



CHALMERS
UNIVERSITY OF TECHNOLOGY



Utilisation of Ferrochrome Slag for Partial Cement Replacement

Technical Evaluation and Life Cycle Assessment of Water-Based and Alkali-Activated Systems

Master's thesis in Industrial Ecology

SIBEL BASARAN

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

MASTER'S THESIS 2026

Utilisation of Ferrochrome Slag for Partial Cement Replacement

Technical Evaluation and Life Cycle Assessment of
Water-Based and Alkali-Activated Systems

SIBEL BASARAN

Department of Technology Management and Economics

Environmental Systems Analysis

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

Utilisation of Ferrochrome Slag for Partial Cement Replacement
Technical Evaluation and Life Cycle Assessment of Water-Based and Alkali-Activated
Systems
SIBEL BASARAN

© SIBEL BASARAN, 2026.

Supervisors: Gulnara Shavaliyeva, Environmental Systems Analysis, Dept of Environmental and Energy Sciences
Ludvig Ånnhagen, Vargön Alloys AB
Examiner: Henrikke Baumann, Environmental Systems Analysis, Dept of Environmental and Energy Sciences

Master's Thesis 2026
Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 73 690 0845

Gothenburg, Sweden 2026

Utilisation of Ferrochrome Slag for Partial Cement Replacement Technical Evaluation and Life Cycle Assessment of Water-Based and Alkali-Activated Systems

SIBEL BASARAN

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

The high greenhouse gas emissions associated with cement production, together with increasing industrial residue generation, create a need for alternative binder materials. Ferrochrome slag (FCS) is generated in large quantities during high carbon ferrochrome production but currently exhibits limited utilisation potential due to low reactivity and chromium-related concerns. This study therefore evaluated processed ferrochrome slag (PFCS) as a partial cement replacement in water-based and alkali-activated cementitious systems.

To improve the utilisation potential of FCS, PFCS was produced through slag treatment, water granulation, drying, and grinding to increase the amorphous phase content and reduce chromium-containing phases. Binder systems containing 10–30% PFCS were initially screened using Vicat setting time measurements. Based on the screening results, systems containing 20% PFCS were further evaluated using isothermal calorimetry, BET, SEM, compressive strength, and Cr(VI) leaching. To evaluate the environmental performance of the selected mortars, a life cycle assessment (LCA) was performed.

The experimental results showed that the 20% PFCS + Water systems exhibited hydration development similar to the cement reference despite prolonged setting behaviour, indicating participation of PFCS in the hydration reactions. Alkali activation further increased PFCS participation and resulted in higher cumulative heat release, although delayed hydration development was observed.

Results from the environmental assessment further showed that PFCS incorporation reduced global warming potential compared with the cement reference. The water-based PFCS system showed the most favourable balance between hydration behaviour, chromium stability, and environmental performance. However, PFCS processing increased freshwater ecotoxicity impacts as a result of FeSi consumption during slag treatment. Alkali activation additionally increased chromium release together with surplus ore potential and freshwater ecotoxicity impacts associated with alkali activator and PFCS production. Overall, the results indicate that PFCS shows potential for partial cement replacement, although optimisation of processing and activation conditions is required to balance technical performance, chromium stability, and environmental impacts.

Keywords: ferrochrome slag (FCS), alkali activation, cement replacement, chromium leaching, hydration behaviour, life cycle assessment (LCA)

Acknowledgements

There are many people I would like to thank for their support throughout this project. Writing an interdisciplinary thesis has been both challenging and rewarding, and the process has taught me a lot along the way.

I would like to thank my supervisor Ludvig Ånnhagen at Vargön Alloys AB and the whole team at VAAB for all the support, guidance, and discussions throughout the project. Your willingness to share your knowledge and always take the time to answer my questions has been incredibly valuable. I would also like to thank my supervisor at Chalmers, Gulnara Shavaliyeva, for all the support and feedback throughout this work. Thank you for helping me organise my thoughts and improve the study throughout the process. I would further like to thank my examiner Henrikke Baumann for valuable input and support.

A special thanks also to everyone who helped me in the laboratory, especially Emmanuela Leventaki, Jenny Bengtsson, and Helen Jansson, for all your help and patience during the experimental work.

Finally, I would like to thank my family, fiancé, and friends for always supporting and encouraging me throughout the project. It has meant a lot to me.

Declaration of AI Use

AI tools were used for language improvement and assistance with Python scripting for figure generation and visualisation of results.

Sibel Basaran, Gothenburg, January 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

a/b	Aggregate-to-binder ratio
Al ₂ O ₃	Aluminium oxide
C–S–H	Calcium–silicate–hydrate
CaO	Calcium oxide
CO ₂	Carbon dioxide
FCS	Ferrochrome slag
FeCr	Ferrochrome
FeO	Iron oxide
FeSi	Ferrosilicon
FETP	Freshwater ecotoxicity potential
GGBFS	Ground granulated blast furnace slag
GWP100	Global warming potential over 100 years
l/b	Liquid-to-binder ratio
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LOQ	Limit of Quantification
MgO	Magnesium oxide
NaOH	Sodium hydroxide
PFCS	Processed ferrochrome slag
SAF	Submerged-arc furnace
SCM	Supplementary cementitious materials
SEM	Scanning electron microscopy
SiO ₂	Silicon dioxide
SOP	Surplus ore potential
SSA	Specific surface area
VAAB	Vargön Alloys AB
w/b	Water-to-binder ratio

Contents

List of Acronyms	ix
Nomenclature	xi
List of Figures	xiii
List of Tables	xv
1 Introduction	1
1.1 Aim	2
2 Background	3
2.1 Ferrochrome Slag	3
2.1.1 Waste Classification and Circular Economy	4
2.1.2 Influence of Processing on Reactivity	4
2.2 PFCS in Cementitious Binder Systems	5
2.2.1 Supplementary Cementitious Materials	5
2.2.2 Alkali Activated Materials	6
2.2.3 Binder Characterisation	7
2.3 Chromium Mobility and Leaching	7
2.4 Life Cycle Assessment of Cementitious Materials	8
3 Materials and Methods	9
3.1 Materials	9
3.2 Screening of cement replacement by PFCS	11
3.2.1 Selection of PFCS replacement level	11
3.3 Binder Characterisation	12
3.4 Mortar Characterisation	12
3.5 Life Cycle Assessment	13
3.5.1 Goal and scope definition	13
3.5.2 System boundary	14
3.5.3 Life cycle inventory analysis	15
3.5.3.1 PFCS Production	16
3.5.3.2 Alkali Activator Production	16
3.5.3.3 Mortar Production and Transport	17
3.5.4 Life cycle impact assessment	17

4	Results and Analysis	19
4.1	Fresh-State Behaviour	19
4.2	Hydration Behaviour	20
4.3	Microstructural Characterisation	22
4.4	Mortar Characterisation	26
4.4.1	Leaching	27
4.5	Life Cycle Assessment	28
4.5.1	Global Warming Potential (GWP100)	28
4.5.2	Surplus Ore Potential (SOP) and Freshwater Ecotoxicity Potential (FETP)	29
4.5.3	Contribution Analysis	30
5	Discussion	33
5.1	Limitations and Future Work	35
6	Conclusion	37
	Bibliography	39
A	Background Datasets Used in the LCA Model	I

List of Figures

2.1	Current FCS production process at VAAB.	3
2.2	Reprocessing of FCS for PFCS production.	4
3.1	Overview of the method. Binder screening was conducted to select the 20% PFCS systems for subsequent binder paste and mortar testing. The selected mortar systems were further evaluated using LCA. Dashed outlines indicate the systems included in the LCA.	10
3.2	System boundaries for the LCA systems considered in this study. (1) Reference mortar based on cement and (2) mortar incorporating processed FCS slag. For the FCS-based system, two alternatives are evaluated in the mortar production stage: (A) water addition and (B) alkali activator addition.	14
4.1	Initial setting time determined by Vicat testing: (i) cement paste mixed with water and (ii) cement paste mixed with alkali activator.	19
4.2	Heat flow curve for the Cement + Water reference binder.	20
4.3	Isothermal calorimetry results for all binders showing (i) full heat flow curve and (ii) detailed view of the hydration stages.	21
4.4	Cumulative heat release during isothermal calorimetry.	22
4.5	SEM micrograph, EDS spectrum and elemental mapping of Cement + Alkali.	24
4.6	SEM micrograph, EDS spectrum and elemental mapping of 20% PFCS slag + Alkali.	25
4.7	Specific surface area for binders with alkali activation.	26
4.8	Mortar cubes after 28 days curing prior to compressive strength and chromium leaching experiments.	26
4.9	GWP100 impact for the investigated mortar systems.	28
4.10	SOP impact for the investigated mortar systems.	29
4.11	FETP impact for the investigated mortar systems.	30
4.12	Process and alkali activator contribution analysis for all indicators.	30

List of Tables

2.1	XRF analysis of PFCS (Weight %).	5
3.1	Characteristic particle size (D_{86}) for cement [35] and PFCS.	9
3.2	Composition of binder pastes used for screening.	11
3.3	Composition of binder mixtures.	12
3.4	Composition of mortar mixtures	13
3.5	Inventory data used in the LCA calculations (per tonne of mortar), presented as lowest–highest values for the best- and worst-case scenarios.	15
4.1	Leaching from one mortar cube in mg/L.	27
4.2	Characterised midpoint impact per functional unit of 1 tonne mortar. Relative changes compared with the reference are shown in italics.	31
A.1	Main datasets and processes used in the LCA model.	I

1

Introduction

The construction sector faces increasing pressure to reduce greenhouse gas emissions and improve resource efficiency. Cement production is associated with high greenhouse gas emissions and the use of mineral resources, primarily due to clinker production [1–3]. In Sweden, the cement industry represents one of the largest sources of industrial greenhouse gas emissions, while upcoming EU ecodesign requirements increase the need for lower-impact cement-based materials [4, 5].

One approach to reduce the emissions of cementitious materials is the partial replacement of cement with industrial by-products and residue materials [6–8]. An example of this is slag-based materials, defined as a by-product from metallurgical processes [9]. Ground granulated blast furnace slag (GGBFS) is currently one of the most common used alternative binder materials due to its cementitious properties and lower carbon emissions compared with cement [10]. However, the future availability of GGBFS is expected to decrease as steel production gradually transitions away from blast furnace processes [11–13]. This creates interest in alternative slag materials from other metallurgical industries.

One potential alternative material is ferrochrome slag (FCS), which is generated during ferrochrome production in submerged arc furnaces (SAF). Ferrochrome is an important alloying material in the production of stainless steel. Vargön Alloys AB (VAAB), located in Vargön, Sweden, is one of the largest high carbon ferrochrome producers in Europe and the only producer in Sweden. During ferrochrome production, approximately 1.8 tonnes of FCS are generated per tonne of ferrochrome alloy. Since the demand for stainless steel is expected to increase [14], FCS generation is also expected to increase. This further increases the need to identify suitable applications for FCS.

Despite the large generation volumes, FCS from current production at VAAB exhibits low reactivity due to its stable crystalline structure and low amorphous phase content, limiting its suitability as an alternative binder material. At the same time, the slag is classified as a non-hazardous waste under code 10 08 09 [15]. Its utilisation potential is limited due to its total chromium content, as chromium can occur in forms that pose risks to human health and the environment. Consequently, additional processing is required before FCS can be evaluated for potential use in cementitious binder systems.

The benefits of alternative binders depend not only on reduced cement consumption but also on their technical performance. Benefits achieved through cement replace-

ment may be offset if larger material quantities are required to obtain comparable performance with cement [16]. The environmental performance of alternative binders is influenced by the processing required to produce the material. For FCS, this is relevant since processing is required to improve its suitability as a binder material while also addressing chromium-related environmental risks. Therefore, both technical and environmental performance must be evaluated when assessing processed ferrochrome slag (PFCS) as a potential binder material.

1.1 Aim

The aim of this study is to evaluate the utilisation potential of FCS through processing into PFCS for use as a partial alternative binder material in cementitious systems. The study assesses the potential benefits and limitations associated with replacing cement with PFCS from technical and environmental perspectives.

2

Background

2.1 Ferrochrome Slag

FCS is generated during ferrochrome production in a SAF, where chromite ore, quartz, coke, and electrical energy are used under reducing conditions to produce high carbon ferrochrome alloy and slag. An overview of the current slag production at VAAB is shown in Figure 2.1.

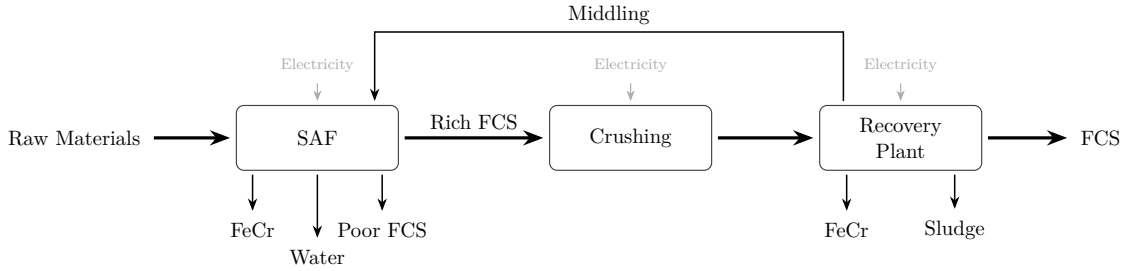


Figure 2.1: Current FCS production process at VAAB.

The structure and composition of the slag depend on raw materials, furnace operation, cooling conditions and post-treatment processes. FCS typically consists of magnesiumoxide (MgO), silicon dioxide (SiO_2), and aluminumoxide (Al_2O_3), together with smaller amounts of calciumoxide (CaO), iron oxides (FeO), and chromium-containing phases. In slag from current production at VAAB, these components are predominantly present in stable crystalline phases such as Mg-rich spinels such as Mg–Al–Cr, together with olivine-type structures.

The dominance of stable crystalline phases influences the behaviour of FCS in cementitious systems [17]. According to earlier research, crystalline structures limit dissolution under conventional hydration conditions, leading to low participation in binder reactions [18]. As a result, FCS from current production is unsuitable as a reactive cementitious binder material and is instead mainly used as an inert aggregate material [17, 18]. However, the limited utilisation potential together with its current waste classification in Sweden means that large quantities of FCS are managed as waste. From a circular economy perspective, increased utilisation of FCS can contribute to reduced waste generation and improved resource efficiency [19].

2.1.1 Waste Classification and Circular Economy

FCS from current production at VAAB is classified as non-hazardous waste but has limited utilisation potential due to its total chromium content (approximately 4%) and uncertainties associated with its long-term environmental behaviour. In Sweden, residue materials are evaluated using a risk-based approach where both chemical composition and environmental compatibility are considered [20]. For a material to be classified as a by-product, four criteria defined in the Swedish Environmental Code must be fulfilled related to continued use, technical suitability, and environmental safety [21]. Current FCS does not meet the final environmental safety criterion due to chromium-related concerns.

This management reflects broader limitations of linear material use, where industrial residues are commonly discarded rather than utilised as secondary resources [19]. Circular economy strategies instead aim to retain materials within productive use through reuse, recycling, and valorisation approaches. From this perspective, FCS can represent a valuable secondary resource if sufficient technical and environmental performance can be achieved [22]. Its utilisation in cementitious mixtures could therefore contribute to reducing the amount of slag requiring disposal, provided that acceptable reactivity, mechanical performance, and environmental compatibility can be achieved.

2.1.2 Influence of Processing on Reactivity

Previous studies have shown that the properties and reactivity of slag materials vary depending on production and processing conditions, which influence their suitability for cementitious applications [23, 24]. In this study, PFCS was produced in a test batch at VAAB in January 2026. The material obtained from this test batch was used for the experimental investigations presented in this study, including material characterisation and evaluation of its performance in cementitious mixtures. The processing route aimed to reduce chromium-related phases and to increase the amorphous fraction of the slag to improve its reactivity. The processing route for FCS is shown in Figure 2.2.

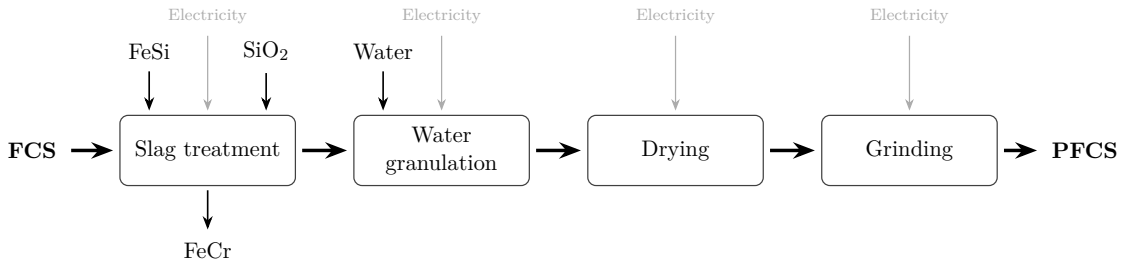


Figure 2.2: Reprocessing of FCS for PFCS production.

PFCS was produced through slag treatment in a furnace, water granulation, drying, and grinding. During slag treatment, silica sand (SiO_2) was used as a flux and ferrosilicon (FeSi) as a reducing agent. This treatment alters the chemical composition of the slag and contributes to reduction of chromium-containing metallic

phases. Following slag treatment, the molten slag was rapidly cooled through water granulation in order to increase the amorphous fraction of the material [18].

After granulation, the slag was dried to remove excess moisture and subsequently ground to increase particle fineness and specific surface area (SSA). These parameters influence dissolution behaviour and reaction kinetics in cementitious systems, since increased SSA enhances reactivity [13]. The test batch demonstrated that PFCS could be produced using the described processing route, but its technical and environmental properties required further investigation to assess its suitability as a potential binder material. The composition of PFCS is shown in Table 2.1.

Table 2.1: XRF analysis of PFCS (Weight %).

	Al ₂ O ₃	CaO	K ₂ O	MgO	MnO	SiO ₂	TiO ₂	Cr	S
PFCS	22.11	3.65	0.14	30.30	0.04	42.39	0.535	0.07	0.18

2.2 PFCS in Cementitious Binder Systems

The suitability of PFCS as an alternative binder material depends on its behaviour in cementitious systems, particularly regarding hydration and binder development. In cement-based materials, these properties are governed by the interactions between binders, fine aggregates, and water. Mortar is a cementitious composite material consisting of these components. The binder phases, for example Portland cement in conventional systems, are responsible for hydration, matrix formation, and strength development, while aggregates contribute to stability and particle packing [25]. Water initiates the hydration reactions that form a hardened binder matrix, primarily through the formation of calcium silicate hydrate (C–S–H), which contributes to strength development in cement-based materials [25, 26].

2.2.1 Supplementary Cementitious Materials

One approach to reduce the environmental impact of cement-based materials is the use of supplementary cementitious materials (SCMs) as partial replacements for cement [13]. Depending on their composition and reactivity, SCMs can contribute to hydration reactions as hydraulic or pozzolanic materials, while less reactive materials primarily function as fillers [7]. Hydraulic materials react directly with water, similarly to cement. In contrast, pozzolanic materials require calcium hydroxide, Ca(OH)₂, released when hydraulic materials such as cement react with water [7]. This enables pozzolanic reactions to contribute to the formation of binding phases such as C–S–H and C–A–S–H [7]. Pozzolanic materials therefore depend on the presence of hydraulic phases within cementitious systems to develop reactivity.

The reactivity and performance of SCMs depend on factors such as chemical composition, particle size, replacement level, and the presence of reactive amorphous phases [7, 13]. Materials with higher amorphous content exhibit higher dissolution

potential and greater participation in binder reactions, whereas predominantly crystalline materials mainly function as fillers. Reactive SCMs therefore contribute not only to reduced clinker demand, but also to strength development and microstructural densification [13].

The PFCS investigated in this study contains low calcium content together with high proportions of SiO_2 and Al_2O_3 . This composition suggests limited hydraulic behaviour under conventional hydration conditions. Instead, PFCS is expected to require hydraulic phases or additional activation to achieve higher reactivity in cementitious systems.

Since PFCS is a newly developed material, its classification differs from that of conventional SCMs. Conventional SCMs such as GGBFS are covered by established standards and specifications for use as cementitious binders, for example SS-EN 15167-1:2006 [10]. Since PFCS is a newly developed material, it is not currently included within such standardised SCM classifications. In this study, PFCS is therefore referred to as an alternative binder material. Its suitability for cementitious applications must instead be evaluated based on technical performance, environmental behaviour, and chromium-related considerations.

2.2.2 Alkali Activated Materials

Other types of alternative binders can involve alkali activated materials, where aluminosilicate precursor materials react under alkaline conditions to form hardened binding structures [27]. Alkali activation can increase dissolution of reactive amorphous aluminosilicate phases and thereby promote formation of additional binding products.

Geopolymers represent one type of alkali-activated material in which cement is fully replaced by reactive aluminosilicate precursor materials activated under alkaline conditions [8]. The alkali-activated cementitious mixtures investigated in this study are not fully geopolymeric, since cement remains as a part of the binder composition. The investigated materials are more accurately described as hybrid binder systems, where conventional cement hydration occurs simultaneously with alkali-activated reactions. Under alkaline conditions, dissolution of the processed slag may increase, potentially enhancing PFCS participation in the binder reactions [28, 29].

Alkali activation can additionally enable higher cement replacement levels and thereby increase the potential environmental benefits associated with reduced clinker use [27]. At the same time, there are environmental challenges associated with alkali activation due to the production of alkali activators. Alkali ions can also remain in the pore solution rather than being fully incorporated into reaction products, which can influence durability and mechanical performance [8]. The purpose of alkali activation in this study was not to investigate fully cement-free geopolymers, but rather to evaluate whether alkaline conditions could improve PFCS reactivity and binder performance in mixtures with partial cement replacement.

2.2.3 Binder Characterisation

Regardless of binder type, the suitability of cementitious materials depends on their setting and hardening behaviour, since the primary function of a binder is to provide sufficient mechanical performance in the hardened state. Setting refers to the stiffening of the cement paste without significant strength development, whereas hardening refers to the development of mechanical strength [26]. These processes are influenced by hydration reactions and binder reactivity, which affect the pore structure and microstructure of the hardened material. Such characteristics are therefore important when evaluating alternative binders.

Binder reactivity can be investigated using calorimetry, since both cement hydration and pozzolanic reactions are exothermic processes [7, 13]. Isothermal calorimetry provides information regarding hydration kinetics and heat evolution during binder development, but calorimetry alone is insufficient to fully describe binder behaviour. PFCS incorporation can influence pore structure and microstructural development compared with conventional cement systems, which can subsequently affect both mechanical performance and chromium mobility in the hardened material. Complementary characterisation methods are therefore required to evaluate different stages of binder development. For PFCS-based systems, evaluation of binder performance must additionally consider how changes in slag reactivity can influence chromium stability within the hardened material.

2.3 Chromium Mobility and Leaching

The use of PFCS in cementitious systems raises environmental concerns related to chromium mobility and leaching behaviour. Chromium in FCS is primarily present as Cr(III) incorporated into stable spinel phases, which reduces chromium mobility and leaching [17]. Consequently, the stable crystalline phases in conventional FCS contribute both to low reactivity and low chromium release. Increasing slag reactivity and altering the chemical environment can influence chromium stability and potentially promote the formation or release of more mobile chromium species, such as Cr(VI) [13, 30].

In PFCS-containing cementitious systems, chromium behaviour is additionally influenced by the chemical environment formed during hydration and hardening. Within the hardened cementitious matrix, chromium can become incorporated into hydration products or physically encapsulated, which can reduce chromium mobility [13]. At the same time, alkaline conditions and increased slag dissolution can increase chromium release. Chromium-related behaviour is therefore important to evaluate in the hardened cementitious material rather than solely in the raw slag.

2.4 Life Cycle Assessment of Cementitious Materials

Based on the introduced technical and chromium-related aspects of PFCS-containing systems, environmental performance also becomes important to evaluate. Processing of FCS and increased amorphous phase content can improve PFCS reactivity, thereby increasing its potential for use as an alternative binder. This may enable partial replacement of Portland cement, which can consequently reduce greenhouse gas emissions associated with clinker production [16]. At the same time, slag processing, activation conditions, and changes in chromium behaviour may introduce additional environmental impacts associated with resource use and chromium-related toxicity. Life cycle assessment (LCA) is therefore a relevant tool for evaluating environmental trade-offs in PFCS-based cementitious systems.

LCA is a standardised methodology used to quantify the environmental impacts associated with a product system throughout its life cycle [31, 32]. The methodology is standardised through ISO 14040 and ISO 14044 and is further described in The Hitch Hiker's Guide to LCA [33]. In cementitious systems, LCA enables evaluation of environmental impacts associated with both material substitution and additional processing requirements.

Previous research has applied LCA to evaluate the environmental performance of FCS in concrete. Das et al. investigated the use of FCS as a complete replacement for natural coarse aggregate using a cradle-to-gate LCA [34]. In the assessment, FCS was considered a zero-emission waste material, while the downstream processing required to prepare the material for use as aggregate was included. The results showed that the use of FCS reduced the environmental impacts compared with conventional concrete [34]. However, the energy required for FCS processing still contributed to the environmental impacts. This shows the importance of including processing requirements when evaluating the overall environmental performance of FCS. In the present study, the slag undergoes a different processing route to reduce its chromium content before being evaluated for partial cement replacement rather than as aggregate.

3

Materials and Methods

This study combined experimental testing with life cycle assessment (LCA) to evaluate PFCS-containing cementitious systems. Experimental testing was conducted at both binder paste and mortar scale. Binder paste experiments focused on hydration behaviour and reactivity, while mortar-scale experiments focused on compressive strength and chromium leaching behaviour. The binder paste experiments were conducted without aggregates in order to isolate binder behaviour. LCA was further used to evaluate the environmental performance of the selected mortar systems.

The methodology was divided into three main stages. First, binder paste screening was carried out to evaluate different levels of cement replacement with PFCS. Based on the screening results, selected systems were further characterised through additional experimental testing at both binder paste and mortar scale. Finally, the environmental performance of the selected mortar systems was evaluated using LCA. An overview of the study workflow is presented in Figure 3.1.

3.1 Materials

The materials used in this study were Portland-limestone cement, PFCS, standard sand, tap water, and an alkaline activating solution. A commercially available CEM II/A-LL 42.5 R cement was used as the reference binder. The cement consists primarily of clinker and limestone, where “42.5” denotes the compressive strength class and “R” indicates high early strength development. The characteristic particle size for cement and PFCS, expressed as D_{86} is presented in Table 3.1. D_{86} represents the particle diameter below which 86% of the particles in the distribution are found. Standard sand with a particle size range of 0–4 mm was used as fine aggregate in all mortar mixtures.

Table 3.1: Characteristic particle size (D_{86}) for cement [35] and PFCS.

Material	D_{86} (μm)
Cement	32
PFCS	155

Depending on the mixture composition, the binder or mortar was mixed with either tap water or an alkaline activating solution. The alkaline solution was prepared from sodium silicate solution (27 wt.% SiO_2 , 8 wt.% Na_2O) and 50 wt.% sodium

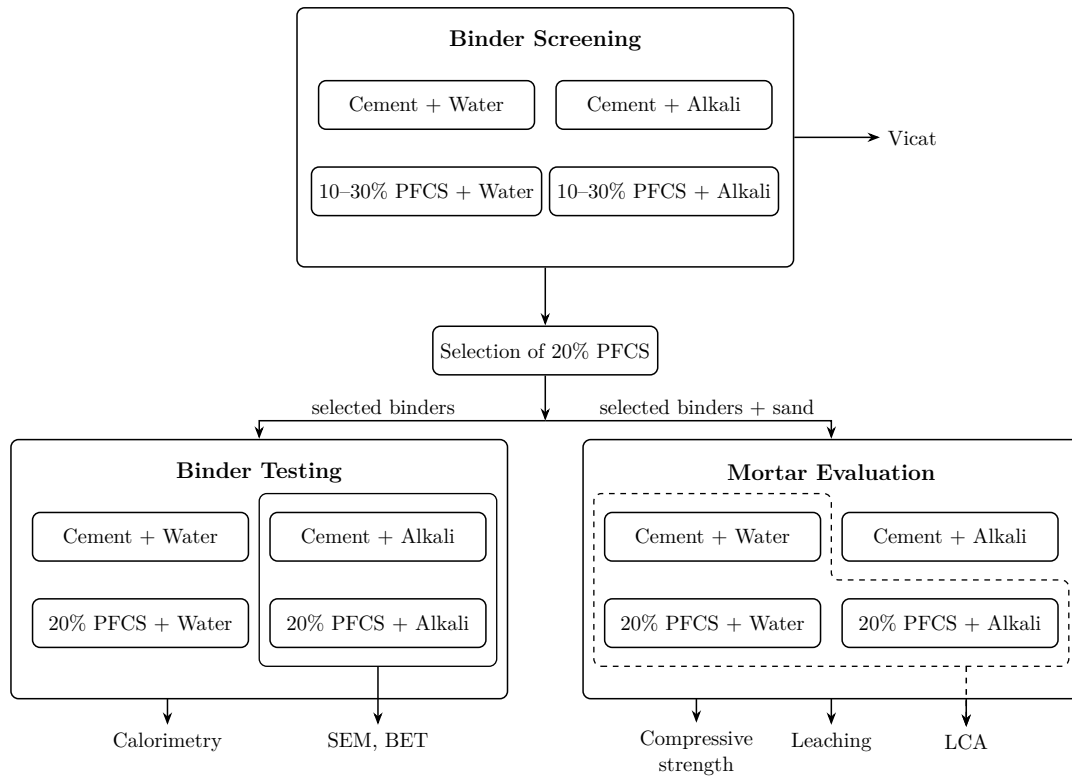


Figure 3.1: Overview of the method. Binder screening was conducted to select the 20% PFCS systems for subsequent binder paste and mortar testing. The selected mortar systems were further evaluated using LCA. Dashed outlines indicate the systems included in the LCA.

hydroxide (NaOH) solution. The activator had a silica modulus ($\text{SiO}_2/\text{Na}_2\text{O}$) of 1.7 and a total solids concentration of 10 wt.%.

3.2 Screening of cement replacement by PFCS

Initial screening was conducted using binder pastes containing 0–30% PFCS replacement of cement in both water-based and alkali-activated systems, as shown in Table 3.2. The screening was used to identify a suitable PFCS replacement level for further investigation. The objective was not to optimise the mixtures, but to evaluate how increasing PFCS incorporation influenced early hydration behaviour and workability. Therefore, a water-to-binder ratio corresponding to 0.30 was maintained for all binder and mortar mixtures. An equivalent water ratio was maintained in the alkali-activated systems, corresponding to a liquid-to-binder (l/b) ratio of 0.34, to allow comparison between the mixtures.

The screening was based on Vicat testing, which measures the setting behaviour of cementitious pastes. Initial setting time was selected as the primary screening parameter since it provides information regarding early-age reaction behaviour and practical workability. The initial setting time was determined from the penetration-time curve using the point corresponding to a 90% change in slope. This criterion was selected to provide a consistent comparative indicator between the systems. Binder pastes exhibiting setting times above approximately five hours were not further considered, since excessively delayed setting behaviour was considered unsuitable for continued investigation.

Table 3.2: Composition of binder pastes used for screening.

Sample	Cement (%)	PFCS (%)	w/b	l/b
<i>Water-based systems</i>				
Cement + Water	100	0	0.30	–
10% PFCS + Water	90	10	0.30	–
20% PFCS + Water	80	20	0.30	–
30% PFCS + Water	70	30	0.30	–
<i>Alkali-activated systems</i>				
Cement + Alkali	100	0	–	0.34
10% PFCS + Alkali	90	10	–	0.34
20% PFCS + Alkali	80	20	–	0.34
30% PFCS + Alkali	70	30	–	0.34

3.2.1 Selection of PFCS replacement level

A PFCS replacement level of 20% was selected for further investigation based on the screening results. The cement product datasheet specifies an initial setting time of 180 ± 30 min for the reference cement [35], which was used as a reference during evaluation of the mixtures. The selected compositions were

required to remain within a reasonably comparable setting time range while still allowing increased PFCS incorporation.

3.3 Binder Characterisation

Binder characterisation was performed using isothermal calorimetry, BET analysis, and SEM. Isothermal calorimetry was used to evaluate hydration behaviour and reaction kinetics related to binder reactivity, BET analysis to evaluate surface area and pore structure influencing dissolution behaviour, and SEM to examine microstructural development related to hardened material properties. The pastes were prepared by mixing the dry binder components with either water or alkaline activating solution until homogeneous pastes were obtained. Binder characterisation was performed on the selected 20% PFCS systems together with corresponding reference systems, shown in Table 3.3.

Table 3.3: Composition of binder mixtures.

Sample	Cement (%)	PFCS (%)	w/b	l/b
<i>Water-based systems</i>				
Cement + Water	100	0	0.30	–
20% PFCS + Water	80	20	0.30	–
<i>Alkali-activated systems</i>				
Cement + Alkali	100	0	–	0.34
20% PFCS + Alkali	80	20	–	0.34

Isothermal calorimetry was performed to evaluate hydration behaviour and heat evolution during the first three days of reaction at 20°C. The measurements were used to assess whether PFCS incorporation and alkali activation altered the hydration behaviour compared with the cement reference systems.

SEM analysis focused on the alkali-activated binder systems, which were expected to exhibit stronger slag interaction and matrix development compared with the water-based systems. The analysis was used to evaluate morphology, elemental distribution, and the presence of reacted or unreacted slag particles within the matrix. Samples were embedded in epoxy and polished prior to analysis. BET analysis was also limited to the alkali-activated systems, since alkali activation was expected to increase slag dissolution and matrix interaction. Cured samples were crushed and degassed at 120°C prior to further treatment at 150°C before nitrogen adsorption measurements at 77 K. The specific surface area was determined using the BET method.

3.4 Mortar Characterisation

Mortar mixtures were prepared using the selected binder systems together with standard sand. Mortar-scale experiments were conducted in order to evaluate compres-

sive strength, chromium leaching, and environmental performance. A fine aggregate-to-binder ratio (a/b) of 2.5 was used for all mortar mixtures. A w/b ratio corresponding to 0.30 was maintained for all systems in order to allow comparison between the different mortar compositions. The examined mortar compositions are presented in Table 3.4.

Mortar mixing was performed according to the procedure described in SS-EN 196-1:2016, while the mixture proportions were adapted for the investigated binders. The fresh mortars were cast into $40 \times 40 \times 40$ mm moulds and stored for 72 h before demoulding. After demoulding, specimens were cured at 20°C and 50% relative humidity until testing. Compressive strength testing was performed on mortar specimens after 7 and 28 days of curing. The measurements were used to evaluate whether PFCS-containing systems were capable of forming hardened structures with measurable mechanical strength.

Table 3.4: Composition of mortar mixtures

Sample	Cement (%)	PFCS (%)	w/b	l/b	a/b
<i>Water-based systems</i>					
Cement + Water	100	0	0.30	–	2.5
20% PFCS + Water	80	20	0.30	–	2.5
<i>Alkali-activated systems</i>					
Cement + Alkali	100	0	–	0.34	2.5
20% PFCS + Alkali	80	20	–	0.34	2.5

Chromium leaching experiments were performed on hardened mortar specimens after 28 days of curing according to SS-EN 16637-2:2023 [36]. Both water-based and alkali-activated systems were investigated in order to evaluate how alkaline conditions influenced chromium release behaviour.

3.5 Life Cycle Assessment

3.5.1 Goal and scope definition

The goal of the LCA was to support the evaluation of PFCS as an alternative cement binder by assessing the environmental trade-offs associated with slag processing, partial cement replacement, and alkali activation. The assessment was performed using an attributional cradle-to-gate approach, where the system boundary included raw material supply, FCS processing, alkali activator preparation, mortar production, and transport. The functional unit was defined as 1 tonne of mortar at the plant gate. The geographical scope of the study was Sweden.

Three mortar systems were evaluated: a reference mortar based on cement (Cement + Water), a mortar with 20% PFCS replacing cement (20% PFCS + Water), and a mortar with 20% PFCS combined with alkali activation (20% PFCS + Alkali). The

selected PFCS replacement level was based on the experimental screening described in Section 3.2 – 3.4. The Cement + Alkali system was not included in the LCA since this system was only used experimentally as a reference for evaluating the influence of alkali on cement hydration. The system was not considered relevant for practical implementation.

3.5.2 System boundary

The system boundaries for the investigated systems are presented in Figure 3.2. The assessment included all processes from raw material extraction to mortar production at the plant gate. For the reference mortar, this primarily included cement production and mortar manufacturing. For the PFCS-containing systems, additional stages included slag treatment, water granulation, drying, grinding, and transport of PFCS to the mortar production site. The incoming FCS was modelled using a cut-off approach, meaning that no upstream environmental burdens from ferrochrome production were allocated to the slag itself. Consequently, the system boundary for PFCS started at the reprocessing stage. For the alkali-activated system, production of the SiO_2 and NaOH solution was additionally included.

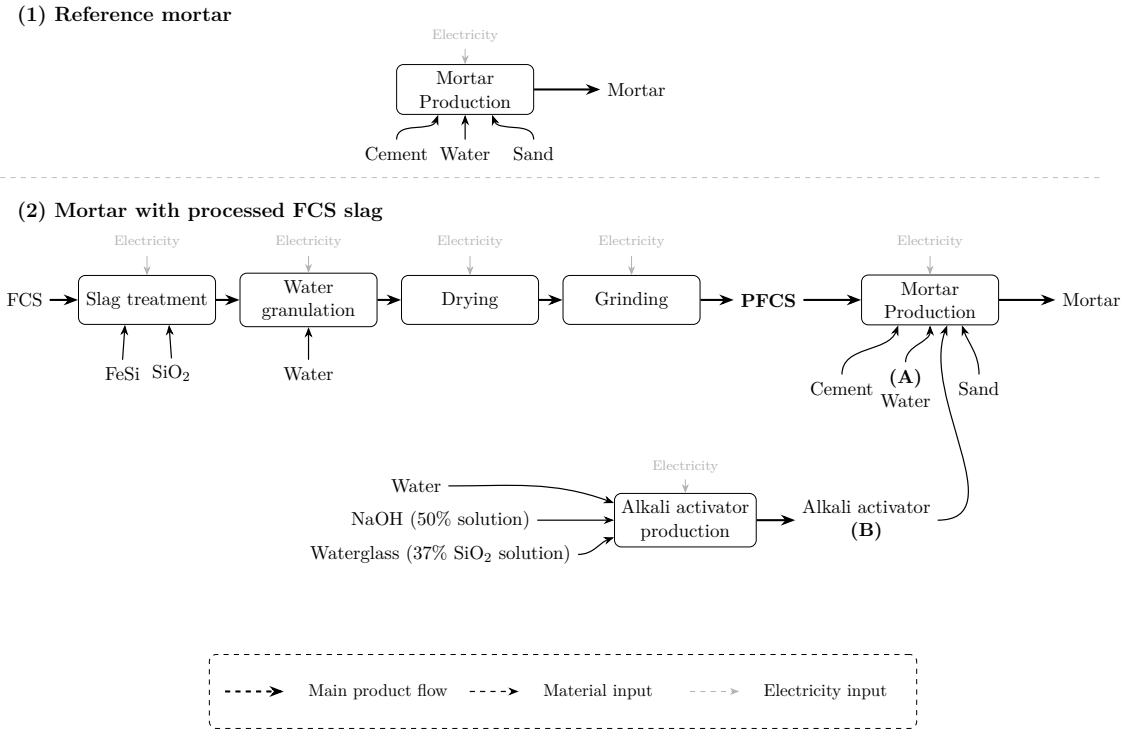


Figure 3.2: System boundaries for the LCA systems considered in this study. (1) Reference mortar based on cement and (2) mortar incorporating processed FCS slag. For the FCS-based system, two alternatives are evaluated in the mortar production stage: (A) water addition and (B) alkali activator addition.

3.5.3 Life cycle inventory analysis

The life cycle inventory (LCI) was developed using primary experimental data, process-specific information from VAAB, literature data, and secondary datasets from Ecoinvent 3.12 [37]. The inventory was modelled in Activity Browser and calculated per functional unit of 1 tonne of mortar.

Primary data for mortar composition and chromium leaching were obtained from the laboratory experiments conducted in this study. Primary data for PFCS processing parameters and transport were obtained from VAAB. Secondary data from Ecoinvent 3.12 were used for electricity production, transport, mortar production, sodium hydroxide production, sodium silicate production, and tap water. Process data from the PFCS test batch were scaled to industrial conditions using the framework proposed by Piccinno et al. [38]. Best- and worst-case scenarios were applied to process stages with scale-up uncertainty. A summary of the inventory data is presented in Table 3.5 and the datasets used in the LCA model are presented in Appendix A.

Table 3.5: Inventory data used in the LCA calculations (per tonne of mortar), presented as lowest–highest values for the best- and worst-case scenarios.

Parameter	Unit	1	2A	2B	Source
PFCS production					
SiO ₂ addition, slag treatment	kg	–	5.0–10.1		SLD-V
FeSi addition, slag treatment	kg	–	1.5		SLD-V
Electricity, slag treatment	kWh	–	3.3–32.7		SLD-V
Electricity, water granulation	kWh	–	0.1–0.8		SLD-V
Water consumption, water granulation	kg	–	41.7–63.2		SLD-V
Cr(VI) release, water granulation	mg	–	0–0.03		SLD-V
Electricity, drying	kWh	–	1.6–4.9		SLD-V
Electricity, grinding	kWh	–	0.4–0.8		SLD-V
Alkali activator production					
NaOH, 50% solution	kg	–	–	4.4	SLD
Waterglass, 37% SiO ₂	kg	–	–	20.4	SLD
Water	kg	–	–	63.7	SLD
Mixing electricity, axial flow	KWh	–	–	0.01–0.04	SLD
Mortar production					
Cement	kg	263.2	210.5	208.3	SLD
PFCS slag	kg	–	52.6	52.1	SLD
Water / activator	kg	78.9	79.0	88.0	SLD
Sand	kg	657.9	657.9	651.0	SLD
Mixing electricity	kWh	27.8	27.8	27.8	A
Transport					
Transport of PFCS slag	tkm	–	100–1000		A

Notes: SLD-V = scaled-up laboratory data from VAAB using the Piccinno et al. framework; SLD = scaled-up laboratory data from this study using the Piccinno et al. framework; A = assumption.

3.5.3.1 PFCS Production

The amounts of SiO_2 and FeSi used for PFCS production were based on primary data from VAAB. The amounts were calculated using the range of SiO_2 and FeSi proportions used during the production of the PFCS batch investigated in this study. Electricity demand for slag treatment was estimated using the scale-up framework proposed by Piccinno et al. [38].

Two slag treatment scenarios were evaluated. In the best-case scenario, rich slag from the SAF was assumed to be transferred directly to slag treatment while still at elevated temperature, requiring only heat maintenance. In the worst-case scenario, the slag was assumed to cool to ambient temperature, resulting in additional reheating demand. Both scenarios assumed a slag treatment duration of 2 h. Ambient temperature was based on the annual mean temperature in Sweden during 2025 (8.7°C) according to SMHI statistics [39]. In addition to energy demand, two flux addition scenarios were evaluated based on VAAB test trials.

Electricity and water consumption for water granulation were estimated using literature data for commercial-scale blast furnace slag granulation [40]. Equivalent industrial-scale PFCS data were unavailable, and blast furnace slag granulation was used as an approximation due to the similar slag treatment and rapid cooling approach. Chromium leaching during water granulation was based on experimentally measured leaching data from VAAB test trials and incorporated into the inventory as emissions to the environment. The measured chromium concentrations were below or close to the limit of quantification (LOQ). Consequently, the best-case scenario assumed zero emissions, while the worst-case scenario assumed emissions corresponding to the LOQ value.

Drying energy demand was estimated using the framework proposed by Piccinno et al. [38]. The best-case scenario assumed 3.5% moisture content after granulation, while the worst-case scenario assumed 10% moisture content. Grinding electricity demand was estimated using the same scale-up framework.

3.5.3.2 Alkali Activator Production

Production of alkali activator was modelled using the Ecoinvent datasets “market for sodium hydroxide, without water, in 50% solution state”, “market for sodium silicate, without water, in 37% solution state”, tap water, and electricity.

Large-scale activator preparation was assumed to be performed on site using axial-flow mixing since axial-flow impellers promote bulk circulation and homogeneous mixing in large-volume liquid systems [41]. The mixing process was scaled using the framework proposed by Piccinno et al. [38]. A mixing volume of 1000 L was assumed. The best-case scenario assumed 15 min of mixing, while the worst-case scenario assumed 45 min.

3.5.3.3 Mortar Production and Transport

Mortar production electricity was based on the Ecoinvent process for cement mortar production (CH), corresponding to 27.8 kWh per tonne of mortar. The same electricity demand was assumed for all investigated mortar systems. Transport of PFCS from VAAB to the mortar production site was modelled using the Ecoinvent process “transport, freight, lorry, >32 metric ton, diesel, EURO 6”. The best-case scenario assumed shorter transport distances, whereas the worst-case scenario represented longer industrial transport routes.

3.5.4 Life cycle impact assessment

The life cycle impact assessment (LCIA) was performed using the ReCiPe 2016 v1.03 midpoint (H) method implemented in Activity Browser. The selected impact categories were climate change, expressed as global warming potential (GWP100) [kg CO₂-eq], surplus ore potential (SOP) [kg Cu-eq], and freshwater ecotoxicity potential (FETP).

Climate change was included due to the high greenhouse gas emissions associated with cement production and the intended clinker replacement by PFCS. SOP was further included to evaluate resource-related impacts associated with PFCS processing and alkali activator production, particularly due to FeSi consumption and chemical production requirements. Since PFCS production also involves chromium release, FETP was additionally included to assess potential freshwater ecotoxicity impacts. The LCIA results were analysed at midpoint level to identify the main contributing processes and potential environmental trade-offs between the investigated systems.

4

Results and Analysis

4.1 Fresh-State Behaviour

Increasing PFCS replacement resulted in progressively longer initial setting times in both the water-based and alkali-activated mixtures, as presented in Figure 4.1. In the water-based mixtures, the measured setting times ranged from 181 to 266 min, while the alkali-activated mixtures showed shorter setting times ranging from 116 to 176 min. The setting behaviour was evaluated using the Cement + water reference, which had an expected initial setting time of approximately 180 ± 30 minutes [35].

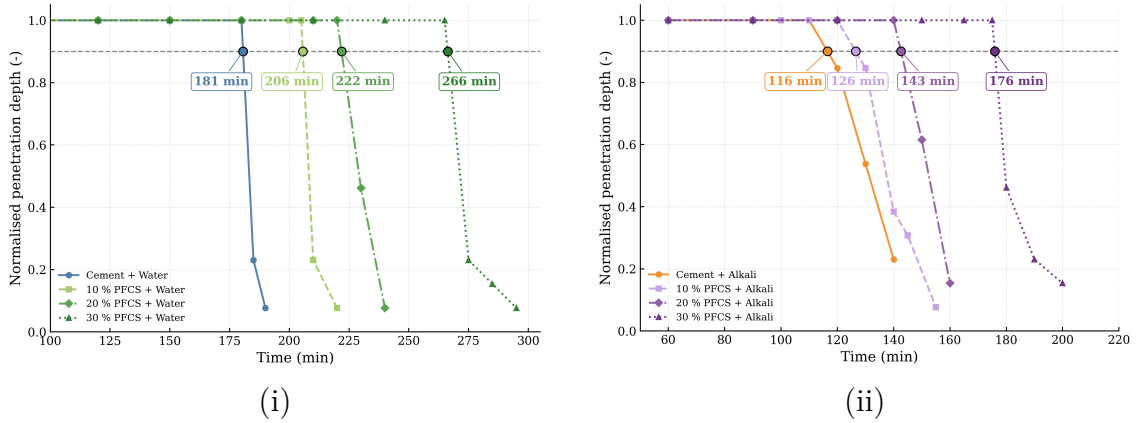


Figure 4.1: Initial setting time determined by Vicat testing: (i) cement paste mixed with water and (ii) cement paste mixed with alkali activator.

Changes in fresh-state behaviour were additionally observed during mixing and casting. Increasing PFCS incorporation increased paste fluidity and workability compared with the cement reference. The 10% PFCS mixtures behaved relatively similarly to cement but resulted in limited cement replacement. In contrast, the 30% PFCS mixtures showed longer setting times together with higher workability. The 20% PFCS mixtures represented a balance between cement replacement and acceptable setting behaviour and were therefore selected for further binder and mortar characterisation.

The delayed setting observed with increasing PFCS incorporation is likely related to partial cement dilution together with the coarser particle size and lower specific surface area of PFCS compared with cement. Since less cement surface was available for early hydration reactions, early stiffening and reaction development likely occurred more slowly. In contrast, the alkali-activated mixtures showed shorter Vicat

setting times than the corresponding water-based mixtures, indicating that alkaline conditions accelerated setting.

4.2 Hydration Behaviour

The calorimetry results indicate that PFCS influenced the hydration behaviour of the investigated binders, although the specific reaction products formed cannot be confirmed within the scope of this study. The measurements instead provide indications of how the reactions developed over time and whether PFCS mainly behaved as an inert filler or participated in the hydration reactions.

Figure 4.2 shows the characteristic hydration behaviour of the Cement + Water reference binder used for comparison. The results are presented per gram of binder. The curve exhibits the typical hydration stages of Portland cement, including an initial dissolution peak (1), induction period (2), acceleration stage with the main hydration peak (3), followed by deceleration (4) and slower continued hydration (5) [42].

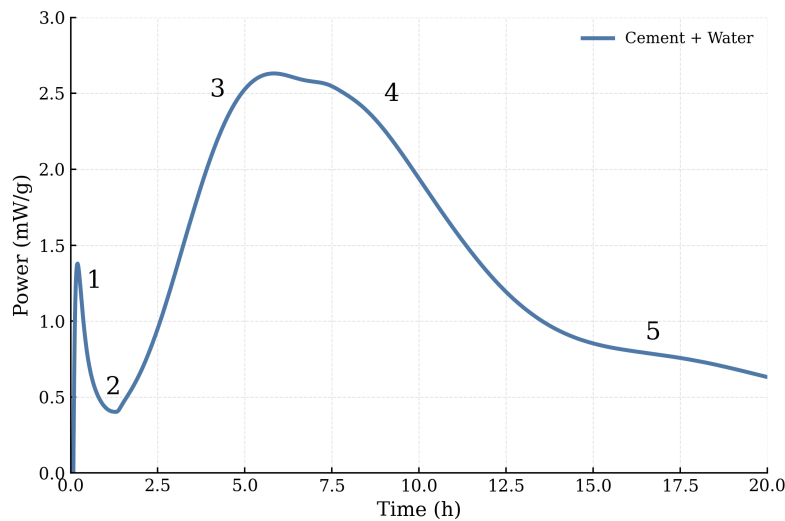
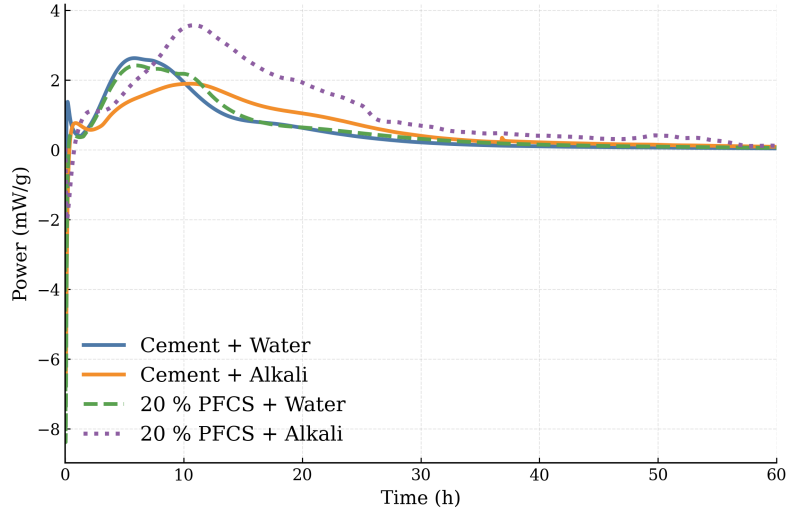


Figure 4.2: Heat flow curve for the Cement + Water reference binder.

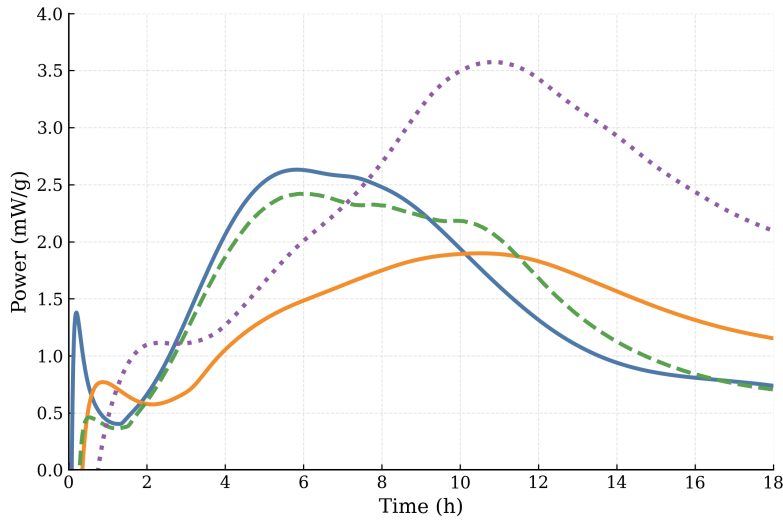
The same hydration stages can also be identified in the remaining investigated systems presented in Figure 4.3, although differences in peak position, intensity, and shape were observed between the mixtures. Compared with Cement + Water, Cement + Alkali exhibited a broader and delayed main hydration peak together with lower maximum peak intensity. This indicates that the alkali activator modified the ordinary cement hydration behaviour rather than simply accelerating the cement reactions. The broader peak suggests that the reactions occurred over a longer time period compared with the cement reference.

The 20% PFCS + Water mixture showed a slightly delayed hydration peak together with lower peak intensity compared with the cement reference. However, the overall hydration profile remained similar to Cement + Water. Replacing 20% of the cement

with PFCS therefore did not strongly disturb the cement hydration process under water-based conditions. One difference was the longer plateau region observed in the PFCS-containing systems, indicating prolonged reaction activity compared with the cement reference. The lower peak intensity can be related to the reduced clinker content following cement replacement, although the lower SSA of PFCS compared with cement may also have contributed.



(i)



(ii)

Figure 4.3: Isothermal calorimetry results for all binders showing (i) full heat flow curve and (ii) detailed view of the hydration stages.

The largest difference was observed for 20% PFCS + Alkali. The main hydration peak occurred at approximately 10–11 h and remained broader over a longer time period than for the remaining mixtures. Despite the delayed reaction development, the peak intensity and cumulative heat release were higher than for the other investigated systems, as presented in Figure 4.4. These results suggest that alkaline conditions altered the reaction development and increased PFCS participation

within the binder system. The increased heat release indicates more extensive reactions within the alkali-activated system and suggests that alkali activation promoted PFCS dissolution and reaction. One possible explanation for the delayed reaction development is the coarser particle size and lower SSA of PFCS compared with cement. Further grinding of PFCS could increase slag dissolution and participation in the hydration reactions in both water-based and alkali-activated systems.

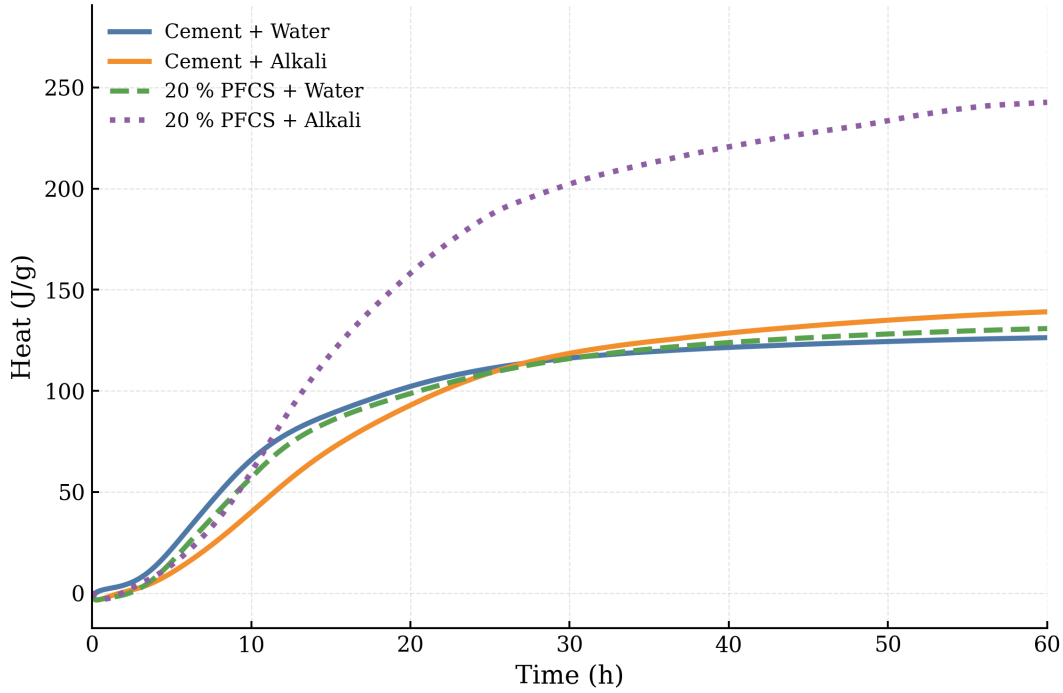


Figure 4.4: Cumulative heat release during isothermal calorimetry.

The calorimetry curves also provide information regarding setting behaviour, since cement setting generally occurs as the system transitions from the induction period into the acceleration stage where heat evolution begins to increase. Although the alkali-activated mixtures showed shorter Vicat setting times in Figure 4.1, the calorimetry results showed delayed and broader main heat evolution in Figure 4.3. This suggests that alkali activation accelerated early paste stiffening before the occurrence of the maximum heat evolution peak, further demonstrating that alkaline conditions altered the overall reaction development compared with conventional cement hydration.

4.3 Microstructural Characterisation

The SEM images showed that PFCS particles were still present within the matrix despite the increased reaction activity observed in the calorimetry results. SEM images of the investigated alkali-activated binders are presented in Figure 4.5 and 4.6. Cement + Alkali exhibited a matrix with smaller distinguishable particles

distributed throughout the matrix. These particles represent partly reacted or unreacted calcium phases from cement remaining within the matrix.

The 20% PFCS + Alkali binder additionally contained larger particles embedded within the surrounding matrix. These angular particles were identified in several regions of the PFCS-containing binder and were enriched in Mg, Al, and Si. Point EDS analysis further indicated higher amounts of Si, Al, and Mg within the surrounding matrix compared with the Cement + Alkali system, while O, C, and Ca remained dominant elements in both systems. However, SEM interpretation remained limited to the analysed surface regions, and some detected elements within the matrix may have originated from the particles rather than fully dissolved reaction products or gel phases. Small isolated Si- and C-rich white spots were also identified in some regions and were associated with residues from the SiC polishing paper used during sample preparation.

The PFCS particles throughout the matrix indicated that part of the slag remained only partly dissolved or unreacted during the investigated curing period. This behaviour is reasonable considering that FCS from current production is dominated by stable spinel and olivine-type crystalline phases. Although the processing aimed to increase the amorphous phase content and improve slag reactivity, PFCS likely still contained residual crystalline structures with lower dissolution potential.

The BET analysis further indicated differences in the microstructural characteristics of the PFCS-containing binder. The PFCS-containing binder had approximately 7% lower specific surface area compared with the alkali-activated cement reference, as presented in Figure 4.7. At the same time, the average pore size increased from approximately 170 nm to 183 nm following PFCS incorporation.

Together, the SEM and BET results indicate that PFCS incorporation with alkali activation resulted in a slightly coarser pore structure and altered matrix development compared with Cement + Alkali. The lower SSA of PFCS together with the larger distinguishable particles observed in SEM further supports the interpretation that part of the PFCS remained only partly reacted within the curing period. Despite the higher heat release observed for the alkali-activated system, the matrix did not appear denser based on the BET results. This suggests that the increased reaction activity associated with the applied alkali activation conditions did not necessarily result in a refined pore structure.

4. Results and Analysis

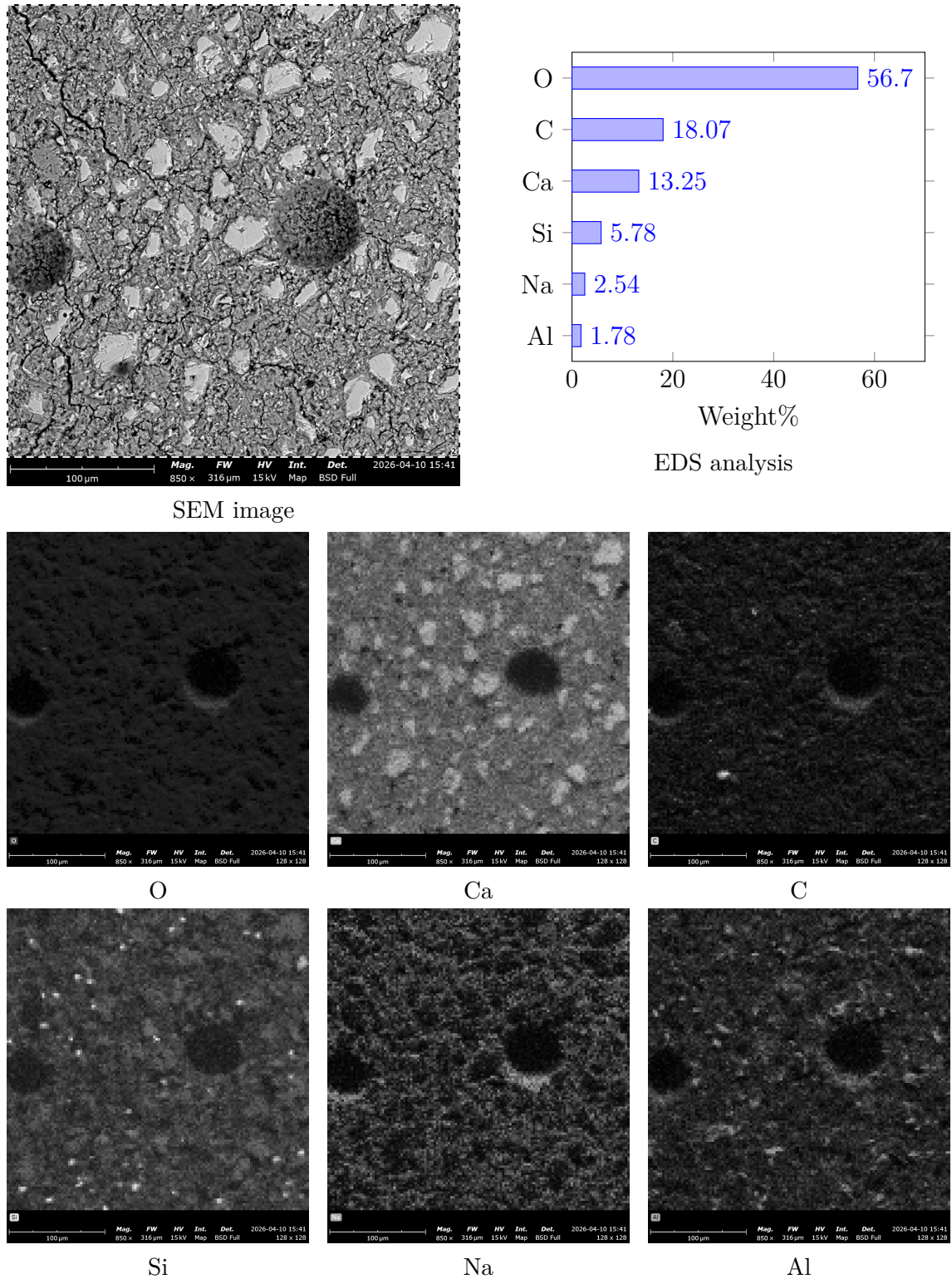


Figure 4.5: SEM micrograph, EDS spectrum and elemental mapping of Cement + Alkali.

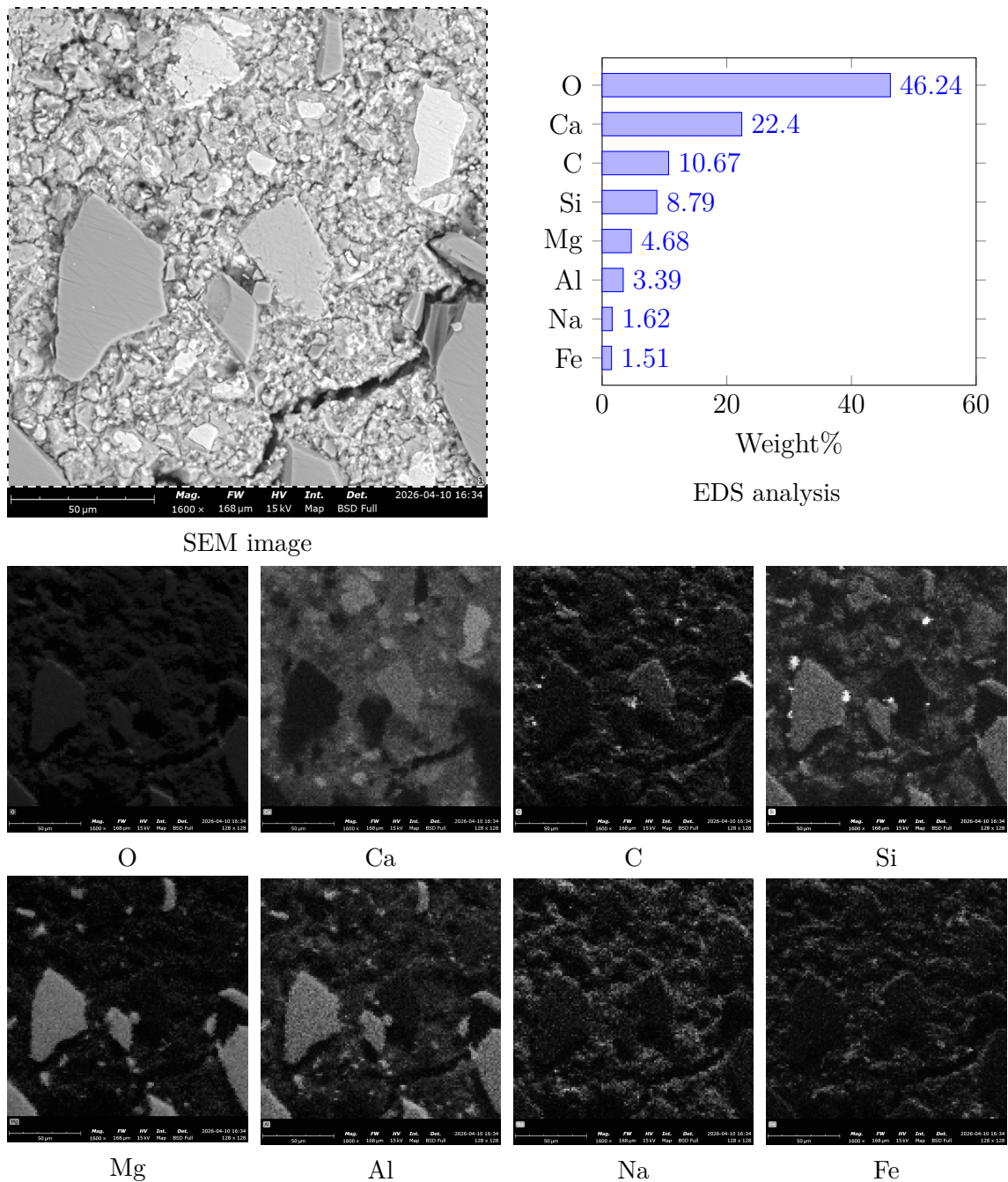


Figure 4.6: SEM micrograph, EDS spectrum and elemental mapping of 20% PFCS slag + Alkali.

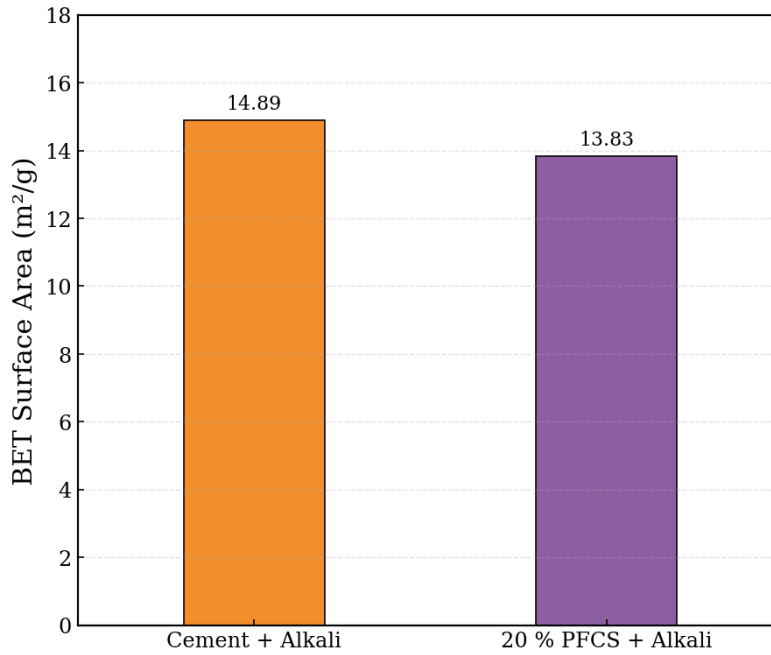


Figure 4.7: Specific surface area for binders with alkali activation.

4.4 Mortar Characterisation

All investigated mortar mixtures formed hardened specimens after curing. However, the mortar cubes exhibited relatively porous and poorly compacted surfaces, as shown in Figure 4.8. The porous morphology was associated with the low w/b ratio together with the absence of superplasticizer, which limited workability and compaction during casting. Consequently, the mortars contained elevated entrapped air content and internal porosity.

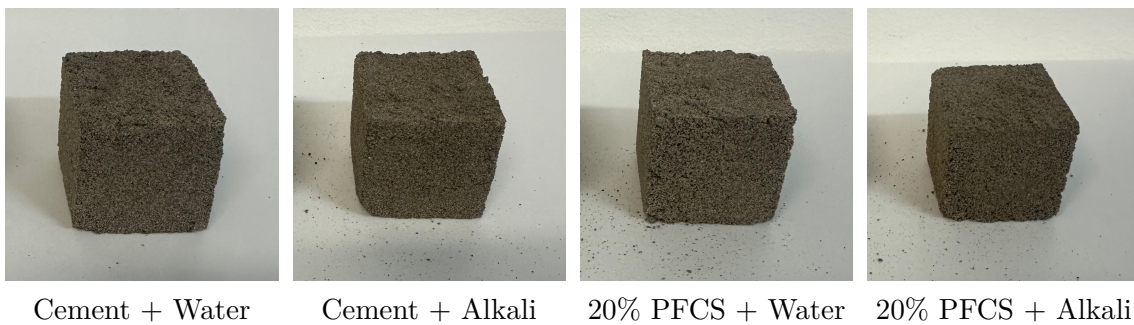


Figure 4.8: Mortar cubes after 28 days curing prior to compressive strength and chromium leaching experiments.

The low w/b ratio was selected to support higher strength development, but the absence of superplasticizer reduced workability and made proper compaction difficult. This was visible from the sandy surface morphology of the mortar cubes and is consistent with the low compressive strengths measured for all investigated systems. The absolute strength values must therefore be interpreted with caution.

Although the measured strengths were low for all systems, relative differences between the mixtures could still be observed. Cement + Water exhibited substantially lower compressive strength than expected after 28 days, with measured values of approximately 3 MPa compared to the expected 42.5 MPa strength range for the cement class [35]. Similar behaviour was observed for the remaining systems. The PFCS-containing systems exhibited higher measured compressive strengths than the cement reference, particularly for 20% PFCS + Water.

One possible explanation for the improved strengths observed for the PFCS-containing mortars is differences in workability and particle packing rather than solely intrinsic binder reactivity. Improved fluidity likely facilitated better compaction and reduced internal void formation compared with the cement reference. The increased cumulative heat release observed for 20% PFCS + Alkali indicates higher overall reaction activity within the binder system, which may suggest potential for improved strength development if the mortar formulation is further optimised through improved particle packing, adjusted water demand, or superplasticizer incorporation.

4.4.1 Leaching

The alkali-activated mortars exhibited higher Cr(VI) release compared with the water-based mortars, as presented in Table 4.1. For all investigated mortars, most Cr(VI) release occurred during the initial leaching period, after which the release rate decreased over time. This indicates that the most accessible chromium species dissolved during the early exposure stage, while the remaining chromium became less available with time. The porous mortar morphology likely influenced the measured values. Due to the poorly compacted structure, leaching likely occurred not only from the external specimen surfaces but also from internal pore surfaces throughout the mortars.

Table 4.1: Leaching from one mortar cube in mg/L.

Sample	6 h	24 h	54 h	Cumulative release
<i>Water-based systems</i>				
Cement + Water	0.065	0.022	0.0070	0.094
20% PFCS + Water	0.052	0.022	0.0095	0.084
<i>Alkali-activated systems</i>				
Cement + Alkali	0.19	0.024	0.0087	0.22
20% PFCS + Alkali	0.17	0.039	0.015	0.23

Higher Cr(VI) release was observed for the alkali-activated mortars compared with the corresponding water-based mortars. Since alkaline conditions increase dissolution of aluminosilicate phases, the results suggest that alkali activation increased chromium mobility within the hardened matrix. In contrast, 20% PFCS + Water did not show higher Cr(VI) release than Cement + Water under the investigated conditions, indicating that PFCS incorporation alone was not the primary cause of the increased chromium release. This indicates that the alkaline conditions associated with activation contributed to the observed chromium behaviour. Part of the

measured chromium release may additionally originate from the cement itself, since chromium-containing phases are present in Portland cement [35].

Overall, the leaching results highlight the balance between increased reactivity and chromium stability in PFCS-containing systems. Alkali activation increased both hydration development and chromium mobility within the investigated mortars, whereas 20% PFCS + Water showed hydration behaviour relatively similar to the cement reference without increasing Cr(VI) release under the investigated conditions.

4.5 Life Cycle Assessment

4.5.1 Global Warming Potential (GWP100)

The environmental assessment showed differences between the investigated mortar systems. Cement production remained the largest contributor to GWP100 across all investigated systems, despite the additional FCS processing stages. As presented in Figure 4.9 and Table 4.2, the PFCS + Water systems showed lower GWP100 impacts than Cement + Water. The lowest climate impacts were observed for 20% PFCS + Water, approximately 13% lower than the cement reference.

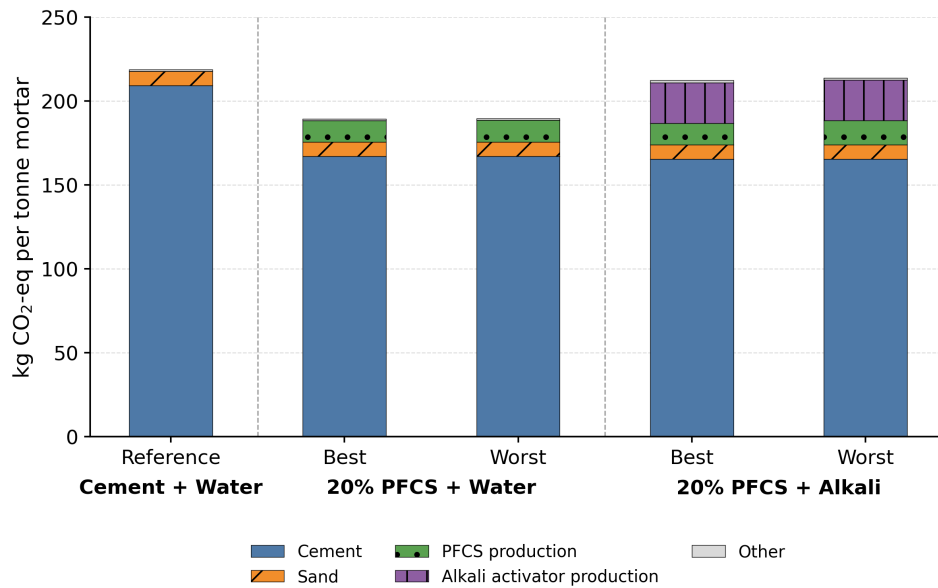


Figure 4.9: GWP100 impact for the investigated mortar systems.

The reduced GWP were mainly associated with partial cement replacement and the resulting reduction in clinker content. In contrast, the alkali-activated systems showed higher GWP100 impacts than the corresponding water-based PFCS systems. Although the alkali-activated systems still showed slightly lower impacts than Cement + Water, part of the climate benefit from cement replacement was offset by the impacts associated with alkali activation.

4.5.2 Surplus Ore Potential (SOP) and Freshwater Ecotoxicity Potential (FETP)

Different trends were observed for the SOP. As shown in Figure 4.10, the PFCS + Water systems showed slightly lower SOP impacts than Cement + Water. In contrast, the alkali-activated systems showed the highest SOP impacts among the investigated mixtures, approximately 23–25% higher than the cement reference. The increased SOP impacts observed for the alkali-activated systems were mainly associated with the additional material and processing requirements related to alkali activation and PFCS treatment. These results indicate that the environmental benefits associated with clinker reduction were partly offset by the additional inputs required for slag processing and activation.

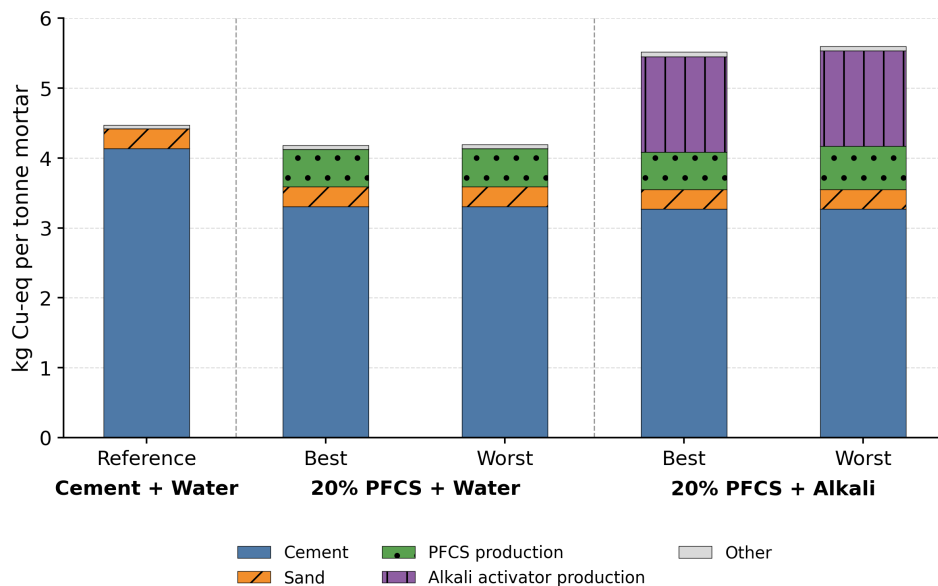


Figure 4.10: SOP impact for the investigated mortar systems.

The differences between the investigated mortars became even more pronounced for freshwater ecotoxicity. As presented in Figure 4.11, all PFCS-containing mixtures showed higher FETP impacts than the cement reference. The increase was moderate for the PFCS + Water systems, while the alkali-activated systems showed considerably larger increases.

The increased FETP impacts were mainly associated with PFCS processing and alkali activation. The highest impacts were observed for the alkali-activated systems due to the additional chemical inputs required for alkali activation. Table 4.2 summarises the characterised midpoint impacts together with the relative differences compared with Cement + Water.

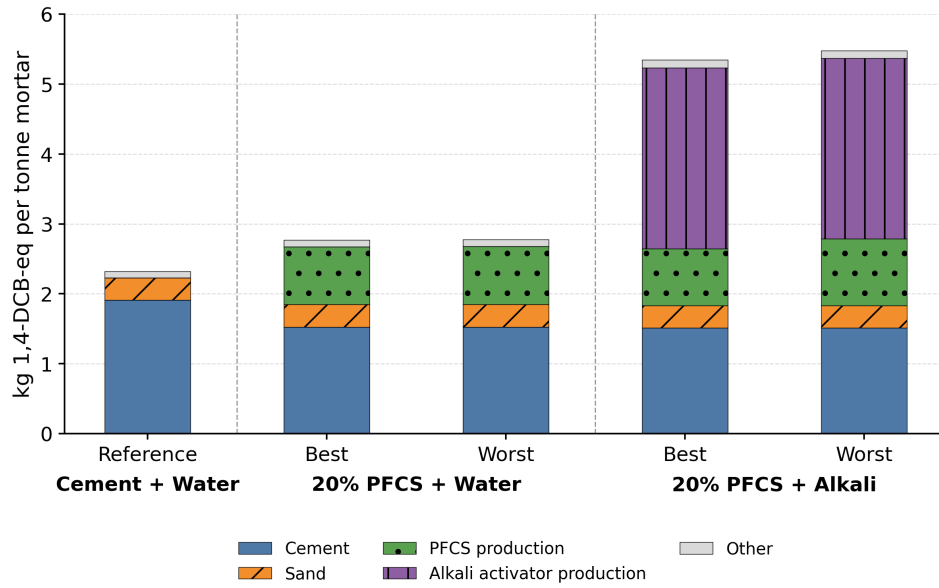


Figure 4.11: FETP impact for the investigated mortar systems.

4.5.3 Contribution Analysis

To better understand the origin of all the observed environmental impacts, contribution analysis was performed for the investigated systems. The contribution analysis showed that cement production, alkali activator production, and slag treatment contributed to the environmental impacts of the investigated systems. Within PFCS production, slag treatment contributed more to the investigated impact categories than water granulation, drying, and grinding combined, as shown in Figure 4.12.

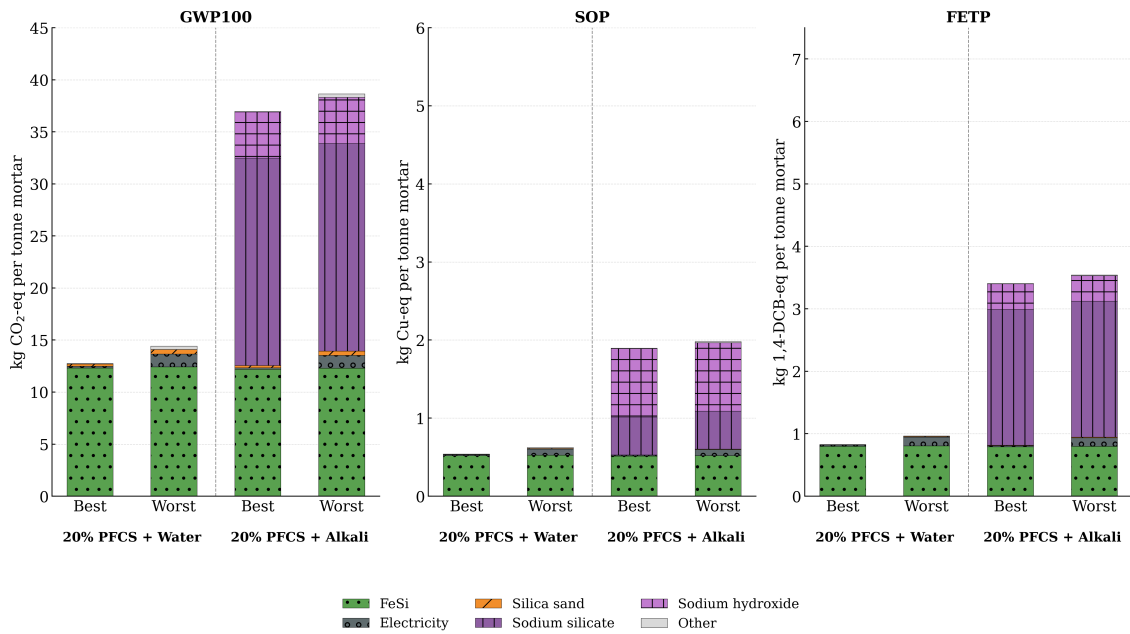


Figure 4.12: Process and alkali activator contribution analysis for all indicators.

Although PFCS incorporation reduced GWP100 through lower clinker demand, the results demonstrate that additional processing and activation steps introduced trade-offs in other impact categories. FeSi represented a large share of the impacts associated with slag treatment and contributed to GWP100, SOP, and FETP. For GWP100, the impacts were mainly associated with the electricity-intensive production of FeSi. In contrast, the higher SOP and FETP impacts were primarily linked to upstream mining, beneficiation, and metallurgical activities within the FeSi supply chain. Sodium hydroxide and sodium silicate further increased impacts in the alkali-activated systems due to the energy- and resource-intensive production processes required for alkali activator production.

Despite the differences observed between the investigated mortar systems, only minor variations were observed between the best- and worst-case scenarios. The best- and worst-case scenarios showed relatively similar impacts across all investigated categories, as summarised in Table 4.2. The scenario assumptions mainly influenced electricity demand and flux addition during slag treatment, while FeSi consumption remained unchanged between the scenarios. Since FeSi contributed to the overall impacts, variations in electricity demand had a smaller influence on the total results.

Table 4.2: Characterised midpoint impact per functional unit of 1 tonne mortar. Relative changes compared with the reference are shown in italics.

Impact category	Cement + Water	PFCS + Water		PFCS + Alkali	
	Reference	Best	Worst	Best	Worst
GWP100 (kg CO ₂ -eq)	218.66	189.35 <i>(-13.4%)</i>	189.61 <i>(-13.3%)</i>	212.25 <i>(-2.9%)</i>	213.81 <i>(-2.2%)</i>
SOP (kg Cu-eq)	4.47	4.18 <i>(-6.5%)</i>	4.19 <i>(-6.3%)</i>	5.52 <i>(+23.4%)</i>	5.60 <i>(+25.1%)</i>
FETP (kg 1,4-DCB-eq)	2.32	2.77 <i>(+19.3%)</i>	2.78 <i>(+19.6%)</i>	5.35 <i>(+130.6%)</i>	5.48 <i>(+136.2%)</i>

Overall, PFCS incorporation reduced GWP100 through partial cement replacement, particularly for the PFCS + Water systems, which showed the lowest climate impacts among the investigated mixtures. In contrast, alkali activation increased SOP and FETP impacts due to the additional inputs required for slag treatment and alkali activator production. The results therefore suggest that increasing PFCS reactivity through alkali activation was associated with environmental trade-offs related to resource use and freshwater ecotoxicity.

5

Discussion

This study provides a preliminary analysis of PFCS as a partial cement replacement in cementitious mortars. Previous studies have mainly utilised FCS as an inert aggregate material, while ferrochrome ash has been investigated as a partial cement replacement for reducing environmental impacts [43–45]. In contrast, the present study evaluated FCS with increased amorphous phase content for use as a partial cement replacement material.

The results suggest that PFCS shows potential for use as an alternative binder material in cementitious systems. Although PFCS incorporation prolonged the setting time, the hydration behaviour of the 20% PFCS + Water system remained broadly similar to the cement reference, showing comparable peak development and heat release. One difference was the more prolonged hydration process observed in the PFCS-containing system, indicating extended reaction activity compared with the cement reference. At the same time, remaining PFCS particles were observed within the hardened matrix of the alkali-activated system, suggesting that stable crystalline phases, likely residual spinels originating from the original FCS, were still present after processing. Such phases have previously been associated with prolonged setting behaviour and lower hydraulic reactivity in FCS systems [3]. Together, the results suggest that slag processing altered the hydration behaviour of FCS and enhanced the reactivity of PFCS, although phases originating from the original FCS still influenced the overall hydration process. Since slag composition and phase development are affected by the production process, variations in hydration behaviour and reactivity can occur between different processed slag batches.

PFCS processing is also connected to chromium stability within the binder systems. The remaining chromium after reduction is likely still associated with stable spinel phases after processing. While such phases may contribute to chromium stability, they simultaneously limit slag dissolution and reactivity. The increased Cr(VI) release observed for the alkali-activated systems further suggests that highly alkaline conditions influenced chromium mobility within the hardened matrix, whereas PFCS incorporation alone did not increase Cr(VI) release.

From an environmental perspective, the primary motivation for using alternative binder materials is to reduce the climate impacts associated with cement production. Accordingly, PFCS incorporation reduced GWP compared with the cement reference through partial clinker replacement, demonstrating the intended environmental benefit of alternative binder utilisation. Similar reductions have previously been reported for ferrochrome waste-based concrete systems [44]. Das et al. [34]

also reported lower GWP for concrete containing FCS compared with conventional concrete, although FCS was used as an aggregate rather than as a binder material. However, the environmental assessment in the present study also showed trade-offs related to PFCS processing and alkali activation, particularly for SOP and FETP. Although the alkali-activated systems still showed lower GWP100 impacts than the cement reference, the additional inputs required for slag treatment and alkali activator production increased impacts in these categories.

Since the environmental assessment was based on a mass-based functional unit, the systems were compared per tonne mortar rather than per achieved technical performance. The alkali-activated PFCS systems exhibited increased hydration activity, meaning that the environmental impacts per achieved function could differ if improved mechanical performance is achieved through further optimisation. In addition, the alkali-activated systems still contained cement within the binder composition, meaning that clinker-related impacts remained. Fully slag-based systems or mixtures with higher PFCS incorporation may therefore exhibit lower environmental impacts [46].

Since only one activator composition was used, the alkali-activated systems should be interpreted as an initial evaluation of whether PFCS could be activated under alkaline conditions. The applied activator formulation was not optimised for matrix densification or technical performance. Non-optimised activator conditions may have affected particle wetting and dissolution within the matrix, potentially contributing to the presence of remaining calcium-rich and PFCS-related particles observed in Figure 4.5 and Figure 4.6. Further optimisation of activator composition and modulus can also influence both technical performance and environmental impacts, since changes in sodium hydroxide and sodium silicate demand would affect the LCA results, although the direction and magnitude of such effects remain uncertain.

Within PFCS processing, FeSi functioned as the reductant used to lower the chromium content of the slag, while simultaneously contributing to GWP100, SOP, and FETP. The environmental performance of PFCS processing may therefore depend on the amount of reductant required to achieve sufficient chromium reduction. FeSi represented only one possible reductant approach in the present study, and alternative reductants can influence both chromium reduction efficiency and environmental performance differently.

The environmental performance additionally depend on regional production conditions and electricity systems. The FeSi, sodium hydroxide, and sodium silicate datasets used in the study were based on other electricity systems (GLO and RER), whereas Swedish electricity production generally has lower climate intensity due to larger shares renewable power. Consequently, the impacts associated with FeSi and alkali activator production differ under Swedish production conditions.

Overall, the results demonstrate that PFCS has potential as a partial cement replacement material, although slag reactivity, chromium behaviour, and environmental impacts associated with processing remained closely interconnected. The

present study adds to previous research by evaluating processed FCS for partial cement replacement and by considering hydration behaviour, chromium stability, and environmental performance within the same study. Further optimisation of PFCS processing and binder formulation is required to balance technical performance, chromium stability, and environmental performance in PFCS-based systems.

5.1 Limitations and Future Work

Since industrial-scale PFCS processing data were unavailable, scale-up assumptions based on the framework proposed by [38] were required within the LCA model. The environmental results should therefore be interpreted as indicative rather than absolute industrial values. In addition, the LCA did not include end-of-life scenarios or long-term chromium release behaviour.

Due to uncertainties associated with laboratory-scale leaching measurements together with the porous mortar morphology, the experimentally measured Cr(VI) values were not directly implemented as absolute emissions within the LCA calculations. The measurements were instead primarily used for relative comparison between the investigated systems. Future studies should therefore investigate long-term chromium release from hardened mortars under extended exposure conditions. If Cr(VI) release from alkali-activated systems increases during long-term exposure, the environmental impacts associated with chromium mobility could become higher than reflected by the present LCA results.

Further material characterisation is required to better understand the reaction mechanisms and hydration behaviour of PFCS-based mixtures. XRD analysis should be performed to identify hydration products and evaluate the formation of C–S–H and potential C–A–S–H phases within the binder matrix. XRD analysis of PFCS would also improve the understanding of its amorphous phase content and the influence of remaining crystalline phases on slag dissolution and reactivity.

Further studies should then focus on optimising the PFCS-containing mixtures. Particle fineness and activator dosage should be investigated first, followed by curing conditions, w/b ratio, and admixture use to improve workability and mechanical performance. The influence of PFCS processing conditions should also be investigated, particularly how reductant addition and cooling conditions affect amorphous phase formation, chromium stability and slag reactivity.

6

Conclusion

PFCS showed potential for partial cement replacement in cementitious systems based on the experimental analyses and LCA performed in this study. PFCS incorporation reduced GWP100 compared with the cement reference in both the water-based and alkali-activated systems due to partial clinker replacement. The 20% PFCS + Water system showed approximately 13% lower GWP100 than the cement reference. Previous studies have also reported lower GWP100 for concrete containing FCS, although FCS has mainly been investigated as an aggregate rather than as a binder material. The present study therefore extends previous research by investigating processed FCS with increased amorphous phase content for partial cement replacement. The water-based PFCS system showed the most favourable overall balance between hydration behaviour, chromium stability, and environmental performance. The hydration behaviour remained broadly similar to the cement reference, although the hydration process was prolonged. PFCS processing also introduced environmental trade-offs related to FeSi consumption during slag treatment, which contributed to FETP. Further studies should investigate the water-based PFCS system using SEM and BET analysis to better understand its microstructure, together with additional compressive strength testing for both water-based and alkali-activated systems.

Alkali activation further increased PFCS participation in the hydration reactions and resulted in increased heat release, indicating enhanced slag reactivity. This suggests that alkali activation may enable higher PFCS replacement levels in future systems. At the same time, the alkali-activated systems exhibited higher chromium release together with increased SOP and FETP impacts associated with alkali activator production and PFCS processing. Compared with the cement reference, SOP increased by approximately 23–25% and FETP by 131–136%, while GWP100 remained approximately 2–3% lower. Although alkali activation improved slag reactivity and reduced GWP100, the overall balance between technical performance, chromium stability, and environmental performance requires further optimisation before broader implementation can be considered. XRD analysis of PFCS and the hardened binders should also be performed to better understand the amorphous and crystalline phases and their influence on PFCS reaction behaviour.

Bibliography

- [1] René Muschter. *Global cement industry - statistics & facts*. Statista. Dec. 17, 2025. URL: <https://www.statista.com/topics/8700/cement-industry-worldwide/> (visited on 02/03/2026).
- [2] R. M. Andrew. “Global CO2 emissions from cement production”. In: *Earth System Science Data* 10.1 (2018), pp. 195–217. DOI: 10.5194/essd-10-195-2018. URL: <https://essd.copernicus.org/articles/10/195/2018/>.
- [3] Shaswat K. Das et al. “Towards Sustainable Construction: Utilization of Ferrochrome Slag as Portland Cement Replacement in Cementitious Composites”. In: *Journal of Sustainable Metallurgy* 9.1 (Mar. 1, 2023), pp. 329–340. ISSN: 2199-3831. DOI: 10.1007/s40831-023-00653-w. URL: <https://doi.org/10.1007/s40831-023-00653-w> (visited on 02/03/2026).
- [4] Naturvårdsverket. *Industrin, utsläpp av växthusgaser*. Dec. 16, 2025. URL: <https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-utslapp-fran-industrin/> (visited on 01/29/2026).
- [5] European Parliament and Council of the European Union. *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC*. June 13, 2024. URL: <http://data.europa.eu/eli/reg/2024/1781/2024-06-28> (visited on 02/03/2026).
- [6] Yanxi Li et al. “Advancement of early strength of supplementary cementitious materials: A review”. In: *Journal of Building Engineering* 119 (Feb. 1, 2026), p. 115172. ISSN: 2352-7102. DOI: 10.1016/j.jobbe.2025.115172. URL: <https://www.sciencedirect.com/science/article/pii/S2352710225034096> (visited on 01/30/2026).
- [7] Barbara Pacewska and Iwona Wilińska. “Usage of supplementary cementitious materials: advantages and limitations”. In: *Journal of Thermal Analysis and Calorimetry* 142.1 (Oct. 1, 2020), pp. 371–393. ISSN: 1588-2926. DOI: 10.1007/s10973-020-09907-1. URL: <https://doi.org/10.1007/s10973-020-09907-1>.
- [8] Ahmad L. Almutairi et al. “Potential applications of geopolymers in construction: A review”. In: *Case Studies in Construction Materials* 15 (2021), e00733. ISSN: 2214-5095. DOI: <https://doi.org/10.1016/j.cscm.2021.e00733>. URL: <https://www.sciencedirect.com/science/article/pii/S2214509521002485>.
- [9] *slag, n.¹ meanings, etymology and more* / *Oxford English Dictionary*. URL: https://www.oed.com/dictionary/slag_n1 (visited on 02/04/2026).

- [10] *Ground granulated blast furnace slag for use in concrete, mortar and grout - Part 1: Definitions, specifications and conformity criteria*. Aug. 10, 2006. URL: <https://www.sis.se/produkter/terminologi-och-dokumentation/ordlistor/byggnadsmaterial-och-byggnader-/ssen1516712006/> (visited on 04/09/2026).
- [11] Naturvårdsverket. *SSAB Luleå – följ ärendet*. Sept. 17, 2025. URL: <https://www.naturvardsverket.se/lagar-och-regler/provningsarenanden/metallindustri/ssab-lulea--folj-arendet/> (visited on 01/28/2026).
- [12] Naturvårdsverket. *SSAB Oxelösund*. URL: <https://www.naturvardsverket.se/lagar-och-regler/provningsarenanden/metallindustri/ssab-oxelosund/> (visited on 01/28/2026).
- [13] Ruben Snellings, Prannoy Suraneni, and Jørgen Skibsted. “Future and emerging supplementary cementitious materials”. In: *Cement and Concrete Research* 171 (2023), p. 107199. ISSN: 0008-8846. DOI: <https://doi.org/10.1016/j.cemconres.2023.107199>. URL: <https://www.sciencedirect.com/science/article/pii/S0008884623001138>.
- [14] Carina Harpprecht et al. “Future environmental impacts of global iron and steel production”. In: *Energy & Environmental Science* 18.16 (2025), pp. 8009–8028. DOI: 10.1039/D5EE01356A. URL: <https://pubs.rsc.org/en/content/articlelanding/2025/ee/d5ee01356a> (visited on 01/30/2026).
- [15] Sveriges Riksdag. *Avfallsförordning (2020:614)*. URL: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/avfallsforordning-2020614_sfs-2020-614/ (visited on 06/05/2026).
- [16] A. Arvizu-Montes et al. “Integrating Life-Cycle Assessment (LCA) and Artificial Neural Networks (ANNs) for Optimizing the Inclusion of Supplementary Cementitious Materials (SCMs) in Eco-Friendly Cementitious Composites: A Literature Review”. In: *Materials* 18.18 (Sept. 14, 2025), p. 4307. ISSN: 1996-1944. DOI: 10.3390/ma18184307. URL: <https://www.mdpi.com/1996-1944/18/18/4307> (visited on 01/30/2026).
- [17] Dejian Pei et al. “Effect of Phase Composition on Leaching Behavior and Mechanical Properties of Ceramics from Ferrochrome Slag and Tundish Slag”. In: *Materials* 15.6 (Jan. 2022), p. 1993. ISSN: 1996-1944. DOI: 10.3390/ma15061993. URL: <https://www.mdpi.com/1996-1944/15/6/1993> (visited on 05/05/2026).
- [18] Chao Ren et al. “Preparation and Hydration Mechanisms of Low Carbon Ferrochrome Slag-Granulated Blast Furnace Slag Composite Cementitious Materials”. In: *Materials* 16.6 (Mar. 16, 2023), p. 2385. ISSN: 1996-1944. DOI: 10.3390/ma16062385. URL: <https://www.mdpi.com/1996-1944/16/6/2385> (visited on 05/05/2026).
- [19] Deborah Andrews. “The circular economy, design thinking and education for sustainability”. In: *Local Economy* 30 (Apr. 21, 2015), pp. 305–315. DOI: 10.1177/0269094215578226.
- [20] Naturvårdsverket. *Farliga ämnen vid avfallshantering och återvinning*. Dec. 18, 2024. URL: <https://www.naturvardsverket.se/vagledning-och-stod/avfall/farliga-amnen-vid-avfallshantering-och-atervinning/> (visited on 02/03/2026).

-
- [21] Sveriges Riksdag. *Swedish Environmental Code (Miljöbalken)*. 1998. URL: <https://beta.rkrattsbaser.gov.se/sfs/item?bet=1998%3A808&tab=grundforfattning> (visited on 02/04/2026).
 - [22] Ellen MacArthur Foundation, Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN), and Deutsche Post Foundation. *Growth Within: A Circular Economy Vision for a Competitive Europe*. Ellen MacArthur Foundation, 2015.
 - [23] Jin-Young Lee et al. “Comparing Properties of Concrete Containing Electric Arc Furnace Slag and Granulated Blast Furnace Slag”. In: *Materials* 12.9 (Apr. 27, 2019), p. 1371. ISSN: 1996-1944. DOI: 10.3390/ma12091371. URL: <https://www.mdpi.com/1996-1944/12/9/1371> (visited on 04/09/2026).
 - [24] Mojca Lončnar et al. “The effect of water cooling on the leaching behaviour of EAF slag from stainless steel production”. In: *Materiali in Tehnologije* 43.6 (2009), pp. 315–321. ISSN: 1580-2949.
 - [25] Dr Topraladoddi Madhavi. “Overview of Building Mortar: Composition, Types and Applications”. In: *International Journal of Innovative Research in Computer Science & Technology* 10 (Special Issue 3 2022). ISSN: 2347-5552.
 - [26] E. Rikard Ylmén. “Early Hydration of Portland Cement: An Infrared Spectroscopy Perspective Complemented by Calorimetry and Scanning Electron Microscopy”. PhD thesis. Gothenburg: Chalmers University of Technology, 2013. URL: <https://api.semanticscholar.org/CorpusID:53696369>.
 - [27] John L. Provis. “Alkali-activated materials”. In: *Cement and Concrete Research*. Report of UNEP SBCI WORKING GROUP ON LOW-CO₂ ECO-EFFICIENT CEMENT-BASED MATERIALS 114 (Dec. 1, 2018), pp. 40–48. ISSN: 0008-8846. DOI: 10.1016/j.cemconres.2017.02.009. URL: <https://www.sciencedirect.com/science/article/pii/S0008884616307700> (visited on 01/29/2026).
 - [28] Mahasakti Mahamaya et al. “Engineering Properties of Cementless Alkali Activated CLSM Using Ferrochrome Slag”. In: *Journal of Materials in Civil Engineering* 35.3 (2023). ISSN: 1943-5533. ISSN: 0899-1561. DOI: 10.1061/(ASCE)MT.1943-5533.0004620. URL: <https://ascelibrary.org/doi/epdf/10.1061/%28ASCE%29MT.1943-5533.0004620> (visited on 02/06/2026).
 - [29] Ke-yu Chen et al. “Developing an indexing methodology for estimating the reactivity of slag from different sources use in alkali-activated materials”. In: *Journal of Non-Crystalline Solids* 647 (2025), p. 123278. ISSN: 0022-3093. DOI: <https://doi.org/10.1016/j.jnoncrysol.2024.123278>. URL: <https://www.sciencedirect.com/science/article/pii/S002230932400454X>.
 - [30] ECHA CHEM. *Chromium (VI) 100.132.559 / Overview - ECHA CHEM*. URL: <https://chem.echa.europa.eu/100.132.559/overview?searchText=hexavalent%20chromium> (visited on 02/03/2026).
 - [31] International Organization for Standardization. *Environmental management – Life cycle assessment – Principles and framework*. International Standard ISO 14044:2006. Geneva, Switzerland, 2006.
 - [32] International Organization for Standardization. *Environmental management – Life cycle assessment – Requirements and guidelines*. International Standard ISO 14040:2006. Geneva, Switzerland, 2006.

- [33] Henrikke Baumann and Anne-Marie Tillman. *The hitch hiker's guide to LCA. An orientation in life cycle assessment methodology and application*. 1st ed. Lund: Studentlitteratur, 2004. ISBN: 978-91-44-02364-9.
- [34] Priyadarshini Das et al. "Performance assessment and life cycle analysis of concrete containing ferrochrome slag and fly ash as replacement materials – A circular approach". In: *Construction and Building Materials* 347 (2022), p. 128609. ISSN: 0950-0618. DOI: <https://doi.org/10.1016/j.conbuildmat.2022.128609>. URL: <https://www.sciencedirect.com/science/article/pii/S0950061822022668>.
- [35] Heidelberg Materials Cement Sverige AB. *Technical Data Sheet - Byggcement Skövde*. Technical Data Sheet. Oct. 30, 2025.
- [36] *Standard - Bygg- och anläggningsprodukter - Bedömning av avgivning av farliga ämnen - Del 2: Metod för dynamisk provning av utlakning från ytor SS-EN 16637-2:2023*. Svenska institutet för standarder, SIS. URL: <https://www.sis.se/produkter/byggnadsmaterial-och-byggnader/byggnadsmaterial/allmant/ss-en-16637-22023/> (visited on 05/15/2026).
- [37] *Ecoinvent version 3*. ecoinvent. URL: <https://ecoinvent.org/sri-login/> (visited on 05/22/2026).
- [38] Fabiano Piccinno et al. "From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies". In: *Journal of Cleaner Production* 135 (2016), pp. 1085–1097. ISSN: 0959-6526. DOI: <https://doi.org/10.1016/j.jclepro.2016.06.164>. URL: <https://www.sciencedirect.com/science/article/pii/S0959652616308514>.
- [39] SMHI. *Året 2025 - Lufttemperatur*. Sveriges meteorologiska och hydrologiska institut (SMHI), 2025. URL: https://www.smhi.se/pd/klimat/pdf_stats/year/SMHI_vov_temperature_25.pdf.
- [40] Hong Wang et al. "Energy–environment–economy evaluations of commercial scale systems for blast furnace slag treatment: Dry slag granulation vs. water quenching". In: *Applied Energy* 171 (2016), pp. 314–324. ISSN: 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2016.03.079>. URL: <https://www.sciencedirect.com/science/article/pii/S0306261916304007>.
- [41] Zikun Xie. "Comparative Analysis of the Flow Field Characteristics of Axial Flow, Radial Flow, and Tangential Flow in Stirring Equipment". In: *Applied and Computational Engineering* 148 (May 2025), pp. 89–93. DOI: 10.54254/2755-2721/2025.23355.
- [42] Gartner, E. M. et al. "Hydration of Portland Cement". In: *Structure and Performance of Cements*. London: Taylor & Francis Group, 2008, pp. 57–107.
- [43] Yaqoob Al Hindasi, Nor Hasanah Abdul Shukor Lim, and Natarajan Rajamohan. "Sustainable application of ferrochrome slag as green aggregate material for novel application in concrete - A review". In: *Journal of Hazardous Materials Advances* 18 (2025), p. 100681. ISSN: 2772-4166. DOI: <https://doi.org/10.1016/j.hazadv.2025.100681>. URL: <https://www.sciencedirect.com/science/article/pii/S2772416625000932>.
- [44] Prasanna Kumar Acharya and Sanjaya Kumar Patro. "Evaluation of environmental disturbance indicator using functional performance and life cycle assessment of ferrochrome waste concrete". In: *Journal of Building Engineer-*

- ing 65 (2023), p. 105788. ISSN: 2352-7102. DOI: <https://doi.org/10.1016/j.jobe.2022.105788>. URL: <https://www.sciencedirect.com/science/article/pii/S2352710222017946>.
- [45] Satyajit Das, Rakesh Kumar Patra, and Bibhuti Bhusan Mukharjee. “Feasibility study of utilisation of ferrochrome slag as fine aggregate and rice husk ash as cement replacement for developing sustainable concrete”. In: *Innovative Infrastructure Solutions* 6.2 (Jan. 24, 2021), p. 85. ISSN: 2364-4184. DOI: 10.1007/s41062-021-00461-9. URL: <https://doi.org/10.1007/s41062-021-00461-9>.
- [46] Peiliang Cong et al. “Comparison and assessment of carbon dioxide emissions between alkali-activated materials and OPC cement concrete”. In: *Journal of Traffic and Transportation Engineering (English Edition)* 11.5 (Oct. 2024), pp. 918–938. ISSN: 20957564. DOI: 10.1016/j.jtte.2023.07.011. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2095756424000953> (visited on 05/24/2026).

A

Background Datasets Used in the LCA Model

Table A.1 presents the background datasets and foreground processes used in the LCA model developed in Activity Browser with Ecoinvent 3.12 [37]. Regionally representative datasets were selected where possible based on the geographical scope of the study.

Table A.1: Main datasets and processes used in the LCA model.

Process	Dataset / process used
Tap water	market for tap water, Europe without Switzerland
Fine aggregate	market for sand, RoW
Electricity	market for electricity, high voltage, SE
Cement production	cement production, CEM II/A, Europe without Switzerland
Ferrosilicon	market for ferrosilicon, GLO
Silica sand	market for silica sand, GLO
Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state, RER
Sodium silicate	market for sodium silicate, without water, in 37% solution state, RER
Transport	transport, freight, lorry >32 metric ton, diesel, EURO6
Chromium VI leaching	chromium VI ion to groundwater, biosphere flow

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY