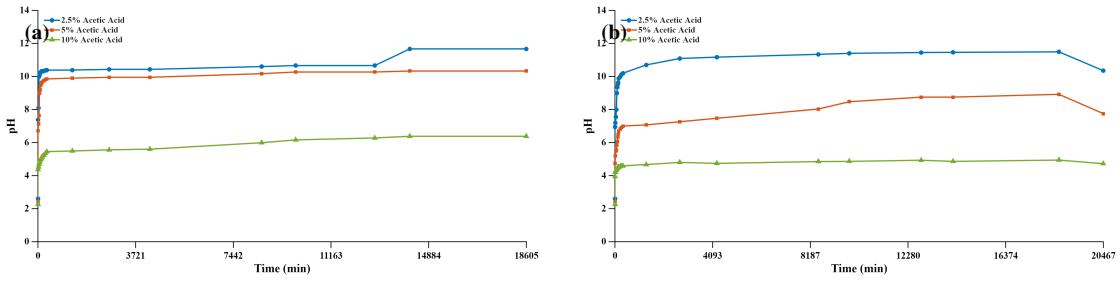


Figure 3.1: pH Comparison: (a) BOF Slag and (b) EAF Slag.

From Figure 3.1, for both slags, the treatment with acid concentration of 2.5% exhibited the highest pH value throughout the experiment, as it reached the maximum value of 11.7 for BOF slag and 11.5 for the EAF slag. The relatively low acid concentration treatment was sufficient to neutralize all the alkaline constituents released from the slag, resulting in a highly alkaline solution.

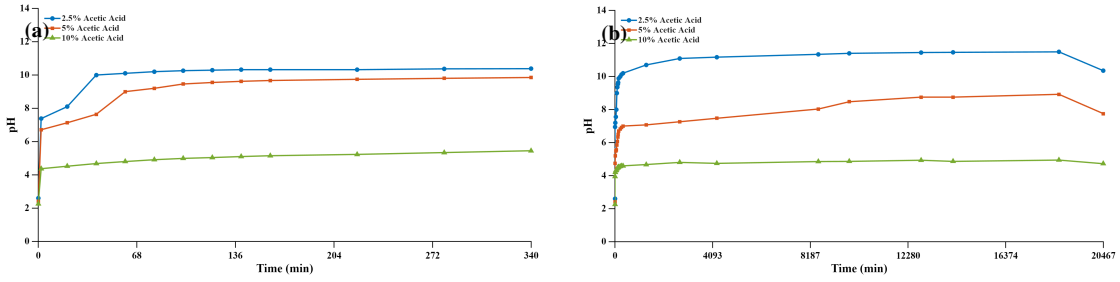


Figure 3.2: pH Comparison first 300 minutes: (a) BOF Slag and (b) EAF Slag.

The treatment with the 5% acidic solution produces intermediate values. The pH value gradually increased before stabilization. The value became constant at 10.3 for BOF slag and 9.0 for EAF slag, indicating greater neutralization of the alkaline species com-

pared with the 2.5% solution while still allowing continuous dissolution of the calcium-containing phase. The highest acid concentration, i.e 10%, maintained the lowest pH value throughout the experiment. It stabilized at 6.3 for BOF slag and 4.8 for EAF Slag. The higher acid concentration effectively neutralized the alkaline compounds released from the slag, thereby limiting the increase in pH value.
Figure 3.2 shows the immediate reaction, i.e for the first 300 minutes, and the change in pH in a clear way. For the BOF slag, the pH value for the lower acid concentration, i.e., 2.5%, increased rapidly to 10 within the first 40 minutes, and after that it remained nearly constant. The medium concentration, i.e., 5%, also shows a gradual increment from 6.5 to around 9.8, while the highest concentration, i.e., 10% treatment, shows only a small increment from around 4.1 to 5.4. EAF slag also shows a similar trend, but the increment in pH value was slower compared with BOF slag. The pH value of treatment with 2.5% concentration increased from 6.8 to 10, while 5% rose from 4.8 to 7.0. The treatment with 10% acid concentration increased only slightly from 3.8 to 4.5, making it comparatively more stable than the others.
Overall, lower acidic concentrations resulted in a higher pH value, whereas the highest acid solution maintained the lowest pH among all the samples throughout the experiment. Also, BOF slag showed a stronger and faster alkaline response in comparison to the EAF slag.

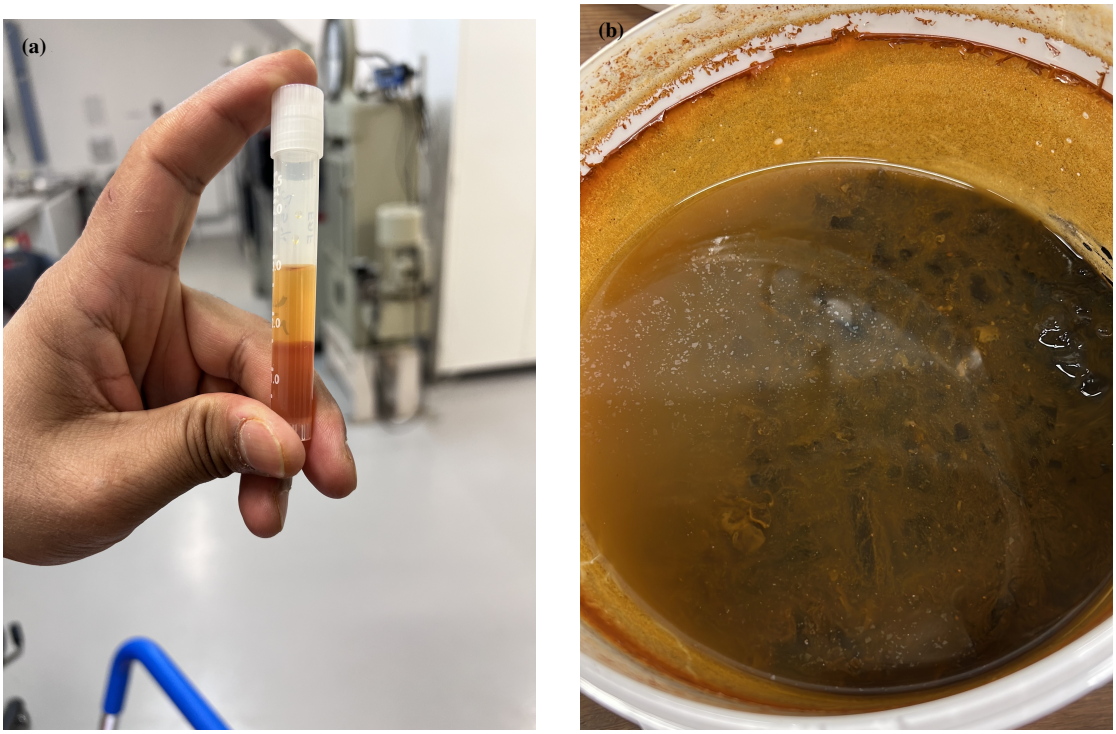


Figure 3.3: Gel Formation During Chemical Pre-Treatment: (a) Brown Gel and (b) Gel Formation.

Interestingly, during the chemical pre-treatment, a layer of brown gel-like substance was observed when the solution was not stirred properly, which is clearly visible in Figure 3.3. This layer appeared to hinder the contact between the acid solution and the slag particles, which resulted in a constant pH value of the solution at around 7. This occurs for the solution with an acid concentration of 2.5%. This observation indicates

that stirring is quite important during the chemical pre-treatment for the effective contact of the slag particles with the acid solution and to avoid the localized accumulation of reaction products.

3.2 Elemental Composition

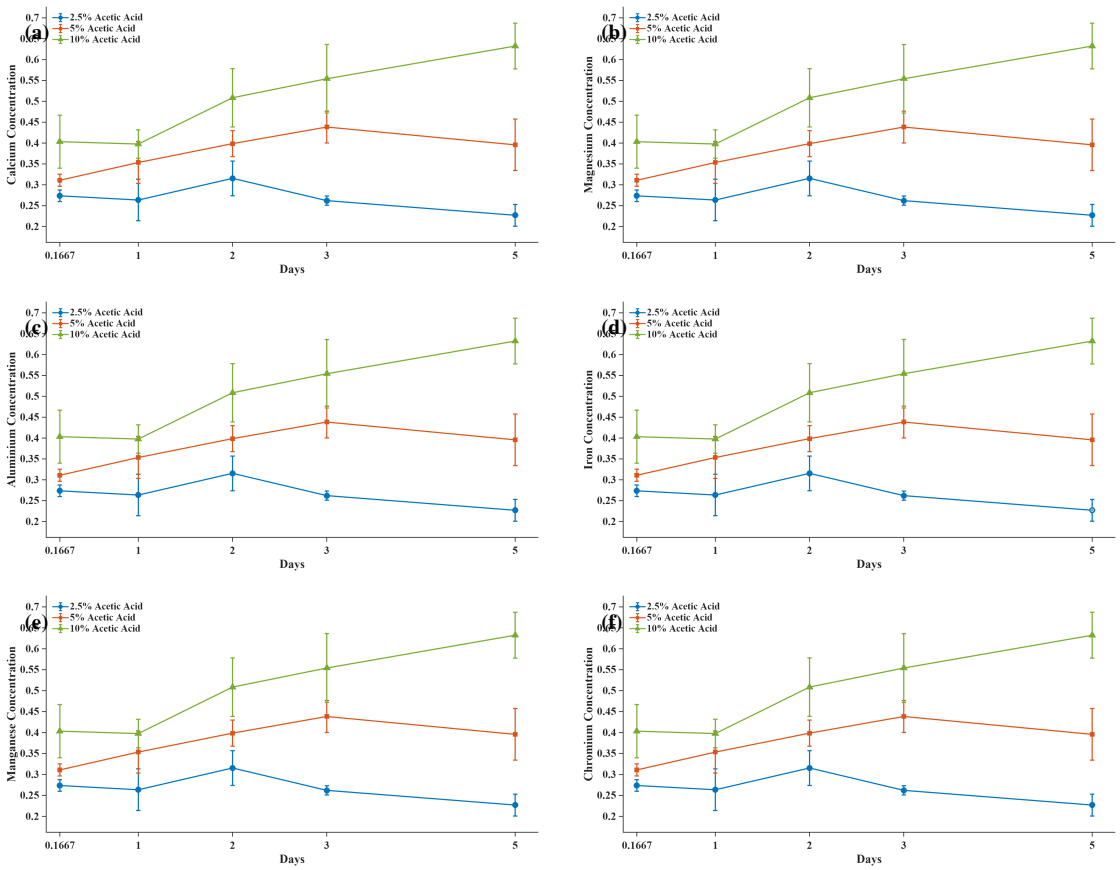


Figure 3.4: ICP results of EAF slag treated with different concentrations of acetic acid for different treatment durations: (a) calcium, (b) magnesium, (c) aluminium, (d) iron, (e) manganese, and (f) chromium.

Figure 3.4 shows the ICP-MS results for the EAF Slags treated with different acid concentrations, i.e., 2.5%, 5%, and 10% at different times. The analysis quantified the dissolved concentrations of elements such as Ca, Mg, Al, Cr, Fe and Mn , of which the first three are mineral-forming elements and the last three are transition metals. The overall results show the clear influence of the acid concentration on the elemental composition. From the graphs, it is clear that the 10% acid concentration treatment produces a higher dissolved metal concentration in comparison to 2.5% and 5%. This trend indicates that increasing the acid concentration enhanced the leaching efficiency of EAF slag by promoting greater dissolution of mineral phases from the EAF slag.
Figure 3.4(a), at 2.5% acid concentration, the Ca concentration initially increased, reaching its highest around 2 days, and then substantially decreased and remained almost constant after 3 days. The 5% acid concentration treatment produced a consistently higher Ca concentration than the 2.5% acid concentration treatment and showed an overall increase during the first several days, followed by a slight decrease at day 5. The 10% acid concentration treatment gave the highest Ca concentration. After the ini-

tial variation, the Ca concentration increased markedly with treatment time and reached its maximum value at day 5. Overall, the graph is clear evidence of an increase in dissolved calcium concentration with increasing acid concentration, with 10% treatment producing the greatest calcium release.
Magnesium also showed the similar behaviour on treating with different acid concentration as shown in Figure 3.4(b). The 2.5% concentration treatment remained at a relatively low level and generally decreased with increasing treatment time. The 5% treatment showed a moderate increase up to day 3, followed by a small decrement at day 5. The 10% treatment showed a clear increasing trend with time and reached its maximum value at day 5.
Remaining elements such as Al, Fe, Cr, and Mn also showed different elemental concentrations under different acid treatment conditions. But in general, 10% acid concentration treatment produces the highest dissolved elemental concentration, while the 2.5% treatment produces the lowest values and often shows decreasing concentration at longer treatment times. The intermediate acid concentration, i.e 5%, showed intermediate behaviour. In Figure 3.4(c), Al showed an initial increase followed by a decline at lower acid concentrations, whereas higher concentrations were maintained under 10% acid concentration treatment. Fe and Mn as shown in figure 3.4(d) and figure 3.4(e) also exhibited the similar behaviour which is higher the acid concentration, greater the dissolved elements while the chromium in figure 3.4(f) remained comparatively lower but followed the same sequence as others.

3.3 Mineralogical Characterization

3.3.1 XRD Analysis of Chemically Pre-Treated Slag

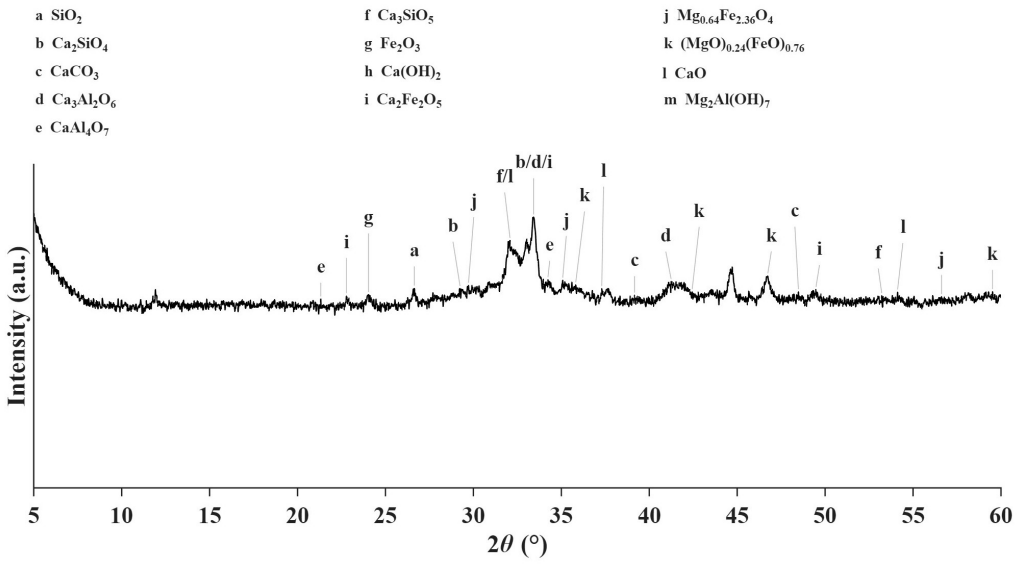


Figure 3.5: XRD analysis of Raw BOF slag.

The chemically treated slag was dried and crushed into powder form. This powder was placed in the sample holder, and an XRD test was performed. The results were then compared with the reference XRD graph, i.e Raw Slag, as shown in Figure 3.5 and Figure 3.6 to identify the peaks. The peaks labelled b and f represent Ca_2SiO_4 and Ca_3SiO_5 respectively, while l represents free CaO. The peak labelled k corresponds to

the RO-type phase, $(MgO)_{0.24}(FeO)_{0.76}$, which exhibits relatively low hydraulic reactivity and is a major drawback of steel slag.

Figure 3.7 represents and compares the XRD patterns of a raw BOF slag with the

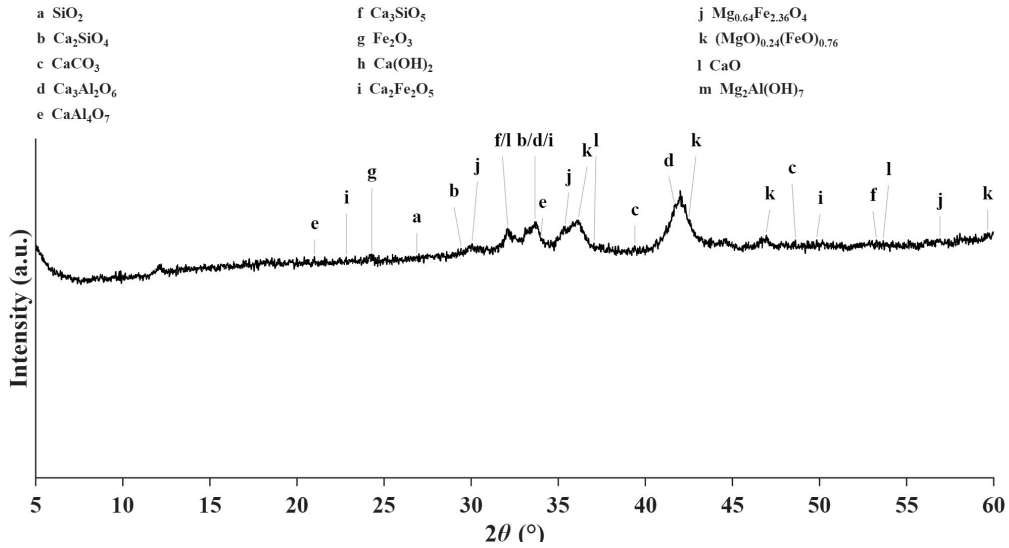


Figure 3.6: XRD analysis of Raw EAF slag.

treated sampled slag with acid concentrations of 2.5%, 5%, and 10%. The BOF slag exhibits several distinctive diffraction peaks; most of the major diffraction peaks remained visible for 2.5% acid concentration treatment, indicating that the original crystalline phases were largely preserved. However, at higher acid concentration treatment, the Ca-Si-related peaks, particularly b and the overlapping peaks, became less distinct, suggesting greater dissolution or alteration of Ca -bearing phases.

Similarly, Figure 3.8 shows the XRD patterns of raw and chemically treated EAF slag.

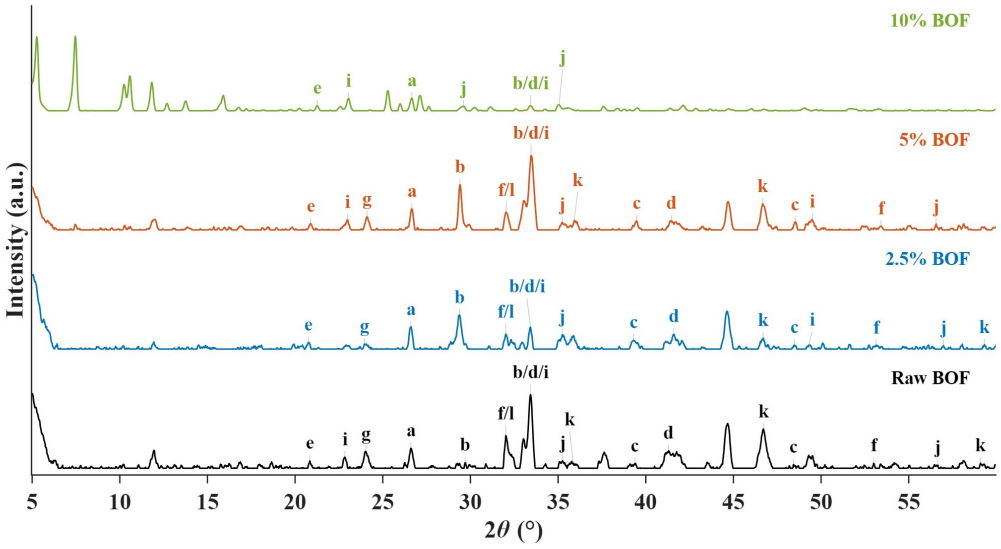


Figure 3.7: XRD comparison of differently treated BOF slags.

The prominent peaks labelled k and d/k are associated with Fe, Mg containing phases,

including the RO-type solid solution. The peaks remained visible after chemical treatment, suggesting that relatively stable crystalline phases existed. In contrast, several Ca-bearing peaks became less distinct with increasing acid concentration treatment, particularly at 10%.

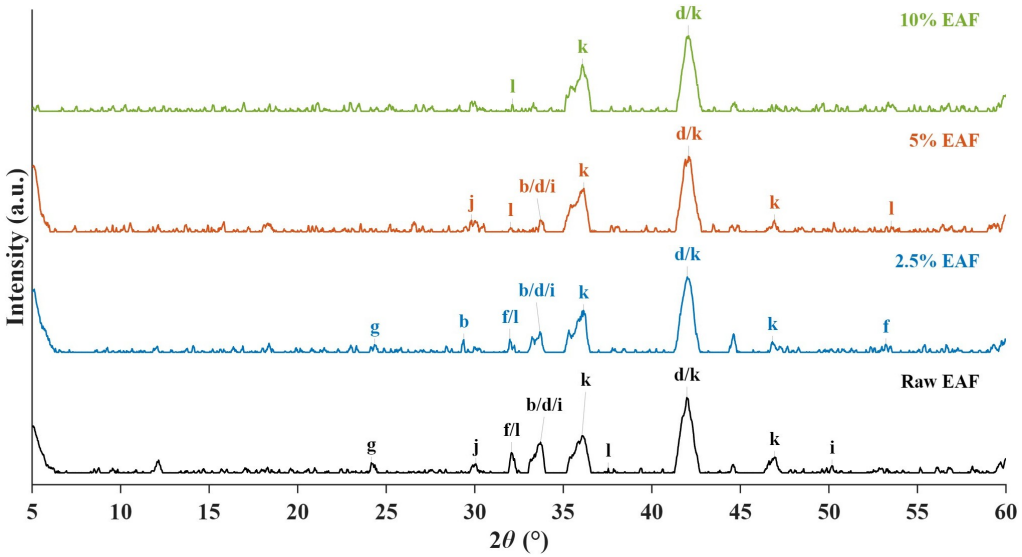


Figure 3.8: XRD comparison of differently treated EAF slags.

Overall, the XRD results indicate that increasing acid concentration promoted greater mineralogical alteration, consistent with the higher dissolved Ca concentration observed in ICP-MS analysis. However, stronger treatment may also reduce potentially cementitious Ca-Si phases. Therefore, an appropriate balance between Ca extraction and preservation of potentially reactive minerals is necessary.

3.3.2 XRD Analaysis of Carbonated Steel Slag

The XRD patterns of the carbonated steel slag, as shown in figure 3.9, demonstrate the change in the mineralogical behaviour of the slag after carbonation under different conditions. The appearance and increased intensity of carbonation-related diffraction peaks indicate the formation of crystalline $CaCO_3$ phases during the mineralization. These observation in the XRD is also supported by the SEM analysis presented in the figure 3.14, where the morphology associated with aragonite and calcite was observed.

The graph in the figure 3.9 compares the XRD patterns of the carbonated steel slag under three different conditions, i.e., CS-80/4h, CS-105/2h, and CS-105/4h. The prominent peaks labelled C correspond to calcite, while A represents aragonite. The overlapping peaks labelled C/A indicate that both carbonate phases contribute to the diffraction patterns.

All three samples exhibit calcite and aragonite peaks, confirming the formation of crystalline carbonate minerals after carbonation. However, differences in peak intensities suggest that temperature and treatment duration influenced the development of carbonate phases. The CS-80/4h sample also showed the greatest carbon-related mass loss in the TGA analysis, supporting greater carbonate formation under this condition.

Overall, the XRD results demonstrate the formation of calcite and aragonite after carbonation, which is further supported by the SEM and TGA analysis. Although the original EAF slag contains relatively stable phases such as the RO phase, the carbonated

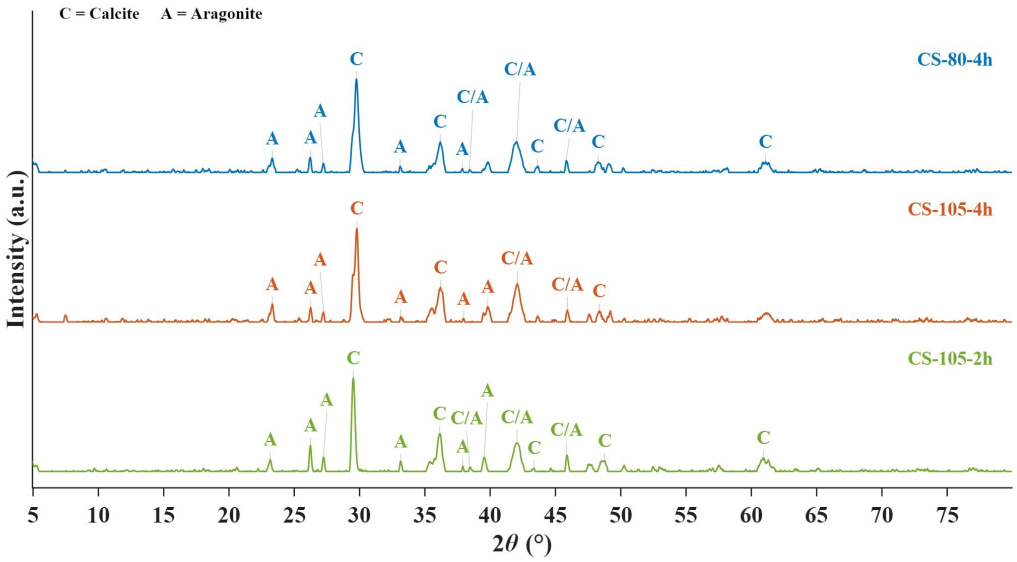


Figure 3.9: XRD comparison of carbonated steel slag carbonated at different parameters.

sample exhibits prominent carbonate reflections, indicating successful mineralization under the investigated conditions.;

3.3.3 TGA of Chemical Pre-Treated Slag

After the chemical pre-treatment for both EAF and BOF Slag, the samples were dried in an oven and subjected to TGA. Figure 3.10 shows the results of TGA behaviour of raw and chemically treated BOF and EAF Slag with different acid concentrations. The curve illustrates the relative change in the mass of the sample with increasing temperature that provides the information regarding the thermal stability and decomposition of different chemical phases that were present in the slag. In comparison, for both slags, the treated slag shows greater mass reduction than the raw slag. Also, the amount of mass reduction is greater for the higher acid concentration, which also indicates that after the chemical pre-treatment, the slag undergoes different chemical reaction that modifies the original mineralogical composition and form those phases that decompose subsequently.

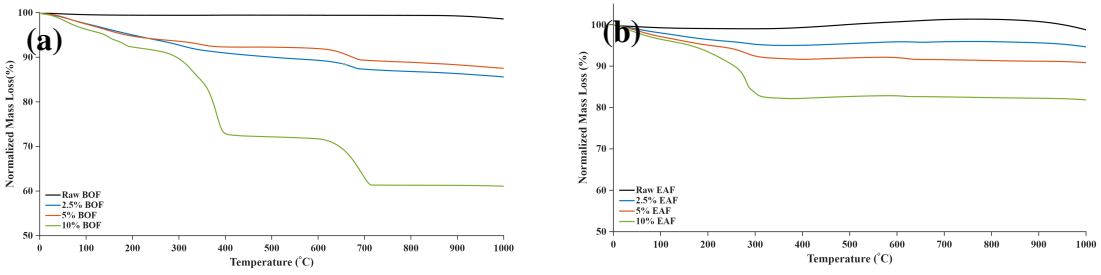


Figure 3.10: TGA comparison of chemically treated slag: (a) BOF slag samples and (b) EAF slag samples.

As shown in Figure 3.10b the raw EAF slag shows relatively high thermal stability within the temperature ranges. The curves remain close to the initial mass during the

entire heating process, which indicates that only a limited quantity of thermally decomposing phases are present in the untreated slag. During the initial phase, a small reduction can be observed, which could be the removal of the absorbed moisture or loosely bound water from the slag particles. After that, the curve remains comparatively stable for all the temperatures. At the highest temperature, approximately 850-1000 °C, a slight reduction of the mass can be observed. However, the magnitude of this change is relatively small compared with that observed in the chemically treated samples.
Figure 3.10b shows that the 2.5% and 5% samples have slightly higher mass losses, mainly around the temperature of 300 °C . The 10% treated sample shows the most significant change in mass loss, where a pronounced mass loss occurs between approximately 200 and 300 °C, reducing the normalized mass to around 82%. This significant mass loss may be associated with the decomposition of compounds formed during acetic acid treatment, such as acetate, together with the release of chemically bound water. After that, the curve remains relatively stable at the higher temperature.
For the BOF slag, a similar trend was also observed, which can be seen in Figure 3.10a, although the changes are more pronounced. From the graph, it can be clearly noted that the raw BOF slag sample shows only limited mass loss, whereas the other concentrated acid samples, i.e., 2.5% and 5%, exhibit gradual reductions with the increase in temperature. Also, 10% BOF samples shows two clear mass loss region which can be seen in Figure 3.10a. The first major reduction can be seen at around 350- 450 °C; the normalized mass decreases significantly, and the second major loss is observed between 650-750° C. The mass loss at the higher temperature is consistent with the decomposition of the carbonate phases.

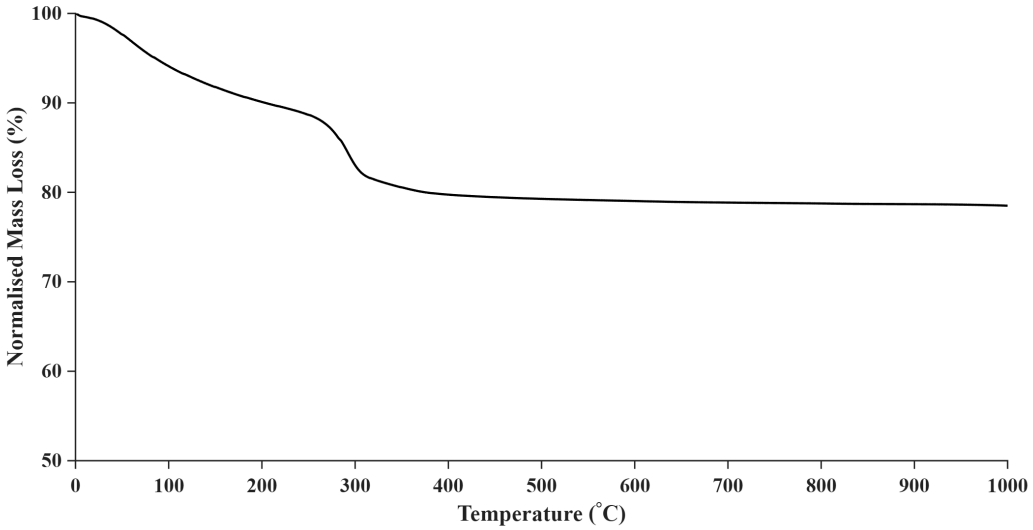


Figure 3.11: TGA graphs of Brown Gel

The brown gel that was obtained and explained in Figure 3.3 was extracted, dried, and the powder form was analyzed by TGA methods, giving the results in Figure 3.11. The graph shows that the sample exhibits a gradual mass reduction at relatively low temperatures approximately at about 250-350° C and then the curve become relatively stable throughout all the temperatures. The majority of the mass decrement was at relatively low temperatures, which could be due to the removal of moisture and chemically bound

water and the decomposition of hydrated or acid treatment-derived compounds present in the gel.

3.3.4 TGA of Carbonated Slag

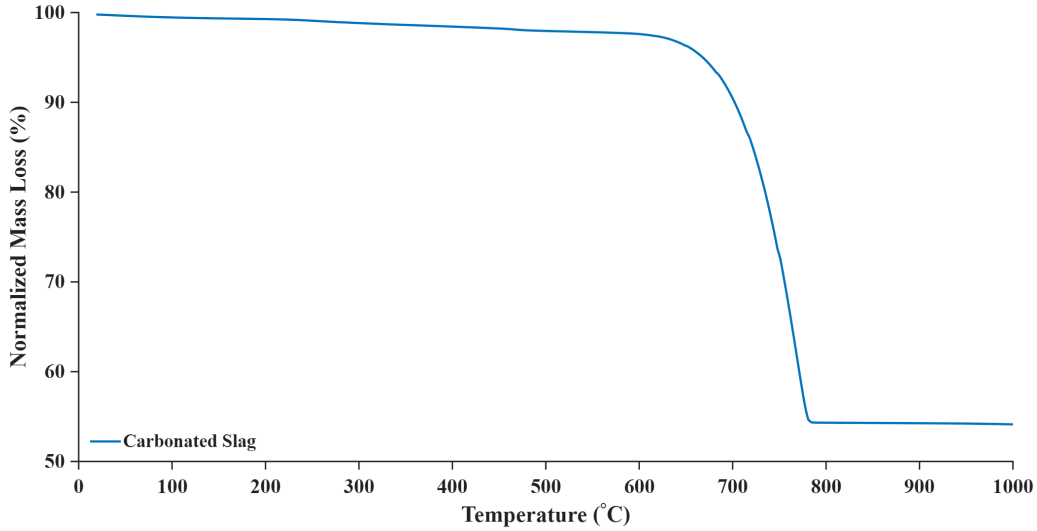


Figure 3.12: TGA graphs of carbonates

Figure 3.12 shows the results of the white powder that were collected after the carbonation of the highest acid concentration by adjusting the pH using calcium hydroxide.

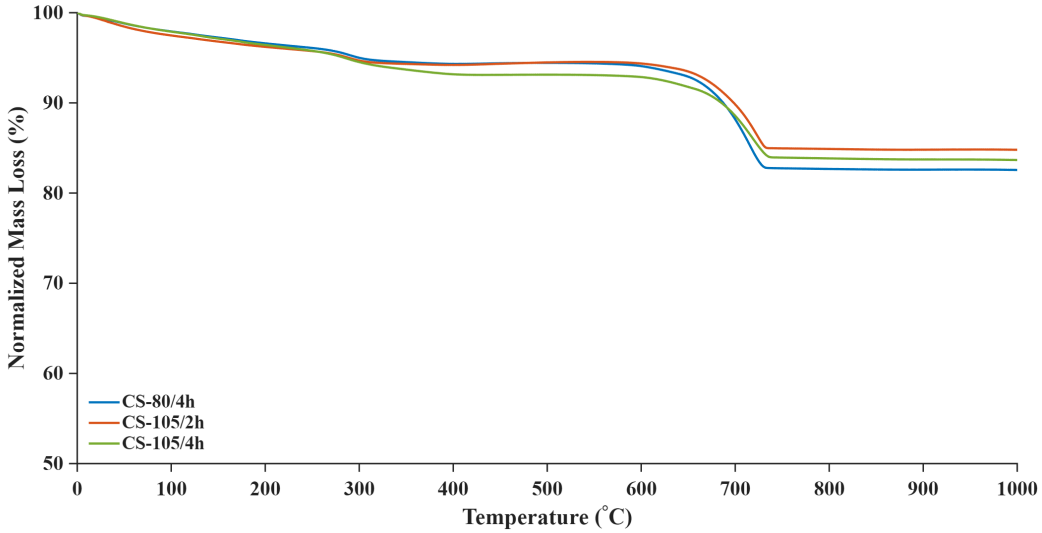
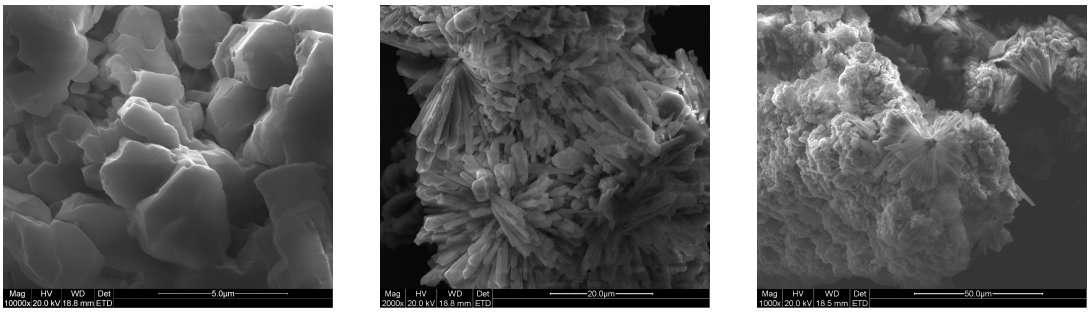


Figure 3.13: TGA graphs of samples with different parameters

From the graph, the sample exhibits distinctly different thermal behaviour. The mass was almost constant until the temperature reached 500-550 °C, indicating relatively high stability at the lower temperature. This temperature range is characteristic of the thermal decomposition of the $CaCO_3$, during which the CO_2 is released.
The Figure 3.13 compares the TGA results of three different samples that are treated

less acid concentration i.e. 2.5% but with three different carbonation parameters which is 80°/4hrs, 105°/2hrs and 105°/4hrs. It shows a similar thermal decomposition pattern. A gradual mass reduction is observed at approximately 300-350°C, which could be related to the removal of the physically and chemically bound water and dehydration of any water phase, after which the curves remain relatively stable until 500-550 °C. After that, noticeable mass loss occurs between 550-750 °C, corresponding to the decomposition region of the carbonate phase and release of CO_2, and supports the presence of calcite and aragonite identified in the XRD analysis .
As shown in Figure 3.13, CS80/4h (i.e. carbonated steel slag, carbonation done at 80° for 4 h) exhibits greater mass loss in this region compared to the other samples. It is followed by CS105/4h, while CS105/2h shows the lowest mass reduction. As all the samples are treated under similar conditions, the changes can be attributed to the carbonation condition. The greater mass loss for CS80/4h suggests that this condition produces relatively higher carbonates than other conditions. Also, increasing the treatment time from 2 hours to 4 hours appears to increase the carbonate formation, but it remains lower than that observed for CS80/4h.
Overall, the TGA results indicate that both carbonation temperature and treatment duration influence carbonate formation, with CS-80/4h exhibiting the highest carbonate-associated mass loss among the investigated samples, suggesting a greater carbonate content under this condition.

3.4 Morphological Analysis



(a) CS-105/4h **(b)** CS-105/4h **(c)** CS-80/2h

Figure 3.14: Morphological view of carbonated steel slag under different carbonation conditions.

Figure 3.14 presents the microstructure or SEM micrographs of the slag carbonated at different parameters,.ie. CS-80/4h, and CS-105/4h. The image shows a heterogeneous microstructure consisting of irregularly shaped particles, compact agglomerates, and crystalline structures of different shapes and sizes. The morphological characteristics indicate the formation of different reaction products during the carbonation process.
As in Figure 3.14b and Figure 3.14c, some particles exhibit rough and irregular surfaces and are clustered together. At higher magnification, elongated and prismatic crystalline structures can be observed, with some crystals growing in clustered and partially radial arrangements. These morphological characteristics of Aragonite-type $CaCO_3$ are consistent with the aragonite phase identified in the XRD analysis. In addition, fine plate-like particles and compact crystalline structures are observed within the agglomerated regions.
Furthermore, Figure 3.14a shows compact and blocky particles with relatively well-

defined rhombohedral morphologies, which are characteristic of calcite-type $CaCO_3$. This observation was also supported by the XRD results, which confirm the presence of calcite in the carbonated slag samples. Overall, the SEM observation, together with XRD results, provides complementary evidence of carbonate formation and demonstrates the heterogeneous microstructure of the carbonated steel slag.

3.5 Mechanical Performance

After the treatment and carbonation, differently treated samples were used to replace 20% of the cement to check the strength. Figure 3.15 shows the compressive strength result of cement and the different slag-containing sample after 4,7 and 28 days of curing. All the samples exhibited a gradual increase in the compressive strength with increase in the curing time which indicates the continuation of the strength development during the testing period. The reference cement sample has the highest strength throughout the testing period,,increasing from approximately 45 MPa at 4 days to about 52 MPa at 28 days.
Among all the different varieties of the samples, the C+CS80/4h (cement replaced with the slag carbonated at 80 degree for 4 hours) shows the best performance. The compressive strength for this sample has increased considerably with the curing time and reached approximately 47 MPa at 28 days. It corresponds to about 90% of the compressive strength of the reference cement indicating the potentiality of maintaing a high level of mechanical performance compared to conventional cement.However, if we compare the early strength was lower in comparison to cement or any other treated samples

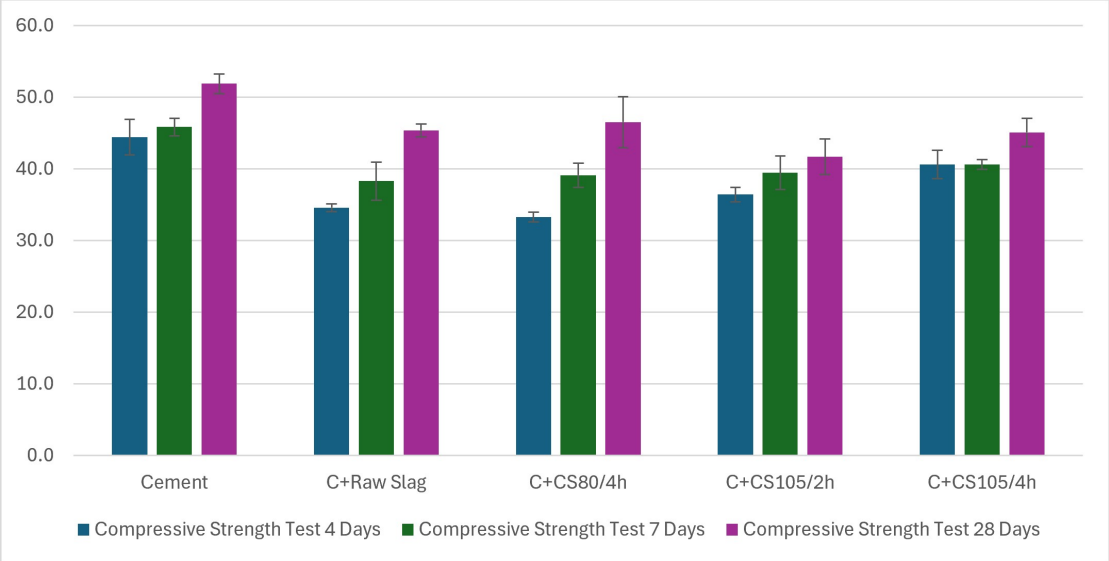


Figure 3.15: Compressive Strength Test of Various Sample

The C+Raw Slag also showed a noticeable increase in strength between 4 and 28 days. It showed a compressive strength of 34.6MPa at 4 days, which increased to around 45 MPa after 28 days. This shows a more pronounced strength development with time compared to initial strength. Also, C+CS105/4h sample exhibits the highest early strength gain reaching 40.6 MPa after 4 days that was almost constanct in 7days too which was a interesting part. Later, after 28 days, the compressive strength rose to 45.1 MPa.

For the C+CS105/2h sample, the compressive strength increased from 36.4MPa at 4 days to approximately 39.5MPa at 7 days, before reaching 41.7 MPa after 28 days. This was the lowest 28-day compressive strength value among the studied slag-containing mixtures, corresponding to approximately 80% of the cement reference value.
Overall, the C+Cs80/4h sample exhibited the highest 28-day compressive strength among the slag-containing mixtures, reaching approximately 47 MPa compared with 45 MPa for the raw slag mixture. This improvement may be attributed to the formation of $CaCO_3$ phases, such as calcite and aragonite, as supported by the XRD and TGA results. These carbonate phases may improve particle packing and provide nucleation sites for cement hydration products, contributing to better strength development. Therefore, carbonation at 80 °C for 4 hours showed the most favourable mechanical performance among the investigated treatment conditions.

4 Conclusion

This section summarizes the results and findings of the study, and the conclusions drawn from them are presented. The limitations of the research and recommendations for future work are also discussed.

This study investigated the optimization of BOF and EAF slags through mechanical and chemical pre-treatment, pH adjustment, and mineral carbonation to evaluate their potential application as SCMS. Although both slags were investigated during the initial stage, further carbonation and mechanical performance studies focused mainly on EAF slag. The pH results demonstrated that acetic acid concentration significantly influenced the alkaline response of both BOF and EAF slags. Lower acid concentrations resulted in higher pH values, whereas higher acid concentrations maintained relatively acidic conditions. Similarly, ICP-MS analysis showed that increasing acid concentration promoted greater dissolution of Ca, Mg, and other elements, with 10% acetic acid treatment producing the highest dissolved concentrations. The XRD results showed that chemical pre-treatment altered the mineralogical composition of both slags. The lower acid concentration of 2.5% preserved more of the original Ca-Si phases, whereas stronger acid treatment caused greater changes in these phases. Furthermore, the persistence of relatively stable Fe-Mn oxide phases, including RO-type phases, indicates that chemical treatment may not eliminate the phases associated with limited hydraulic reactivity. Therefore, the selection of acid concentration requires a balance between Ca extraction and preservation of potentially cementitious minerals.

Following carbonation, XRD analysis identified the formation of calcite and aragonite in the treated EAF slag. The TGA results further supported carbonate formation through characteristic mass losses associated with carbonate decomposition. Among the investigated conditions, CS-80/4h exhibited the highest carbon-related mass loss, followed by CS-105/4h and Cs-105/2h, indicating that both carbonation temperature and treatment duration affect the formation of carbonate minerals

The SEM analysis revealed heterogeneous microstructures containing elongated and prismatic crystals resembling aragonite, together with compact and rhombohedral particles characteristic of calcite. These observations were consistent with the carbonate phases identified by XRD and provide additional morphological evidence of carbonate formation.

The compressive strength results showed that C+CS80/4h achieved the highest 28-day strength among the slag-containing mixtures, reaching approximately 47 MPa compared with 45 MPa for raw slag and 52 MPa for the reference cement. This improvement may be associated with the formation of $CaCO_3$ phases, which could improve particle packing and contribute to cement hydration. Therefore, carbonation at 80 °C for 4 hours provided the most favourable mechanical performance among the investigated conditions.

4.1 Limitations and Future Scope

Despite the systematic experimental investigation, several limitations should be acknowledged, mainly related to the materials, treatment conditions, and laboratory-scale evaluation. This study was limited to BOF and EAF slags, whose chemical and mineralogical compositions may differ from other steel slags. Therefore, future studies should investigate a wider range of steel slags to evaluate the applicability of the pro-

posed treatment methods.
The chemical treatment was limited to three different concentrations of acetic acid, while other parameters such as acid-to-slag ratio, temperature, and duration were not fully optimized. Furthermore, due to time limitations, the final carbonation experiment focused mainly on EAF slag. Future studies should investigate both slags under different carbonation conditions to identify the optimum treatment conditions.
Finally, the experiments were conducted at a laboratory scale, and their industrial feasibility was not evaluated. Further research should consider energy consumption, chemical and water requirements, acid recovery, and environmental impacts to assess the practical application of the proposed treatment methods.

5 References

[1] Robbie M. Andrew. "Global CO2 Emissions from Cement Production". In: *Earth System Science Data* 11 (2019), pp. 1675–1710. DOI: 10.5194/essd-11-1675-2019.

[2] U.S. Environmental Protection Agency. *Sources of Greenhouse Gas Emissions*. U.S. Environmental Protection Agency. 2023.

[3] Global Cement and Concrete Association. *Cement and Concrete Industry Net Zero Action and Progress Report 2025/26*. Accessed: 14 September 2026. Global Cement and Concrete Association, 2025. URL: https://gccassociation.org/cement-and-concrete-industry-net-zero-action-and-progress-report/.

[4] Karen L. Scrivener, Vanderley M. John, and Ellis M. Gartner. "Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-Based Materials Industry". In: *Cement and Concrete Research* 114 (2018), pp. 2–26. DOI: 10.1016/j.cemconres.2018.03.015.

[5] Ellis Gartner and Tongbo Sui. "Alternative Cement Clinkers". In: *Cement and Concrete Research* 114 (2018), pp. 27–39. DOI: 10.1016/j.cemconres.2017.02.002.

[6] International Energy Agency. *Tracking Industry 2022: Cement*. Paris: International Energy Agency, 2022.

[7] International Energy Agency. *CO2 Emissions in 2022*. Paris: International Energy Agency, 2023.

[8] Pierre Friedlingstein et al. "Global Carbon Budget 2022". In: *Earth System Science Data* 14 (2022), pp. 4811–4900. DOI: 10.5194/essd-14-4811-2022.

[9] G. Habert et al. "Environmental impacts and decarbonization strategies in the cement and concrete industries". In: *Nature Reviews Earth Environment* 1 (2020), pp. 559–573. DOI: 10.1038/s43017-020-0093-3.

[10] Barbara Lothenbach, Karen Scrivener, and R. Douglas Hooton. "Supplementary Cementitious Materials". In: *Cement and Concrete Research* 41.12 (2011), pp. 1244–1256. DOI: 10.1016/j.cemconres.2010.12.001.

[11] Maria C. G. Juenger, Ruben Snellings, and Susan A. Bernal. "Supplementary Cementitious Materials: New Sources, Characterization, and Performance Insights". In: *Cement and Concrete Research* 122 (2019), pp. 257–273. DOI: 10.1016/j.cemconres.2019.05.008.

[12] Ruben Snellings. "Assessing, Understanding and Unlocking Supplementary Cementitious Materials". In: *RILEM Technical Letters* 1 (2016), pp. 50–55. DOI: 10.21809/rilemtechlett.2016.12.

[13] M. D. A. Thomas. *Optimizing the Use of Fly Ash in Concrete*. Skokie, IL: Portland Cement Association, 2007.

[14] A. M. Neville. *Properties of Concrete*. 5th ed. Harlow: Pearson Education, 2011.

[15] H. F. W. Taylor. *Cement Chemistry*. 2nd ed. London: Thomas Telford, 1997.

[16] P. Kumar Mehta and Paulo J. M. Monteiro. *Concrete: Microstructure, Properties, and Materials*. 4th ed. New York: McGraw-Hill Education, 2014.

[17] ACI Committee 232. *Use of Fly Ash in Concrete (ACI 232.2R-03)*. Farmington Hills, MI, 2003.

[18] ACI Committee 233. *Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete (ACI 233R-03)*. Farmington Hills, MI, 2003.

[19] Intergovernmental Panel on Climate Change. *Climate Change 2021: The Physical Science Basis*. Cambridge: Cambridge University Press, 2021. DOI: 10.1017/9781009157896.

[20] Pierre Friedlingstein et al. "Global Carbon Budget 2022". In: *Earth System Science Data* 14 (2022), pp. 4811–4900. DOI: 10.5194/essd-14-4811-2022.

[21] European Commission. *The European Green Deal*. Brussels, 2019.

[22] Stockholm Exergi. *Stockholm Exergi Closes its Last Coal-Fired CHP Plant*. 2020.

[23] Government Offices of Sweden. *Ban on Coal, Oil and Natural Gas Extraction*. 2022.

[24] Ali Hasanbeigi and Cecilia Springer. *Global Steel at a Crossroads*. Tech. rep. Global Efficiency Intelligence, 2022.

[25] International Energy Agency. *Iron and Steel Technology Roadmap*. Tech. rep. Paris: International Energy Agency, 2023.

[26] John L. Provis and Jannie S. J. van Deventer. *Alkali Activated Materials: State-of-the-Art Report*. Dordrecht: Springer, 2018.

[27] Nadine M. Piatak, Michael B. Parsons, and Robert R. Seal II. "Characteristics and Environmental Aspects of Slag: A Review". In: *Applied Geochemistry* 57 (2015), pp. 236–266. DOI: 10.1016/j.apgeochem.2014.04.009.

[28] Harald Motz and Jürgen Geiseler. "Products of Steel Slags: An Opportunity to Save Natural Resources". In: *Waste Management* 21.3 (2001), pp. 285–293. DOI: 10.1016/S0956-053X(00)00102-1.

[29] World Steel Association. *Steel Industry Co-products*. 2023.

[30] World Steel Association. *Steelmaking Process*. 2022.

[31] Richard J. Fruehan. *The Making, Shaping and Treating of Steel*. 11th ed. AISE Steel Foundation, 1998.

[32] B. Das et al. "An Overview of Utilization of Slag and Sludge from Steel Industries". In: *Resources, Conservation and Recycling* 50.1 (2007), pp. 40–57. DOI: 10.1016/j.resconrec.2006.05.008.

[33] E. B. Pretorius. "Fundamentals of Fluxing and Slag Chemistry". In: *Iron and Steel Technology* (2002).

[34] M. Tossavainen et al. "Characteristics of Steel Slag under Different Cooling Conditions". In: *Waste Management* 27.10 (2007), pp. 1335–1344. DOI: 10.1016/j.wasman.2006.08.002.

[35] World Steel Association. *World Steel in Figures 2024*. 2024.

[36] M. Kriskova et al. “Effect of Mechanical Activation on the Hydraulic Properties of Stainless Steel Slags”. In: *Cement and Concrete Research* 42.6 (2012), pp. 778–788. DOI: 10.1016/j.cemconres.2012.02.016.

[37] Caijun Shi. “Steel Slag—Its Production, Processing, Characteristics, and Cementitious Properties”. In: *Journal of Materials in Civil Engineering* 16.3 (2004), pp. 230–236. DOI: 10.1061/(ASCE)0899-1561(2004)16:3(230).

[38] P. E. Tsakiridis et al. “Utilization of Steel Slag for Portland Cement Clinker Production”. In: *Journal of Hazardous Materials* 152.2 (2008), pp. 805–811. DOI: 10.1016/j.jhazmat.2007.07.093.

[39] International Energy Agency. *Iron and Steel Technology Roadmap*. Tech. rep. Paris: International Energy Agency, 2020.

[40] Carlo Pellegrino and Valeria Gaddo. “Mechanical and durability characteristics of concrete containing EAF slag as aggregate”. In: *Cement and Concrete Composites* 31.9 (2009), pp. 663–671. DOI: 10.1016/j.cemconcomp.2009.05.006.

[41] J. M. Manso, J. J. González, and J. A. Polanco. “Electric Arc Furnace Slag in Concrete”. In: *Journal of Materials in Civil Engineering* 16.6 (2004), pp. 639–645. DOI: 10.1061/(ASCE)0899-1561(2004)16:6(639).

[42] Marco Pasetto and Nicola Baldo. “Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags”. In: *Journal of Hazardous Materials* 181.1–3 (2010), pp. 938–948. DOI: 10.1016/j.jhazmat.2010.05.104.

[43] World Steel Association. *Steelmaking Process*. 2023.

[44] I. Z. Yildirim and M. Prezzi. “Chemical, Mineralogical, and Morphological Properties of Steel Slag”. In: *Advances in Civil Engineering* 2011 (2011), p. 463638. DOI: 10.1155/2011/463638.

[45] D. Bulatbekova et al. “Effects of Basic Oxygen Furnace, Electric Arc Furnace and Ladle Furnace Slags on Cement Hydration and Concrete Performance: A Review”. In: *Journal of Building Engineering* 91 (2024), p. 110577. DOI: 10.1016/j.jobe.2024.110577.

[46] G. Adegoloye et al. “Mineralogical Composition of EAF Slag and Stabilisation of Free Lime by Weathering”. In: *Construction and Building Materials* 115 (2016), pp. 171–178. DOI: 10.1016/j.conbuildmat.2016.04.036.

[47] Sebastian Teir et al. “Dissolution of steelmaking slags in acetic acid for precipitated calcium carbonate production”. In: *Energy* 32.4 (2007), pp. 528–539. DOI: 10.1016/j.energy.2006.06.023.

[48] Sumit Srivastava et al. “Carbonated steel slags as supplementary cementitious materials: Reaction kinetics and phase evolution”. In: *Cement and Concrete Composites* (2023), p. 105213. DOI: 10.1016/j.cemconcomp.2023.105213.

[49] Yanfeng Fang et al. “Semi-dry and aqueous carbonation of steel slag: Characteristics and properties of steel slag as supplementary cementitious materials”. In: *Construction and Building Materials* 425 (2024), p. 135981. DOI: 10.1016/j.conbuildmat.2024.135981.

[50] Raghavendra Ragipani, Sankar Bhattacharya, and Akkihebbal K. Suresh. "A review on steel slag valorisation via mineral carbonation". In: *Reaction Chemistry & Engineering* 6 (2021), pp. 1152–1178. DOI: 10.1039/D1RE00035G.

[51] Xiaolong Sun et al. "Mechanical activation of steel slag to prepare supplementary cementitious materials". In: *Journal of Building Engineering* 60 (2022), p. 105200. DOI: 10.1016/j.jobe.2022.105200.

[52] Meng Li et al. "Influence of Steel Slag Particle Size on Mechanical Properties and Hydration of Cementitious Materials". In: *Sustainability* 16.5 (2024), p. 2083. DOI: 10.3390/su16052083.

[53] Byung-Gi Cho, Yong-Seok Choi, et al. "Effect of Mechanical Activation of Steel Slag on Hydration and Strength Development of Cementitious Materials". In: *Construction and Building Materials* 98 (2015), pp. 310–317. DOI: 10.1016/j.conbuildmat.2015.08.095.

[54] *ASTM C136/C136M-19: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. West Conshohocken, PA: ASTM International, 2019. DOI: 10.1520/C0136_C0136M-19.

[55] Guihua Wang, Yan Wang, and Zongjie Gao. "Use of Steel Slag as a Granular Material: Volume Expansion Prediction and Usability Criteria". In: *Journal of Hazardous Materials* 184.1–3 (2010), pp. 555–560. DOI: 10.1016/j.jhazmat.2010.08.071.

[56] W. J. J. Huijgen and R. N. J. Comans. "Carbon Dioxide Sequestration by Mineral Carbonation: Literature Review". In: *Energy Research Centre of the Netherlands* (2005).

[57] S. Y. Pan, E. E. Chang, and P. C. Chiang. "CO2 Capture by Accelerated Carbonation of Alkaline Wastes: A Review". In: *Journal of Environmental Management* 105 (2012), pp. 107–129. DOI: 10.1016/j.jenvman.2012.03.027.

[58] Z. Wang et al. "Chemical Activation of Steel Slag for High-Performance Cementitious Materials: A Review". In: *Construction and Building Materials* 344 (2022), p. 128174. DOI: 10.1016/j.conbuildmat.2022.128174.

[59] R. M. Santos et al. "Leaching Behaviour of Steel Slag and Recovery of Valuable Elements: A Review". In: *Minerals Engineering* 149 (2020), p. 106237. DOI: 10.1016/j.mineng.2020.106237.

[60] S. Kodama et al. "Development of a New pH-Swing CO2 Mineralization Process with a Recyclable Reaction Solution". In: *Energy* 33.5 (2008), pp. 776–784. DOI: 10.1016/j.energy.2008.01.013.

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