

UTILISATION OF SEWAGE SLUDGE **ASH** IN **LOW STRENGTH** **CONCRETE**

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كلمة سعادة وزير البيئة والتغير المناخي

تهتم دولة قطر في ظل التوجيهات السامية لحضرة صاحب السمو الشيخ تميم بن حمد آل ثاني أمير البلاد المفدى - حفظه الله ورعاه - بدعم وتعزيز البحث العلمي والابتكار، حيث بذلت الدولة جهوداً كبيرة في تطوير التعليم والبحث العلمي، من خلال بناء ثقافة وبيئة متكاملة للبحث العلمي والابتكار والتطوير، بالإضافة إلى استثمارات واسعة في البنية التحتية لقطاع البحوث العلمية والابتكار وبناء شراكات علمية مع مراكز بحوث عالمية حققت إشادة واعترافاً عالمياً بمخرجات البحوث العلمية والتطبيقية القطرية.

ومن هذا المنطلق، فقد نقّذ فريق البحث العلمي برئاسة وزارة البيئة والتغير المناخي بحثاً علمياً حول معالجة مشكلة مخلفات الصرف الصحي الصلبة واستغلالها الاستغلال الأمثل في بعض الصناعات الانشائية والخلطات الاسمنتية التي يمكن استخدامها في بعض المشاريع، لخدمة الوطن والمجتمع في قطر، تنفيذاً للاستراتيجية الشاملة للوزارة في التعامل مع كافة أنواع النفايات سواء الناتجة عن المواقع السكنية أو التجارية أو الصناعية، أو قطاع البناء والتشييد وغيرها.

وبمناسبة إصدار هذا الكتاب العلمي أود أن أتقدم بالشكر الجزيل لفريق البحث العلمي الذي أنجز هذا العمل الكبير وضمّنه جميع المعلومات والبيانات العلمية والفنية والتقنية والتي استغرقت أكثر من ثلاثة سنوات، كما أود أن أشكر أيضاً الصندوق القطري لرعاية البحث العلمي بمؤسسة قطر على إشرافه وتمويله هذا البحث وتعاونيه الدائم مع الوزارة، والشكر موصول إلى جميع الجهات الحكومية والأكاديمية والقطاع الخاص التي تعاونت مع فريق البحث العلمي في هذا البحث الهام والذي يتماشى مع رؤية قطر 2030.

والله ولى التوفيق

الدكتور / عبدالله بن عبدالعزيز بن تركي السبيعي
وزير البيئة والتغير المناخي

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Preface

The purpose of the book is to support the government strategy of sustainable development, through effective waste management and circular economy. The Qatar National Vision 2030 places great emphasis on preserving and protecting the environment, as one of four pillars of national development, alongside social, economic, and human development. The Qatar National Environment and Climate Change (QNE) strategy was further developed to enhance the environmental vitality, improve the well-being of population, and ensure economic resilience. Improving waste management and building a circular economy is one of the identified QNE priorities that contributes to environmental vitality and enhanced productivity, resources, and economic resilience.

Innovative research was conducted to convert sewage sludge waste into green cement that was further used in the development of high-value construction products. In Qatar, approximately 50,000 tonnes of sewage sludge waste (dry weight) are generated annually as by-product from the treatment of municipal wastewater. Limited quantity of the generated sludge is used in landscaping and the majority are sent to landfills. Sewage sludge contains a range of contaminants, such as heavy metals, pathogens, and organic pollutants, and its disposal presents significant challenges due to its potential impact on human health and the environment.

The process of producing new green cement and construction products involved different stages of assessing the physical and chemical characterisations of sewage sludge ash (SSA); activating the SSA waste using different techniques to produce green cements; developing quality construction products of low-strength concrete; applying the newly developed products in full-scale site trials, monitoring performance in service, and quantifying the environment and cost benefits of the new green construction products.

The new SSA green cement and binder systems offer the benefits of resource recovery from sewage sludge waste, reduce reliance on energy-intensive Portland Cement (PC), and support the green and sustainable construction in Qatar.

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List of Acronyms

Ashghal	Public Works Authority
CBM	Cement Bound Mixture
CDW	Construction & Demolition Waste
CH	Hydrated Lime
CKD	Cement Kiln Dust
DNWWTP	Doha North Wastewater Treatment Plant
EW	Excavation Waste
HBM	Hydraulically Bound Mixture
IRD	Infrastructure Research & Development
MECC	Ministry of Environment and Climate Change
MM	Ministry of Municipality
MPa	Mega Pascal
Ms	Silicate Modulus
MSW	Municipal Solid Waste
MSW-FA	Municipal Solid Waste – Fly Ash
MSW-IBA	Municipal Solid Waste – Incinerated Bottom Ash
Mt	Million Tonnes
N	Sodium Hydroxide
NDS-1	Qatar First National Development Strategy
NDS-2	Qatar Second National Development Strategy
NPRP	National Priorities Research Programme
PC	Portland Cement
QCS	Qatar Construction Specification
QNRF	Qatar National Research Fund
QNV	Qatar National Vision
QSTP	Qatar Science & Technology Park
RCA	Recycled Concrete Aggregate
SEM	Scanning Electron Microscopy
SS	Sodium Silicate
SSA	Sewage Sludge Ash
TGA	Thermogravimetric Analysis
TSE	Treated Sewage Effluent
XRD	X-ray diffraction

Executive Summary

The book is aimed at developing innovative green cement from local solid waste of sewage sludge ash (SSA). The green cement is used for the development of high-value construction products for effective waste management and reduced reliance on Portland cement (PC) and natural resources. The project is delivered by a consortium led by the Ministry of Environment and Climate Change (MECC), Infrastructure Research and Development (IRD QSTP), Queen's University of Belfast (QUB), with key stakeholders from the Ministry of Municipality (MM), Public Works Authority (Ashghal), and the construction industry.

Approximately 50,000 tonnes of sewage sludge waste (dry weight) are generated annually as by-product from the treatment of municipal wastewater in Qatar. Sewage sludge contains a range of contaminants, such as heavy metals, pathogens, and organic pollutants, and its disposal presents significant challenges due to its potential impact on human health and the environment. Up to 48% of the generated sludge is thermally dried to produce pellets for landscaping and the remaining is sent to landfills. The use of sludge pellets in landscaping is declining with government plan to restrict landfilling from June 2024.

The process of producing new green cement and construction products involved different work packages (tasks) of assessing the physical and chemical characterisation of main solid waste materials and identifying the most suitable for the development of green cement; activating the powder waste using different techniques to produce green cement; developing quality construction products; applying the newly developed products in full-scale site trials, monitoring performance in service, and quantifying the environment and cost benefits of the new products.

SSA was activated by blending with other calcium-based materials of PC, hydrated lime, and cement kiln dust (CKD) and used to produce low-strength concrete products of concrete blocks, foam concrete and cement bound materials. The SSA concrete products exhibited delayed setting time and reduced compressive strength, compared to conventional PC concrete. Microstructural analysis indicated pozzolanic reactivity of reactive alumina and sulfate in SSA with the calcium source in PC, hydrated lime and CKD to form ettringite and monosulphates (AFm) that contribute to the strength and enhanced pore structure of concrete. Full-scale site trials were conducted to produce concrete blocks and foam concrete for the reinstatement of depressions around manholes in road pavement. The SSA concrete performed similar to the conventional concrete made with 100% PC.

Environmental and cost assessments were made on the newly developed SSA green cement and concrete products. The green cement products exhibited substantial reductions in heavy metal concentrations due to the solidification of these contaminants within the hydration products of concrete. The carbon footprint calculation indicated higher total greenhouse gas emissions for SSA, compared to PC. However, more work is required to optimise the incineration process and consider the high calorific value of SSA for co-combustion and recovered heat for drying the sludge before incineration. Sewage sludge pellets have no current commercial value, and the cost of processing through incineration and grinding was found the same as the market price of the PC.

The new SSA green cement and binder systems offer the benefits of resource recovery from sewage sludge waste, reduce reliance on energy-intensive PC, and support the green and sustainable construction in Qatar.

1 Introduction

The state-of-the-art infrastructure developed in Qatar consumes large quantities of resources and impacts on the environment. Considering the shortage of quality construction materials in Qatar and waste generation from massive infrastructure project, there is a need to develop advanced and friendly-environment construction materials to support the government strategy of sustainable development.

This book presents the outcomes of a research project “NPRP 12S – 0306 – 1902417” on the “Development of a Novel Technology for Producing Green Cement and Advanced Construction Materials from Solid Waste”. The project is funded by the Qatar National Research Fund (QNRF) and is delivered by a consortium led by the Ministry of Environment and Climate Change (MECC) and Infrastructure Research and Development at the Qatar Science & Technology Park (IRD QSTP), together with key stakeholders from the Ministry of Municipality (MM), Public Works Authority (Ashghal), and representatives from the cement and concrete industry in Qatar.

The project is aimed at developing innovative “green cement” from solid waste, accumulated in Qatar. Large quantities of solid waste materials are produced in Qatar every year, which could be successfully used to preserve natural resources and the environment (Al-Kuwari and Hassan, 2023). The Qatar National Environmental and Climate Change (QNE) Strategy emphasises the importance of waste management and circular economy as one of the identified priorities to improve environmental vitality and enhanced productivity, resources, and economic resilience. Transforming waste from landfills to useful construction products and preserving the use of energy-intensive Portland cement (PC) will open new opportunities for resource recovery, circular economy, and sustainable development within the construction industry in Qatar.

PC production is energy-intensive through the heating of limestone and clay together in kilns at elevated temperatures of 1100-1700°C and, with each tonne producing a similar amount of CO₂ with global emissions of 4.1 billion tonne (Mt) of CO₂ per annum. Cement remains a globally important product worldwide with a proximately 4100 Mm³ used each year (Statista, 2024). Its environmental impact worldwide cannot be ignored, especially with the current technological race against time to reduce greenhouse gas (GHG) emissions, in particular CO₂ emission as the main cause of global warming.

The massive infrastructure development, witnessed in Qatar, is associated with waste generation that could impact on the environment. The challenges being posed by waste generation can be turned into wealth through waste recycling and conversion into construction materials, especially in a country like Qatar with shortage of natural resources and high demand of construction materials. Solid waste materials can be recycled into quality products to compensate for the large quantities of imported materials with cost and energy saving. Figure 1-1 shows the quantities of solid waste generated in Qatar between 2010 and 2018, as obtained from the Planning and Statistics Authority (PSA, 2019). Construction waste accounts for the majority of waste generation.

The generation of solid waste reached a peak of 12 million tonnes (Mt) between 2011 and 2013 and declined from 2014 onwards to reflect the implementation of sustainable development in practice. The Qatar National Development Strategy (2011-2016) recognised the impact of waste on environment and provided a waste management hierarchy, with avoidance and reduction of waste before reuse and recycling, and disposal only as a last resort. The Qatar Second National Development Strategy – NDS-2 (2018-2022) focused on the large volumes of solid waste accumulated in landfills and set a recycling target of 15% of solid waste over the course of NSD-2, with a more specific target of recycling 20% in construction projects by 2022.

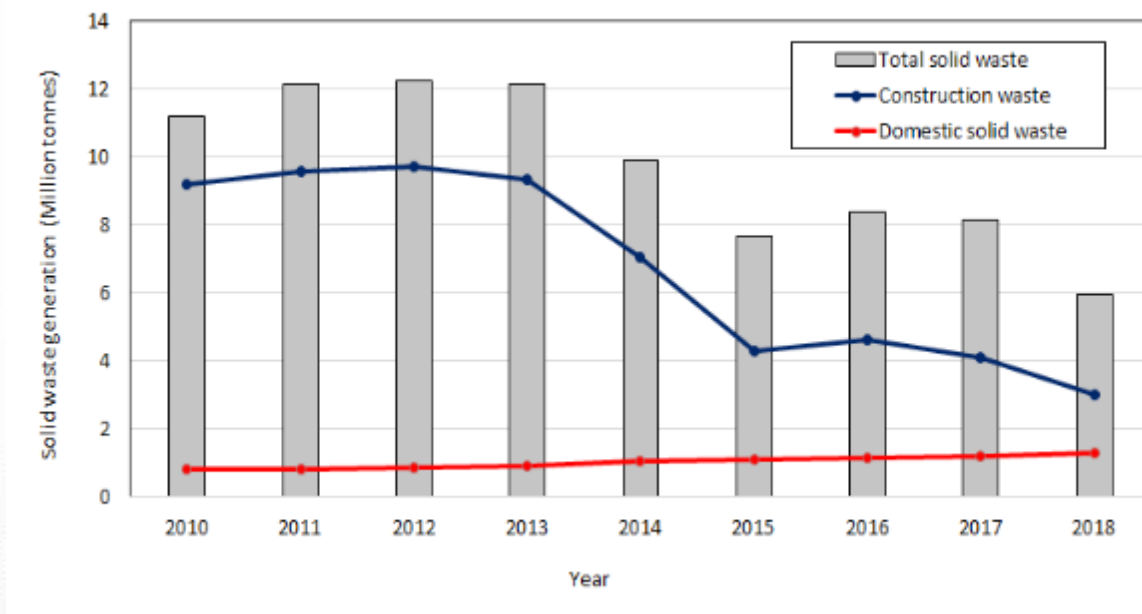


Figure 1-1 Solid waste generation in Qatar (PSA, 2019)

The reduction of waste generation from 2014 onwards to reach 6 Mt in 2018, 50% reduction compared to 2012, is not related to reduce construction activities. In fact, construction continued at increase rate for the development of a world-class infrastructure for hosting the 2022 World Cup. Conservative use of materials and recycling of construction waste are the main reason for reducing construction waste, which was achieved through the provision of appropriate guidance documents (Hassen et al., 2015) and the government perception of recycling and sustainable development. According, a major change was made in the Qatar Construction Specification (QCS, 2014) to permit the use of construction waste in various applications. Qatar was the first country in the region to develop a national standard on the use of recycled materials in construction (QS 29, 2012), which was later adopted as a Gulf standard in 2015 (GSO 2489, 2015).

1.1 Qatar National Vision 2030

The Qatar National Vision (QNV) 2030, launched in 2008, aims at transforming Qatar into advanced society capable of achieving sustainable development. The vision sets four pillars for achieving sustainable development: human development, social development, economic development and environmental development. The latter is defined as a balance between development needs and protection of the environment. The vision further states that “Economic development and protection of the environment are two demands neither of which should be sacrificed for the sake of the other”. The QNV 2030 also conforms with the Sustainable Development Agenda and the decisions of the numerous conferences of the Member States of the UN Framework Convention on Climate Change (UNFCCC).

1.2 Qatar 3rd National Development Strategy (2024-2030)

The third NDS-3 (2024-2030) was issued in 2024 as a continuation of the NDS-1 (2011–2016) and NDS-2 (2018–2022) and aiming to achieve the goals and aspirations of the Qatar National Vision (QNV) 2030, ensuring and maintaining commitment of the implementing agencies, and highlighting the achievements and lessons learned from the NDS-1 and NDS- 2. One of the main success factors emphasised in the NDS-3 for conserving the natural resources, protect ecosystems, reduce greenhouse gas emissions, and build resilience against future environmental threats.

Several of the key environmental outcomes listed in the QNDS-3 are related to sustainability, including:

- Raising awareness among the population to protect the environment.
- More sustainable urbanization. One of the most effective strategic approaches to sustainable urban development is the use of green building and green infrastructure.
- Reducing waste, by encouraging sustainable practices.
- Promoting the growth of the circular economy market for recycled and reused materials.
- Reduced emission, GHG emissions will be reduced by 25% until 2030. “Qatar will implement mitigation measures across key sectors, including oil and gas, power and water, transportation, and building, construction, and industry”.
- Preserve the environment, “Qatar will ensure environmental components such as air, water, and land are well-managed and protected”.

QNDS-3 introduces programs that contribute to changing societal behaviour to reduce waste generation and thus encourages society to enhance sustainable environmental awareness.

1.3 Qatar National Environmental and Climate Change Strategy

The Qatar National Environmental and Climate Change (QNE) Strategy was further developed with the objectives of enhancing the environmental vitality, improving the well-being of population, and ensuring economic resilience. These objectives are to be achieved under five identified priorities of reducing greenhouse gas (GHG) and air pollutant emissions, restoring biodiversity abundance, establishing sustainable water management, improving waste management and building a circular economy, and enhancing land use productivity, Figure 1-2. Specific targets are set for the identified priorities to be achieved by the end of 2030.

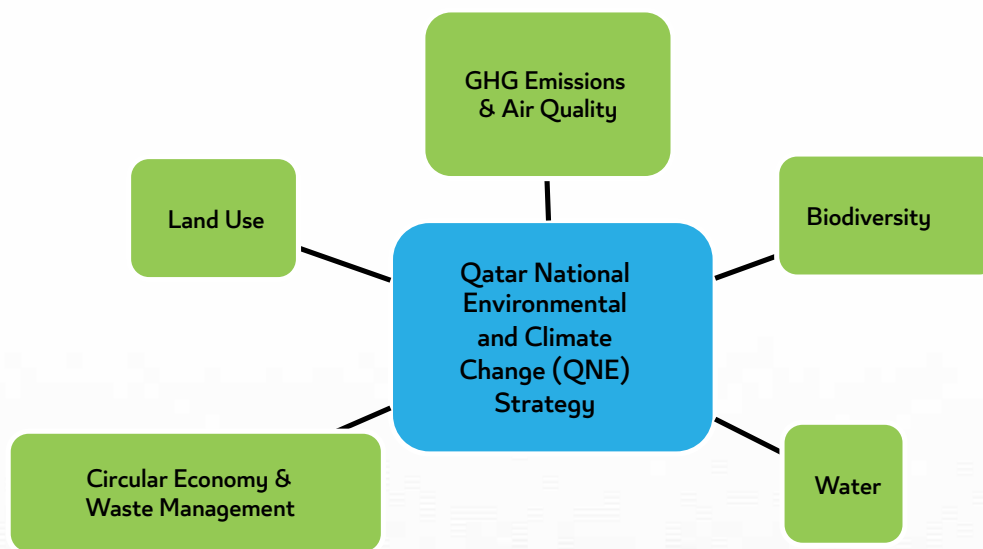


Figure 1-2 Priorities of the QNE Strategy

The QNE targets to reduce greenhouse gas emissions by at least 25 % by 2030. It is also committed to enhancing ambient and indoor air quality in line with the latest scientific development, and the installation of over 30 air quality monitoring stations equipped with internationally approved technology.

The QNE also targets to ensure sustainable and integrated management of all water resources. The country will reduce groundwater extraction by 60%, reduce daily household water consumption by a third and double desalination via reverse osmosis or more sustainable technologies amongst other targets.

The QNE will enhance critical infrastructure for sustainable waste management and drive more circular use of materials. The set targets for the waste management and circular economy priority are:

- Account for 100% of all waste materials.
- Achieve a 15% material recycling rate of municipal wastes.
- Close and rehabilitate 100% of unsanitary landfill.
- Use 35% of recycled materials in construction projects.
- Achieve 30% of circular procurement in public infrastructure.

- 50% reduction in per capita food waste at retail and consumer levels; and encourage reduction of food losses along production and supply chain.
- Apply circular industry principals across industrial cities.

The project provides a route for the development and implementation of innovative and low-cost construction products. The new products would be expected to preserve the environment through the utilisation of existing solid wastes accumulated in landfills, reduce reliance on imported materials, and consequent energy savings. Such development could be implemented by decision-makers in sustainable construction and waste management strategies to support the Qatar Vision 2030.

The project has four major objectives associated with developing the technology for:

- Producing green cementitious materials “green cement”.
- Developing high quality construction products from the green cement.
- Assessing performance of new products in full-scale construction.
- Cost and environmental assessment.

The main solid waste materials available in Qatar, with potential use for the development of green cement, are presented in Chapter 2. Information on these waste materials was collected from the relevant authorities together with their current utilisation. Chapter 3 covers the physical and chemical characteristics of identified waste materials and preliminary paste and mortar testing to identify the suitable waste material for the development of green cement.

The development of green cement involved activation of the waste material to produce different binder systems for various applications. Chapter 4 covers the activation of waste to produce different green cement systems. Different techniques were considered, including blending with different proportions of PC, hydrated lime, cement kiln dust, and alkali solutions. The properties of the green cement systems as well as the microstructural were analysed to understand the cementitious behaviour of the newly developed concrete products.

The main use of the green cement was to produce low-strength concrete applications. Chapter 5 covers the laboratory development of concrete mixtures to simulate real products of concrete blocks, foam concrete and cement bound materials. The development products were tested and assessed for compliance with national and international specifications for use in the desired applications. The performance and durability of the development green cement products were assessed in Chapter 6, together with the microstructural analysis required to understand the hydration products and stability for the developed green cementitious products.

Site trials were carried out to demonstrate how the newly developed products, made with the SSA green cement systems, could be applied to meet the required standards and comply with national specifications. As described in Chapter 7, two site trials were considered for the proposed non-structural concrete applications to include concrete blocks and foam concrete.

A carbon footprint study was conducted to assess the greenhouse gas (GHG) emissions produced during the production of both the SSA and concrete products in Chapter 8. Similarly, the cost associated with the processing and production of SSA was calculated and compared to that of conventional cementitious binders.

The project is delivered by the project team and in collaboration with a group of key stakeholders from the construction industry to ensure project outcomes are practical and could be easily implemented in practice.

2 Waste Materials for Green Cement

2.1 Introduction

Three solid waste materials were initially identified for the development of green cement to include sewage sludge and municipal solid incinerated waste of bottom and fly ashes. These waste materials are currently generated in large quantities, proportional to increased population, and have no commercial value as the majority are sent to landfills. This chapter reviews the processes involved in the generation of these waste materials, current market applications and commercial value.

2.2 Sewage Sludge

Domestic sewage sludge biosolids, also known as sewage sludge (SS), is a by-product of domestic wastewater treatment and is produced in large quantities worldwide. Wastewater treatment is the process used for the removal of contaminants from domestic wastewater or sewage to convert the water into a treated sewage effluent (TSE) with minimum impact on the environment. Wastewater treatment is essential to protect human health, the environment and water quality and security, given the pressure of water scarcity in Qatar and the wider region. The sewage sludge generally goes through treatment of thickening, stabilization, dewatering and thermal drying before beneficial reuse or disposal.

Improvement of waste management has greatly improved the quality of treated wastewater; however, the SS may still pose adverse environmental threats if not properly managed (Lam et al., 2016). Sewage sludge is a sink for contaminants, and its production increases every year due to population growth, leading to environmental challenges.

SS sludge has historically been viewed as a waste product because of its potential to contain high levels of contaminants and has thus largely been disposed of. Because of the inhomogeneity and tremendous differences in the concentrations of its components, it is difficult to determine or define a standard composition for sewage sludge, which is mainly composed of organic substances. Sewage sludge contains plant nutrients such as nitrogen (N) and phosphorous (P), inorganic minerals, as well as harmful substances such as pathogens and heavy metals that can negatively impact the environment.

Landfilling of organic waste without appropriate treatment can pollute the surrounding air, soil, and groundwater environments. When organic landfilled wastes decompose, they create methane gas (CH₄), which is very explosive and flammable. Another significant landfilling concern is leachate management, where heavy metals can become mixed with and contaminate surface waters, groundwater and soils. Inappropriate waste disposal can also attract mice and flies that carry infectious diseases, causing severe environmental health consequences due to pollution and spread of diseases. Dried waste materials, especially fine particles may be resuspended by wind and spreading diseases to different locations (Western Cape EADP, 2021).

2.2.1 *Production of Sewage Sludge*

There are approximately 24 wastewater treatment plants in Qatar with the capacity of producing more than 250 million m³ of TSE and 40,000 tonnes of SS per year. Table 2-1 gives the annual production of TSE and SS in Qatar between 2013 and 2018 (PSA, 2019).

Table 2-1 Annual production of treated wastewater (TSE) and SS in Qatar (PSA, 2019)

Year	2013	2014	2015	2016	2017	2018
TSE (x1000 m ³)	158,790	173,933	197,492	209,518	231,473	257,829
SS (tonnes)	27,170	32,066	39,717	41,551	41,554	37,688

Sewage treatment typically consists of three basic processes: preliminary treatment, primary settlement and secondary treatment. Preliminary treatment involves grit removal and screening to remove larger material such as rags, towels, etc. In primary settlement the sewage flows through large tanks where the smaller organic material is allowed to drop out. During the secondary treatment stage, the wet sludge is aerated to aid bacteria in breaking down its mass, after which the resulting secondary sludge is allowed to settle. The sludge produced by the primary settlement process and the secondary oxidation process is combined to form the untreated sludge often known as 'raw sludge'. If raw sludge is stored it will putrefy, become acidic, producing hydrogen sulphide and other volatile sulphur compounds. Raw sludge is generally fed directly to a digester for further digestion by anaerobic or aerobic bacteria after which it can also be fed to a dryer. The digestion process produces methane and carbon dioxide.

Prior to drying the sludge is usually dewatered by mechanical means, aided by the addition of a polymer to bind the sludge together. Free water is removed to achieve around 20% dry solids. The material produced is referred to as "sludge cake", which may be stored for later transportation to another site for drying. The sludge can be further dried using a thermal drier to reduce the water content into the sludge, normally 90% dry solids.

In Qatar, approximately 800,000 cubic metres of sewer are collected every day, with the majority through the sewerage system and 15% by tankers. On average, each cubic metre of sewer contains approximately 0.16 kg of dry sludge. Therefore 128 tonnes of dry sludge are generated every day, amounting for approximately 47,000 tonnes per year.

Ashghal is the government authority responsible for the design, construction, delivery, operation and maintenance of all drainage projects including storm and rainwater, wastewater and sewerage drainage and treatment across Qatar. Table 2-2 shows more recent sludge production in Qatar between 2020 and 2022, as received from the Drainage Network Operations and Maintenance (DNOM) department at Ashghal. It also provides information on the utilisation and disposal of sewage sludge in Qatar.

Table 2-2 Production and disposal of sewage sludge in Qatar

Mix	2020	2021	2022
Total sludge production (tonnes/year)	43,165	41,349	49,048
Produced dried pellets at DN STW TDP	20,689	15,294	14,937
Pellets to landscape	12,877	18,201	9,645
Pellets at store	20,435	16,971	22,501
Landfill	22,476	26,055	34,111

Current practice is to transfer the sewage sludge cake to the Doha North Sewage Treatment Works (DNSTW), which is equipped with facilities for thermal drying to reduce the volume of SS. The sludge is produced as a cake and transported to the DNSTW for thermal drying. Transporting sewage sludge cakes, which contain up to 80% water, may greatly increase the cost of transport and exhaust the road network of Qatar. Thermal drying at the DNSTW produces dried SS pellets, 2-5mm in size, with reduced moisture content of less than 10%. Figure 2-1 shows the sewage sludge cake and the sewage sludge pellets, produced after thermal drying.

**Figure 2-1 Sewage sludge cake (left) and thermally dried sludge pellets (right)**

Table 2-2 shows that between 2020 and 2022, the annual amount of dried sewage sludge produced in Qatar varied between 41,000 and 49,000 tonnes (dried solids). During this period, between 30-48% of the produced sewage sludge in Qatar was dried to produce sewage sludge pellets, and the remainder sewage sludge was landfilled. A varying proportion (60 – 120%) of the pellets produced each year were distributed to landscape customers with the remainder being stockpiled, Figure 2-2. As a result, in 2022, a total of 22,501 tonnes of sewage sludge pellets were held in stockpile and not utilised. The result in Table 2-2 indicates the reduced use of dried pellets in landscaping with time, as well as the increased amount of SS materials sent to landfill. The government of Qatar is considering the ban on landfilling of sewage sludge, which is expected to come into place in June 2024.

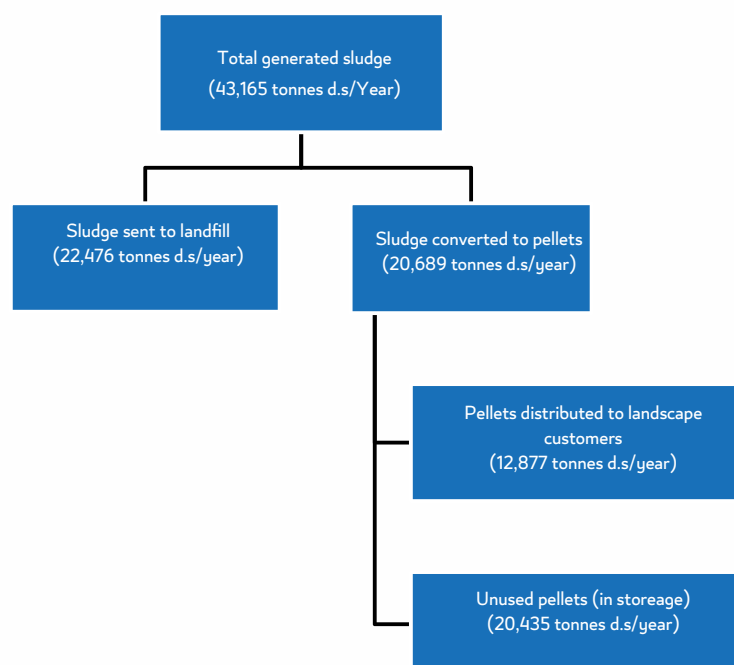


Figure 2-2 Sludge generation and utilisation in Qatar (2020)

2.2.2 Ban on Landfill

As part of the QNE Strategy, the government is planning to prevent or restrict the disposal of waste to landfills. Ashghal are interested in developing a local market for the utilisation of SS waste, especially as the landfill of this material will be prohibited from the middle of 2024. SS was successfully used in this project for the development of green cement, that can replace PC in the production of controlled low-strength concrete applications.

Untreated sewage sludge cake does not appear to have any current use in Qatar. Between 52 to 70% of sewage sludge was landfilled between 2020-2022. Current supply of dried sewage sludge pellets significantly exceeds demand, and this is expected to increase after the ban on landfilling sewage sludge is implemented in June 2024. Therefore, sewage sludge does not appear to have any economic or purposeful use in Qatar and as such has been considered in this project for support the QNE strategy of waste management and circular economy.

2.2.3 Sewage Sludge Incineration

Incineration of sewage sludge is gaining attention with the potential use of incinerated sewage sludge ash (SSA) in construction (EEA, 2021). SSA can be used as a partial replacement for cement in concrete production, thus addressing the environmental concerns associated with sludge disposal, and reducing the demand for traditional Portland cement (PC), which is a significant source of greenhouse gas emissions.

SS samples were collected from the DNSTW and transported to a waste treatment company for incineration in the Mesaieed industrial city, South of Qatar. The SS pellets were collected loose in 2 jumbo bags, with a total weight of 780 kg and transported using a special vehicle provided by Ashghal. The incineration was conducted at the begging of the week after cleaning the incinerator chamber to avoid any contamination with previously incinerated materials. The SS samples were incinerated for 3 hours at a temperature of 800-900°C and left for air cooling before storage in drums.

Figure 2-3 shows the incineration plant used for the thermal treatment of the SS, whereas the incinerated sludge in the drums is shown in Figure 2-4. The amount of SS collected after incineration was 198 kg, with approximately 30 kg waste at the bottom of furnace, compared to the original fed material of 780 kg. This indicated that the solid content collected after incinerating the SS at 800-900°C is approximately 29% of the original SS pellets.



Figure 2-3 Incineration plant used for the sewage sludge



Figure 2-4 SS drums with a top view of the incinerated sludge

More quantities of SS materials were incinerated during the project and the summary of incinerated sewage sludge ash is given in Table 2-3.

Table 2-3 Properties of incinerated SS pellets

Materials	CV (Cal./gm.)	pH	Flash point (°C)	Moisture content (%)	LOI (%)	Total solids (%)
Thermally dried SS Pellets	3837	6	>60	4.17	67.81	95.83

The sewage sludge has a high calorific value, measured in this project as 3837 calorie/gm. Akdağ et al. (2018) reported high caloric values, between 1931 and 3852 calorie/gm, for sewage sludge from different treatment processes, and co-combusted with coal in coal-fired plants for energy recovery. Wiechmann et al., (2015) reported the advantage of co-combustion of sewage sludge in coal-fired plants and cement plants to reduce fuel consumption and potential use as additive for the cement industry.

The pH of sewage sludge can vary depending on several factors including the treatment processes and any additives or amendments. Typically, sewage sludge pH ranges from acidic to slightly alkaline between 6 to 8. The results in Table 2-3 shows a slightly acidic value of 6.

The flash point of sewage sludge can vary depending on several factors including its composition, moisture content, and any volatile components present. The moisture content of the pellets is relatively low and hence the flash point is also low, with its high organic content contributes to its flammability. The high organic content is reflected in the loss of ignition (LOI) value of 67.81%.

2.3 Municipal Solid Waste

Municipal solid waste (MSW), also known as garbage or trash, is non-hazardous disposable materials generated by household or household like. They comprise household waste collected by local authorities, some commercial and industrial wastes e.g. from offices, schools, shops etc. that may be collected by the local authority or a commercial company. The disposal of MSW is generally overseen by the municipality and includes sending the materials to either a recycling centre for processing or a landfill for dumping.

MSW is collected in different waste transport stations and is largely used to produce Energy-from-Waste in the Domestic Solid Waste Management Centre (DSWMC), near Masaieed. The DSWMC is designed to treat 2,300 kg of mixed MSW per day. Managing waste properly is essential for building sustainable and liveable cities, by reducing our reliance on landfills and significantly cutting down the many factors that adversely impact our environment.

Table 2-4 shows the domestic solid waste generation in Qatar between 2013 and 2018, as obtained from the Planning & Statistics Authority (PSA, 2019).

Table 2-4 Municipal solid waste generation between 2013-2018 (PSA, 2019)

Year	2013	2014	2015	2016	2017	2018
Domestic solid waste (1000 kg)	930	1,048	1,096	1,155	1,184	1,313
Population (M)	2,004	2,216	2,438	2,617	2,725	2,760
Rate (kg/capita/day)	1.27	1.30	1.23	1.21	1.19	1.30

The generation of MSW increases with increasing population, with the average rate of 1.2 to 1.3 kg/capita/day. The standard approach for the recovery of energy from the incineration of MSW is to utilise the combustion heat through a boiler to generate steam. The steam can be used for the generation of power via a steam turbine. The energy recovery from waste incineration is estimated to be 30 MW per day, exported to the national grid after meeting plant power requirements.

2.3.1 Production of IBA and FA

The mixed waste materials in the MSW have little value, but once separated they can replace virgin materials in the manufacturing of new products. Separation of recyclable materials would also reduce the amount of waste sent to treatment (incineration) and to landfill.

Separation of the mixed waste is initially carried out using rotating drums, which automatically shred, mix and homogenise the waste. At the end of the drum, an integrated screening section produces three waste fractions. The undersize fraction (<40mm) containing mostly organic materials and is sent to the compost plant. The middle size fraction (40-300mm) containing most of metals and plastics and is sent to the recycling storage area. Further separation is conducted for the ferrous materials using magnets, non-ferrous metal materials using eddy current separators, and plastics of PET and HDPE using Near Infra-Red separation. The MSW fraction above >300mm of inorganic materials is collected for incineration through water-cooled grates and furnaces.

The MSW is incinerated at 800-900°C for a duration of 45, producing around 21 tonnes/hour of incinerator bottom ash (IBA). The calorific value of MSW is generally 9,000 kJ/kg (2151 calorie/gm) during the normal days, but the value could be reduced to 7,000 kJ/kg (1673 calorie/gm) in Ramadan, where large amounts of food are wasted. The heat released from burning converts water to steam, which is then sent to a turbine generator to produce electricity. After incineration, fly ash (FA) is collected as a residue of the flue gas, and produced at a capacity of 40 tonnes/day.

The ash generated ranges from 15-25% (by weight) and from 5-15% (by volume) of the raw MSW processed (EPA, 2019). Fly ash refers to the fine particles that are removed from the flue gas and includes residues from other air pollution control devices, and typically amounts to 10-20% by weight of the total ash. The remaining 80-90% is IBA, which has the main chemical components of silica (sand and quartz), calcium, iron oxide, and aluminium oxide. The chemical composition of the ash varies depending on the original MSW feedstock and the combustion process.

After combusting the MSW, the IBA is discharged and quenched with water. The main purpose of water quenching is to quickly cool the material and reduce the amount of dust. However, water quenching could also affect the characteristics of IBA by reducing pH, soluble salts, and forming calcium hydroxide because of the lime being hydrolysed (Dhir et al., 2017). Work by Inkaew et al. (2016) indicated that quenching significantly changed the morphology and mineralogy of IBA, as the quenched product was dominated by amorphous and microcrystalline calcium-silicate-hydrate (CSH) phases with the main mineral phases, of calcite, Friedel's salt, hydrocalumite and portlandite as detected by XRD. After water quenching and cooling, the ash is divided into different size fractions:

- IBA (0-8mm): produced at a capacity of 80 tonnes/day
- IBA (8-40mm): produced at a capacity of 40 tonnes/day

Considering the quantity of FA of 40 tonne/day and the above quantities of IBA, the total production of FA and IBA accounts for more than 50,000 tonnes per year. The resultant IBA and FA are currently sent to landfill and compacted after mixing with Portland cement, rate of 100 kg cement for each 15 tonnes of ash, to solidify heavy metals.

3 Selection of Waste Materials

3.1 Introduction

Volumes of accumulated solid waste materials of sewage sludge (SS) and municipal solid waste (MSW) in Qatar continue to increase annually with a potentially negative impact on human health and the environment. This chapter covers the physical and chemical properties of these waste materials and potential use for the development of green cement and innovative concrete products. Based on the outcomes, the most suitable waste material was selected for further development.

3.2 Solid Waste Materials

Three solid waste materials were initiated used for the development of green cement to include SS, municipal solid waste of fly ash (MSW-FA) and municipal solid waste of incinerator bottom ash (MSW-IBA). The MSW is incinerated in an Energy-from-Waste plant in the Domestic Solid Waste Management Centre (DSWMC), under the management of the Ministry of Municipality. The SS was sourced from the Doha North Sewage Treatment Works (DNSTW), under the management of the Public Works Authority (Ashghal). The SS is initially produced as a sludge cake, which is thermally dried to produce sludge pellets, size of 2-5mm, with reduced moisture content of 6%.

The MSW ashes are incinerated during production at 800-900°C for a duration of 45 minutes. The SS waste material was incinerated using a local furnace at the same temperature range of 800-900°C but for longer duration of 2 to 3 hours. The increased incineration time is considered for SS to minimise the organic content of the material. Figure 3-1 shows the incinerated waste materials of MSW-FA, MSW-IBA, and sewage sludge ash (SSA) before grinding.



Figure 3-1 Incinerate waste of municipal solid waste fly ash (left) bottom ash (middle) and incinerated sewage sludge (right)



Figure 3-2 Ball-mill grinding machine used in the investigation

The incinerated waste materials were grinded into powder to break down their particle sizes, comparable to that of cement, and enhance their reactivity as cement replacement materials. Grinding of the materials was carried out in a dry process using the ball-mill shown in Figure 3-2. Milled solid waste were converted into powder passing 200 μ (microns), with homogeneous and consistent appearance.

3.2.1 *Properties of waste material*

The grading curves of solid waste materials together with the grading curves of PC are shown in Figure 3-3. The waste materials showed coarser grading than PC, with finer grading of the MSW-FA in comparison to SSA and MSW-IBA. Powder materials passing 75 μ m play the greatest part of cement hydration, and the results in Figure 3-3 show that more than 90% of the PC particles are passing 75 μ m, whereas between 65% and 76% for the solid waste materials.

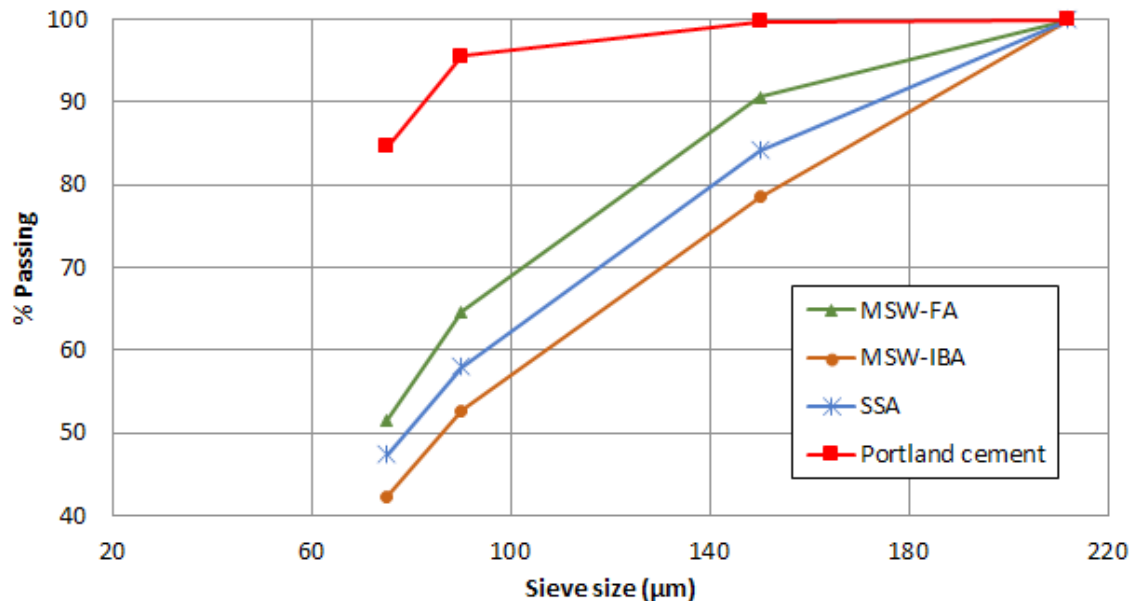


Figure 3-3 Grading of waste materials and Portland cement

Table 3-1 summarises the physical and chemical properties of the waste materials and PC powders. PC has the highest specific gravity, followed by the SSA, MSW-IBA and MSW-FA. The Blaine Fineness method was used for the determination of the fineness of powder materials, as per BS EN 196-6 (2018). The Blaine air-permeability test measures the resistance of compacted particles to airflow and is mainly used for checking the consistency of the grinding process and controlling the production of cement. The PC gave a surface area value of 3130 cm²/g. The MSW-FA, which was collected as dust from the hot flue gas in the plant, exhibited the highest surface area of 7220 cm²/g, greater than double the value of PC. The SSA and MSW-IBA gave intermediate values of 4950 cm²/g and 4670 cm²/g, respectively. The contrast between the grading and surface area results may be attributed to the particle shape and texture of the waste materials that influence the surface area.

Table 3-1 Properties of waste materials and Portland cement

	MSW-FA	MSW-IBA	SS	PC
Specific gravity (SG)	2.61	2.66	2.99	3.17
Blain Fineness (cm ² /g)	7220	4670	4950	3130
pH	12.3	9.8	11.4	13.0
Chloride	12.59	0.58	0.12	0.09
Sulfate, SO ₃ (%)	7.0	0.7	0.9	3.3
Loss on Ignition, LOI (%)	18.0	12.9	2.8	1.6

The pH results indicate that all materials are alkalis, with PC exhibiting the highest alkalinity of 13 and the lowest of 9.8 for the MSW-IBA. The SS and MSW-FA have high alkalinity of 11.4 and 12.3, respectively.

BS EN 197-1 (2011) limits the chloride content of cementitious materials to a maximum of 0.1%. The results in Table 3-1 show that only PC complies with the chloride requirement, whereas the SSA gave a marginally higher value of 0.12%. MSW-FA exhibited the highest chloride content of 12.59%. BS EN 197-1 also limits the sulfate content (SO_3) to a maximum level of 3.5% and the loss on ignition (LOI) to a maximum of 5.0% by weight of the total binder content. Table 3-1 shows that all the waste materials contain less than 3.5% of SO_3 , except the MSW-FA which contains a high sulfate content of 7.0%. Only PC and SSA satisfied the BS EN 197-1 requirement of <5.0% LOI.

The properties of solid waste materials indicate lack of compliance to BS EN 197-1 as cementitious materials for use in structural concrete applications, especially for the MSW-FA and MSW-IBA. Despite the higher chloride and LOI contents, the solid waste materials were studied further for potential use as cementitious materials in non-structural concrete products. Only SSA possessed any potential for use in structural concrete applications.

3.2.2 *Chemical characterisation of waste materials*

The chemical characterisation of the solid waste materials was conducted using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The chemical composition of PC is generally expressed as oxides with main elements of calcium, silica, alumina and iron oxides. Calcium and silicate oxides consist of at least two-thirds by mass. Table 3-2 gives the chemical composition of PC, which includes almost 80% of CaO and SiO_2 , with less contents of aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). The ratio by mass (CaO)/(SiO_2) shall be not less than 2.0, and the content of magnesium oxide (MgO) shall not exceed 5.0 % by mass (BS EN 197-1).

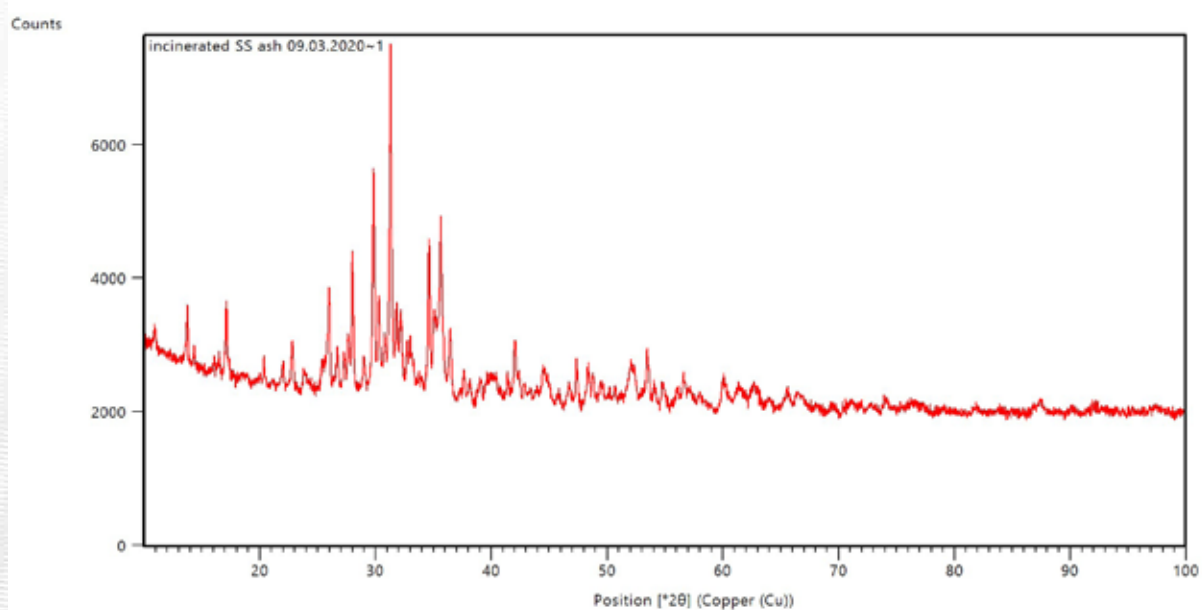
MgO may cause unsoundness of the concrete and thus produce deleterious expansion that leads to disintegration of concrete. For this reason, most international standards limit the content of MgO in cement to a maximum of 4 to 6 %. This behaviour is mainly observed when the material is burned at high temperatures exceeding 1400°C , however, at lower temperature at $700\text{--}1000^\circ\text{C}$ the MgO is more reactive, causing early age expansion and more importantly has a high carbon capture capacity with the ability to reduce CO_2 emissions by 73% (Ruan and Unluer, 2016).

The main oxide components of the incinerated waste materials used in this investigation, as determined from XRF, are those of CaO, SiO_2 , Al_2O_3 , Fe_2O_3 , similar to that of PC. The mineralogical composition of the incinerated solid materials, as determined from XRD, are plotted in Figure 3-4, Figure 3-5, and Figure 3-6 for the SSA, MSW-FA and MSW-IBA, respectively.

The chemical composition of SSA is given in Table 3-2 together with the other solid waste materials from MSW. The SSA is mainly composed of CaO, SiO_2 , P_2O_5 , MgO, and Fe_2O_3 , making 88% of the total oxides. The XRD trace in Figure 3-4 is dominated by whitlockite (calcium phosphate). Hydroxyapatite is also present together with the minerals of olivine and pyroxene (silicate minerals).

Table 3-2 Chemical composition of waste materials and Portland cement

Type	MSW-FA	MSW-IBA	SSA	PC
SiO ₂	11.24	33.84	20.17	20.49
Al ₂ O ₃	4.25	7.02	5.70	4.43
Fe ₂ O ₃	1.17	10.39	8.11	3.13
CaO	39.16	25.60	28.85	61.78
MgO	2.40	2.51	8.87	3.63
SO ₃	5.94	0.72	0.76	3.27
Na ₂ O	4.97	2.26	1.05	0.21
K ₂ O	4.00	0.83	1.78	0.95
TiO ₂	0.91	0.64	0.55	0.24
Mn ₃ O ₄	0.05	0.07	0.07	0.07
SrO	0.079	0.076	0.180	0.18
P ₂ O ₅	1.39	2.52	13.58	0.11
LOI	15.01	13.32	2.75	1.58

**Figure 3-4 Powder XRD traces obtained from SSA**

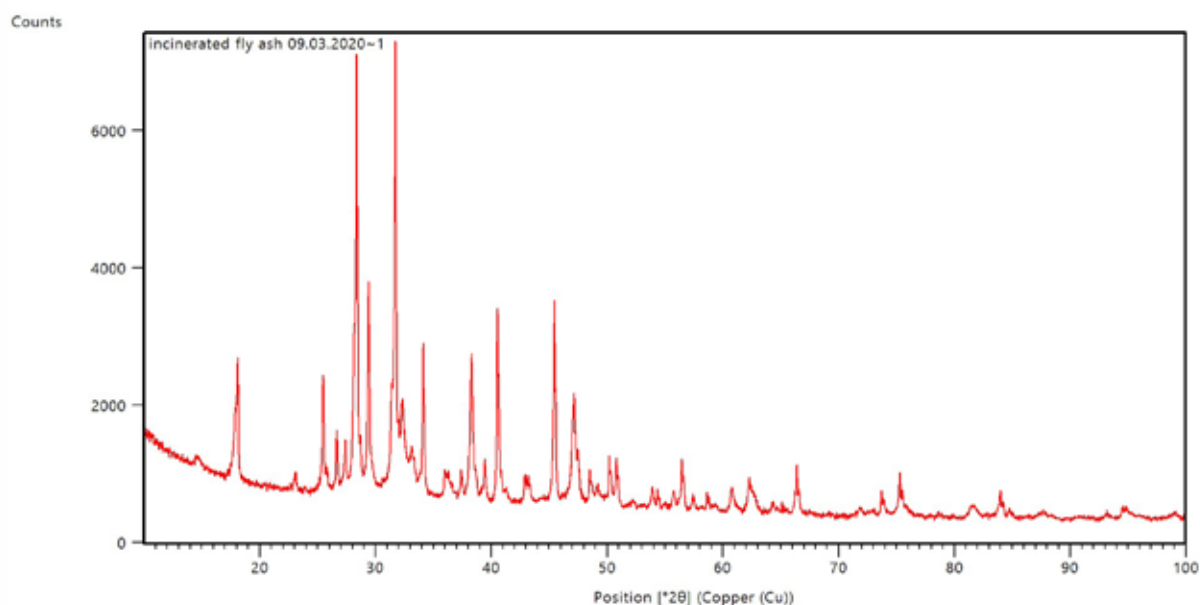


Figure 3-5 Powder XRD traces obtained from MSW-FA

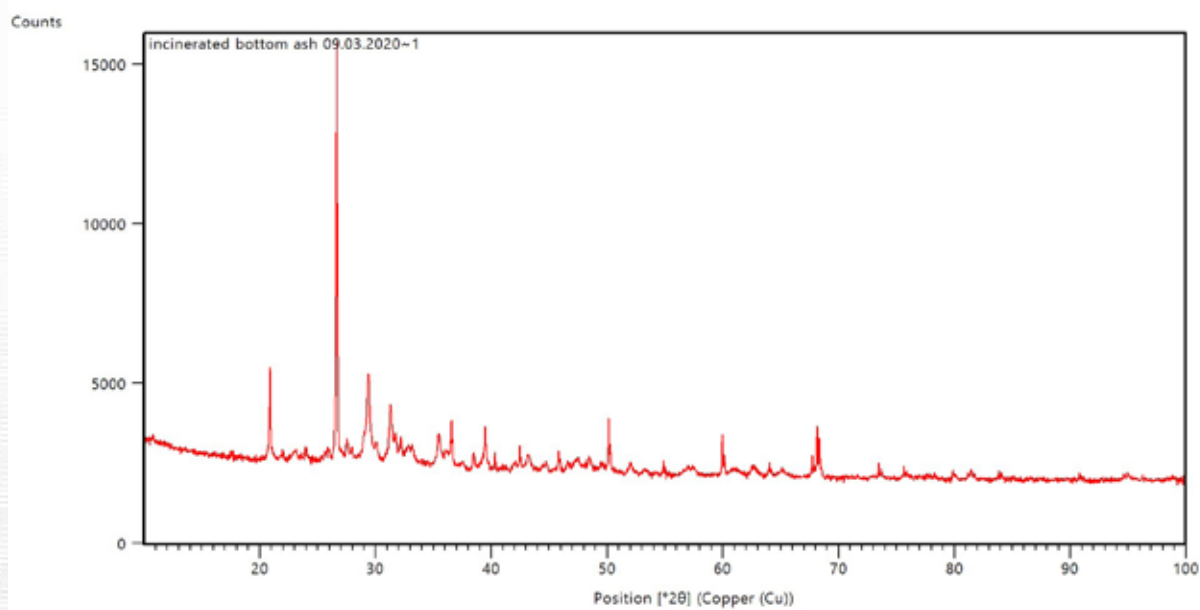


Figure 3-6 Powder XRD traces obtained from MSW-IBA

The SSA is low in calcium (CaO) compared to PC, but contains adequate amounts of silica and alumina that could possess pozzolanic reaction. Tantawy et al. (2012) reported a relatively low pozzolanic reactivity of SSA due to the presence of a large amount of crystallised SiO_2 and the particles are with irregular shapes and large porosity. SSA has a high phosphorus content, 13.6 % of P_2O_5 , which could impact on the setting and hardening properties of cement, making its chemical composition distinguished from cementitious materials. The LOI of the SSA is extremely low, lower than 3%.

MSW-FA was found to have a relatively higher content of CaO and less SiO₂, compared to IBA and SSA. The XRD trace in Figure 3-5 shows a mixture of crystalline and amorphous mineralogy. The MSW-FA is high in chlorides (NaCl, KCl – perhaps calcium chloride too), calcite, calcium hydroxide and sulphates (anhydrite). Phosphates (hydroxyapatite) are present too. FA also has the highest content of alkalis (Na₂O and K₂O) and sulfur trioxide (SO₃) compared to IBA and SS. The high chlorides and sulfates in the MSW-FA are detrimental to the properties of concrete and may limit its wider use at a high content.

Figure 36 shows the XRD trace obtained for the MSW-IBA. The mineralogy seems to be predominately quartz, calcite, feldspar and some other minerals like akermanite (calcium magnesium silicate). The XRD examination indicates low reactivity of the MSW-IBA, which may limit its use as a cementitious binder.

3.3 Paste and mortar mixtures

The incinerated solid waste materials were used to replace PC at different proportions of 25%, 50% and 75% by weight of binder. Testing was carried out in the laboratories of the Qatar National Cement Company (QNCC). Cement paste specimens were used for studying the effect of different solid wastes on the consistency, setting time and soundness (expansion) properties, as per BS EN 196-3 (2016). The mortar specimens were used for the determination of compressive strength at the ages of 2, 7, and 28 days. A summary of the test results is given in Table 3-3.

The control mixture was made with 100% PC and labelled (100% PC) in Table 3-3. Mixtures made with solid waste materials were labelled based on the type of waste materials and percentage of cement replacement. For example, mixture labelled as (25% FA) is made by replacing 25% of PC with MSA-FA, (50% IBA) means replacing 50% of PC with MSW-IBA, and (75% SSA) for replacing 75% of PC with SSA.

3.3.1 Cement paste testing

A rotating laboratory mixer was used for the blending of waste materials with PC for the preparation of paste specimens. Figure 3-7 shows the V-shape mixer used in the investigation to produce homogeneous specimens. The materials are introduced into the mixer and rotate through 360° via mechanical transmission. Rotation of the cement paste minimising the settlement and segregation of solid particles and produce homogeneous mixtures.

The consistency was measured using the Vicat apparatus, as shown in Figure 3-8. The apparatus is completely automatic thereby eliminates possible test inaccuracies of the results. The test is based on the penetration of a plunger to 5-7 mm from the bottom of the Vicat mould as a measure of the standard consistency. Cement paste with different proportions of solids to water are made and placed in the moulds. A plunger fitted into the needle holder is then brought into contact with the top surface of the paste and released. The penetration of the plunger, under its own weight, to a depth of 6±1 mm from the bottom is considered as the standard consistency. The water content at the standard consistency is expressed as a percentage of the mass of dry solids. Typical values of cement consistency are ranged between 25 and 35%.

Table 3-3 Properties of solid waste as cement replacement materials

Mix	Consistency (%)	Setting time (min)		Soundness (mm)	Compressive strength (MPa)			Strength factor, k ($f_{ck_x} / f_{ck_{pc}}$)
		Initial	Final		2d	7d	28d	
100% PC	26.5	135	210	2.0	22.9	36.6	44.8	1
25% FA	27.0	15	45	2.0	11.7	20.0	30.4	0.68
50% FA	28.5	45	75	4.0	0.0	8.5	17.5	0.39
75% FA	31.0	30	75	5.0	0.0	0.0	5.3	0.12
25% IBA	25.0	195	225	3.0	13.2	20.6	23.4	0.52
50% IBA	26.0	225	315	4.0	3.9	11.3	11.6	0.26
75% IBA	27.5	150	210	5.0	0.0	0.0	3.7	0.08
25% SS	25.0	180	255	4.0	21.6	30.6	37.1	0.83
50% SS	26.0	285	355	0.0	11.8	18.2	24.9	0.56
75% SS	26.5	375	ND	2.0	0.0	5.3	7.6	0.17

**Figure 3-7 A rotating V-shape mixer for homogeneous cement paste specimens**

Water is essential for the hydration of cement to harden and develop strength. When water is mixed with cement, it starts hydration. Excessive addition of water in the mix results in high voids after hardening and low strength, whereas inadequate water results in less hydration and loss of strength. The consistency test determines the amount of water required for the complete hydration of cement particles, which is also used for testing the setting time and soundness.



Figure 3-8 Setting time measurements of cement paste (Vicat equipment)

The consistency results of the different paste mixtures are given in Table 3-3. The consistency of PC is 26.5%, within the typical range of cement. Increasing the content of FA into the paste from 25% to 75% increased the consistency from 27% to 31%, respectively. FA had the highest particles surface area, greater than double of that of PC, and would therefore require more water to achieve the standard consistency. The addition of IBA and SSA at 25%, 50%, or 75% had marginal effect on the standard consistency.

The initial and final setting of the different cementitious materials are carried out using the Vicat's apparatus, Figure 3-8, as per BE EN 196-3 (2016). Setting time is the time required for stiffening of cement paste to a defined consistency. The setting time of cement includes the initial setting time and the final setting time. The initial time refers to the time that cement turns into paste by mixing with water and begins to lose its plasticity. The time that cement completely loses its plasticity by mixing with water and begins to have a certain structural strength is known as the final setting time.

It is essential that cement set neither too rapidly nor too slowly. Rapid setting would shorten the time between mixing and transporting the concrete to place on site, whereas long setting time tends to slow up the work due to slow strength development at early age.

The results of setting time are graphically presented in Figure 3-9 and numerically in Table 3-3. The initial and final setting time of the PC were 135 and 210 minutes, respectively. The addition of 25% FA to PC greatly reduced the initial and final setting time to 15 and 45 min, a reduction of 89% and 79%, respectively when compared to PC. Considering the high content of free lime (CaO) in the FA, it will result in faster setting time, higher heat of hydration, lower strength levels and volume instability (unsoundness), leading to cracking. Previous work by Kikuchi (2001) showed that the addition of MSW-FA for clinker production shortened the setting time and decreased workability. While the MSW-FA provides a good source of lime, rather than limestone used in cement, its use can contribute to reduction carbon emissions. However, the material would require pre-treatment for the removal of salts (chlorides and sulfates) and heavy metals.

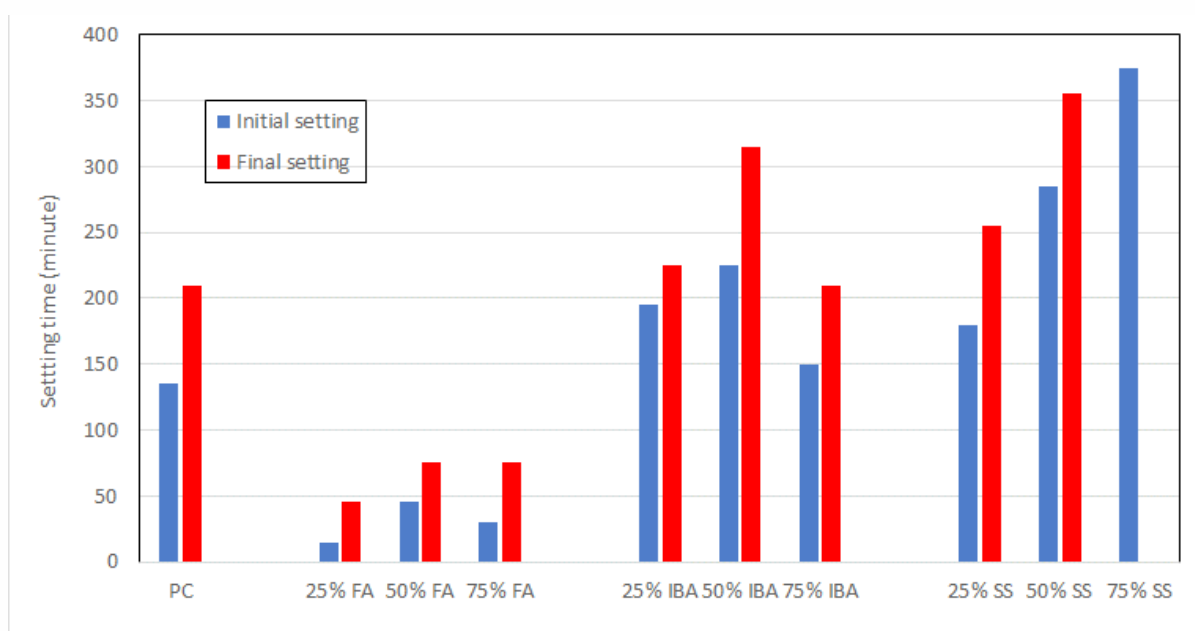


Figure 3-9 Setting time of Portland cement mixed with solid waste materials

In contrast to the FA, the addition of SSA was found to retard the initial and final setting of PC. When compared to PC, the deviations in initial and final setting were 33% and 21% for 25% SSA, 111% and 69% for 50% SSA, respectively. When 75% SSA was used, the initial setting time was increased 375 minutes (277% higher than PC) and the final setting time was not determined as it exceeded 12 hours. The retarding effect of SSA on setting time is mainly due to the presence of high phosphorus oxide (P_2O_5) and its ability to bind with calcium available in cement and gypsum, added to control cement setting. The phosphorus element reacts with calcium, forming calcium phosphates and releasing sulfate, which in turn causes a prolonging of the cement hydration development and thus the setting time. Furthermore, crystallization of gypsum needles starts to form in the pores which cause loss of consistency and finally flash set (Sigvardsen and Ottosen, 2016). While slow setting may impact on early strength development, it could be seen as an advantage for use in road construction such as cement and other hydraulically bound materials (Hassan et al., 2004). The hot weather in Qatar could greatly accelerate the rapid hardening of cement and evaporation of mixing water, and hence influence the strength and cracking of cement bound materials. Developing new cementitious materials with increased setting time would provide more time for transporting and handling the mixtures on site before hardening and improve the cracking and performance of pavement.

The use of IBA also increased the setting time of cement, but the retarding effect was much less than that of SSA. The results in Table 3-3 show that the initial setting of 25% IBA was 195 min, 44% higher than that of PC, and the final setting was 225 min, only 7% higher than PC. Increasing the IBA content to 50% increased both the initial and final setting of cement, but the deviation was less when 75% of IBA are used to replace PC. The retardation effect of IBA on cement hydration was attributed to the organic matters contained in the IBA (Tang et al., 2016). Thermal pre-treatment was therefore recommended to burn out all the organic materials and thus reducing the retardation effect on cement.



Figure 3-10 Soundness test of cement paste specimens

Once the PC has set, it is essential that it does not undergo a large change in volume or expansion that could disrupt the hardened cement. Such expansion may take place due to additional reactions from the compounds present in the waste materials, such as free lime, sulfate, and magnesia. The soundness of the paste materials is tested using Le Chatelier apparatus, Figure 3-10, as per BS EN 196-3 (2016).

The Le Chatelier apparatus consists of a small split cylinder of spring brass (30mm diameter and 30mm height), with indicators attached on each side of the split. The length of each indicator is 165mm, so the widening of the split, caused by paste expansion, is greatly magnified at the end of the tow indicators. The split is first filled with the paste, then cured in wet environment (relative humidity not less than 98%) at 20°C for 24 hours and the distance between the 2 indicators is initially measured. The whole assembly is placed in water and gradually brought to boiling in 30 minutes. After boiling for 3 hours, the assembly is taken out, after cooling, the distance between the indicators is measured again. The increase in distance represents the expansion of the paste, which is limited to 10mm by BS EN 197-1 (2011).

The results in Table 3-3 show that the soundness value for PC is 2mm. Increasing the FA and IBA content in the paste resulted in higher soundness values, but the highest value is 5mm, lower than the maximum specified in BS EN 197-1. The high expansion in the FA blended specimens is due to the free lime causing flash setting and expansion of the mixtures.

The high expansion of the IBA may be attributed to the presence of unburnt aluminium. During the incineration process, most of the inorganic substances are oxidised, including aluminium to form a stable chemical compound of aluminium oxide (Al_2O_3). However, not all inorganic substances are expected to be oxidised. Typical MSW ashes are known to have relatively high concentration of metallic aluminium, which reacts with the high alkalinity of cement and releases a great amount of hydrogen gas, which get entrapped within the matrix causing expansion with reduction in concrete strength (An et al., 2014).

Inconsistent soundness results were found for the SSA. The use of 25% SSA increased the soundness to 4mm, whereas the use of 75% SS gave identical soundness to the PC of 2mm. The soundness of 50% SSA was zero, indicating no expansion of the tested paste sample.

3.3.2 *Mortar testing*

Mortar specimens were prepared with the replacement of waste materials and tested for compressive strength. Compressive strength is the most common property used to characterise cement paste, mortar and concrete, and widely used worldwide for specifying concrete for structural and non-structural applications. The mortar mixtures were prepared in the weight proportions provided in BS EN 196-1 (2016) of 1 part of cementitious material to 3 parts of sand to 1 half part of water (water to binder ratio of 0.5). The mortar materials were mixed mechanically using an electrical mixer. The fresh mortar mixtures were cast into prism moulds of 40x40x160mm, Figure 3-11. The moulds were covered for 24 hours, before de-moulding and curing in a water tank kept at $20\pm 2^{\circ}\text{C}$ until testing.

The compressive strength testing was carried out at the ages of 2, 7, and 28 days, and the results are presented in Figure 3-12 and also given in Table 3-3. The PC mixture attained compressive strength values of 22.9 MPa at 2 days (≥ 20 MPa) and 44.8 MPa at 28 days (≥ 42.5 MPa), and therefore classified as Strength Class 42.5 R according to BS EN 197-1. The addition of waste materials, as cement replacement, resulted in lower compressive strength.

For the MSW-FA waste material, replacing 25%, 50% and 75% of PC with FA reduced the 28-day compressive strength by 21.1%, 60.9%, and 88.3%, respectively. Increasing the FA content caused lower compressive strength. In fact, at 75% FA replacement, the mixture did not attain any measurable strength at 2 and 7 days, and only achieved 5.25 MPa at 28 days. Similar trend was observed for the MSW-IBA but with further reduction in strength. The reduction of 28-day strength, compared to PC, at IBA replacement of 25%, 50% and 75% was 47.9%, 74.1%, and 92.7%, respectively. Similarly, the IBA mortar did not achieve any measurable strength at 75% replacement at the ages of 2 and 7 days, and only reached 3.7 MPa at 28 days.

The best performance of the investigated waste materials was found with the SSA. Whilst the SSA also reduced the compressive strength at different replacement levels, but the reduction was lower compared to FA and IBA materials. The best performance of SSA was when replacing 25% of PC, with compressive strength values of 21.6, 30.6, and 37.1 MPa compared to 100% PC of 22.9, 36.6 and 44.8 MPa, at 2, 7, and 28 days, respectively. At 28 days, the reduction of compressive strength for SSA mixture was 17.3%, 44.5%, and 83.0% at cement replacement levels of 25%, 50%, and 75%.



Figure 3-11 Casting of the fresh mortar prism specimens

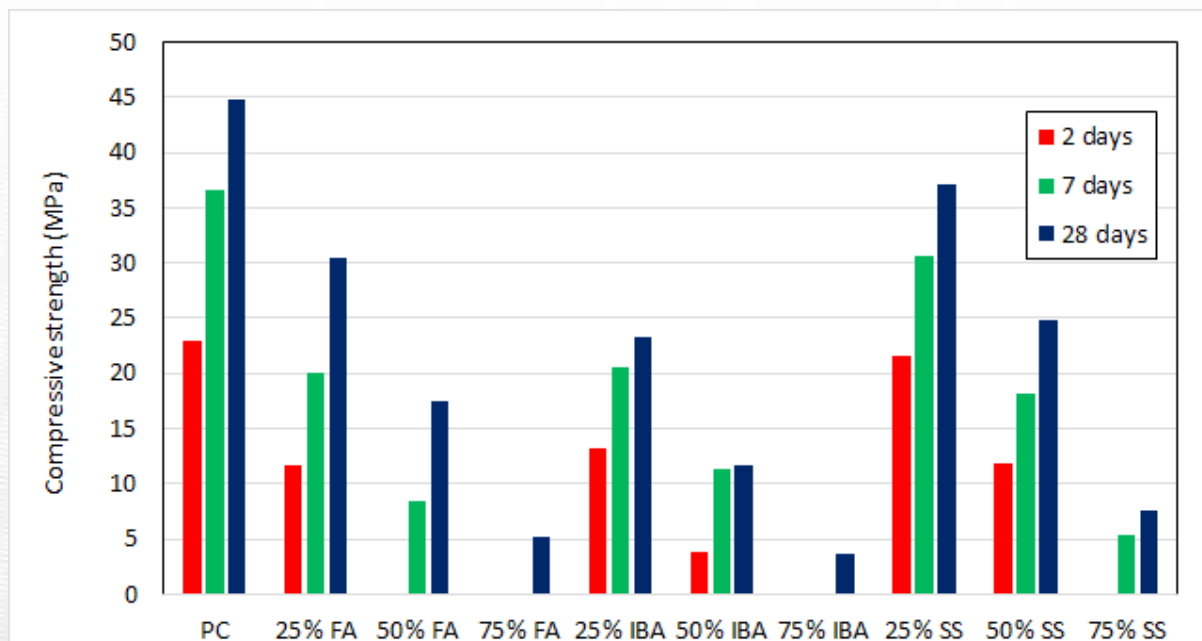


Figure 3-12 Compressive strength of the different mortar mixtures

The results generally show that increasing the content of solid waste (FA, IBA, and SS) from 25% to 75% reduces the compressive strength of the mortar samples, with the highest reduction associated with the use of IBA followed by FA and SSA. The best compressive strength results of the waste materials were achieved at the lowest replacement levels of 25%. Further work is planned to optimise the content of waste materials while maintaining similar strength characteristics to Portland cement.

When comparing the cementitious properties of the investigated waste materials to Portland cement, it could be seen that MSW-FA has the finest particle sizes and highest surface area, hence resulted in increased water demand compared to PC. Increasing the FA content resulted in higher consistency. The presence of high free lime content in the FA caused flash setting and accelerated hardening and unsoundness at high replacement levels. The accelerated setting and expansion of the FA samples adversely affected the compressive strength of the mortars. It is recommended for further testing to reduce the FA content to below 25% not to impair the properties of mortar and concrete.

In contrast to the FA, the MSW-IBA had a particle surface area smaller than PC but a high organic content as reflected in the high LOI result. The high organic content is due to the unburnt materials from the incineration process and greatly impacts on cement hydration. The initial and hardened setting of IBA blended mixtures was clearly higher than that of PC. The high expansion reflected in the soundness testing could be attributed to the release of hydrogen gas (An et al., 2014) and leading to low strength development.

Within the solid waste investigated, SSA had the lowest chloride content with a similar surface area to Portland cement. The high phosphorus oxide (P_2O_5) of SS resulted in increased setting time, which could be an advantage for road construction. SS also achieved the best compressive strength results when compared to other investigated waste materials. At 25% replacement level, the reduction in strength was between 7 and 17% of the PC strength at different tested ages between 2 and 28 days. Higher compressive strength could be achieved at lower replacement levels, which will be considered in the second stage of the study.

3.4 Summary

Three solid waste materials of municipal solid waste (MSW) of fly ash (FA) and incinerated bottom ash (IBA) and sewage sludge ash (SSA) were considered in this work for use as cement replacement materials. The solid waste materials contain similar oxide components to PC but failed to comply with BS EN 197-1, especially for the MSW-FA and MSW-IBA in terms of salt and LOI contents. Only SSA possessed any potential for use in structural concrete applications.

The solid waste materials were used to replace PC at different levels of 25, 50, and 75%, by weight of binder, for the development of paste and mortar mixtures. FA increased the water demand of the paste whereas the IBA and SSA had marginal effect on consistency. FA also accelerated the initial and final setting whereas SSA and IBA delayed the setting time. The retarding effect was more pronounced for the SSA with its high content of phosphorus. The use of solid waste materials reduced the compressive strength of mortars, and the reduction was proportional to the replacement level. Within the investigated solid waste materials, SSA exhibited the best performance in terms of water demand and compressive strength when compared to MSW-FA and MSW-IBA materials. Non-structural concrete products of 7 to 25 MPa could be achieved by replacing 50 to 75% of PC with SSA.

4 Activation of Sewage Sludge

4.1 Introduction

The SSA was activated using different techniques to include blending with PC, hydrated lime (CH), cement kiln dust (CKD), and alkali solutions. The PC, CH and CKD are calcium-rich materials and commonly used in the construction industry, whereas the alkali activation is a relatively new technology for the repolymerisation aluminosilicate materials with alkaline activators to produce a cementitious binder.

The effect of different activation techniques on the fresh and hardened properties of mortars is discussed in this chapter. Microstructural analysis was conducted on the binder systems to analyse the composition of different SSA mixtures.

4.2 Portland Cement Activation

PC Class 42.5 N (CEM-1) conforming to BS EN 197-1 (2011) was used throughout the investigation and was supplied by the Qatar National Cement Company (QNCC). A new batch of SSA was used in this investigation, which was supplied as pellets from the Ashghal DNSTW plant. The pellets were incinerated at 800 to 900 °C for 3 hours and grinded to similar particle sizes as PC, passing 100 µm. The fine aggregate used was local washed sand supplied by the QNCC. Tap water, as per QCS 2014, was used for mixing the mortar mixtures.

Mortar mixtures were prepared with different replacement levels of PC with SSA, up to 100%. Table 4-1 gives the mix proportions of the different mortar mixtures. The control mix was made with 100% PC (100PC), and the remaining mixtures were made by replacing 25%, 50%, 75%, and 100% of PC with SSA. The mortar mixtures were prepared in the weight proportions provided in BS EN 196-1 (2016) of 1 part of cementitious material: 3 parts of sand: 1 half part of water (water to cement ratio of 0.5).

Table 4-1 Mortar mix proportions for SSA-PC mixtures (Weight %)

Mix	Binder (%)		Sand (%)	Water	Water/binder
	PC	SSA			
100PC	100	0	300	50	0.5
75PC-25SSA	75	25	300	50	0.5
50PC-50SSA	50	50	300	50	0.5
25PC-75SSA	25	75	300	50	0.5
100SSA	0	100	300	50	0.5

The mortar materials were mixed mechanically, using an automatic mortar mixer as shown in Figure 4-1, with a bowl capacity of 5 litres. The binder and water were mixed initially for 30 seconds before adding the fine aggregate. The mixer is equipped with an automatic sand dispenser which fills the sand into the mixing bowl over a period of 30 seconds. The mortar ingredients were mixed for additional 3 minutes, to have a total mixing time of 4 minutes. The fresh mortar was cast into cube moulds of 50x50x50mm as shown in Figure 4-1.



Figure 4-1 Mortar mixing and cube preparation

The cubes were filled in two layers, with each layer manually compacted with a tamping rod of 25 times. Immediately after compaction, the mortar moulds were sealed in plastic bags and initially cured for 24 hours in an oven set at $40 \pm 2^\circ\text{C}$, as shown in Figure 4-2. On the following day, the mortar cubes were demoulded and cured in sealed plastic bags at $25 \pm 2^\circ\text{C}$ until testing. The fresh mortar samples were tested for fresh density, as per BS EN 1015-6 (1999), flow table to BS 4551-1 (1998) and ASTM C1437-20 (2020), and cube compressive strength at different ages.

The mixtures were designed to have adequate workability to enable mortar spreading, and Figure 4-3 shows the flow table testing of the 100% PC (control) and the 100% SSA mortars. The SSA binder is of darker colour to that of PC. With the flow table test, a truncated cone was filled with mortar samples and placed at the centre of the flow table. The truncated cone was removed leaving the mortar sample which was dropped continuously for 25 times. The flow indicates the workability of the sample.

Cement paste specimens were also made with the same binder ratio as per Table 4-1, but without the fine aggregate. Testing of standard consistence and setting times of cement pastes is made as per BS EN 196-3 (2016) and shown in Figure 4-4.



Figure 4-2 Sealed cube moulds and oven curing



Figure 4-3 Flow table testing of PC (left) and SSA (right)

The setting time test measures two parameters of initial and final setting. The initial setting time is regarded as the time elapsed between the moments that the water is added to the cement, to the time

that the paste starts losing its plasticity. The final setting time is the time elapsed between the moment the water is added to the cement, and the time when the paste has completely lost its plasticity and has attained sufficient firmness to resist certain definite pressure. Both parameters are crucial for construction purposes, as short initial setting time will reduce the shelf life of the material for pouring and compacting on site, whereas long final setting time will affect the early strength development of the mixtures.

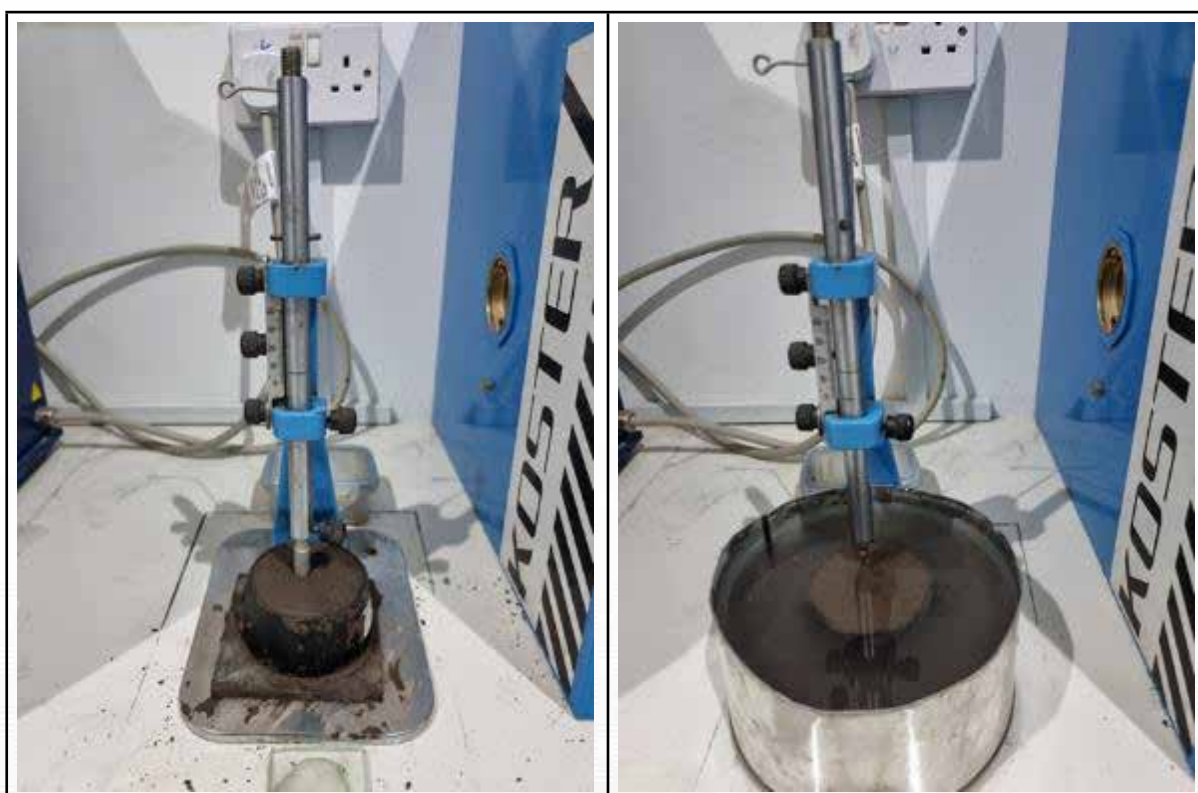


Figure 4-4 Setting time testing of cement paste specimens

The summary of paste and mortar testing is summarised in Table 4-2 for the different mixtures. The consistency results ranged from 26 % for the 100PC to 50 % for the 100SSA. SSA powder had a higher surface area of 4950 cm²/g, which is 58% higher than the surface area of PC (3130 cm²/g). Increasing the surface area and fineness of the binder increases the water demand as given in Table 4-2. The standard consistency of 100PC paste is 26%, and the value increases with increasing the SSA replacement to reach 50% for the 100SSA. Cyr et al. (2007) reported that SSA is composed of irregular grains with a high specific surface area that lead to a high-water demand. Monzo et al. (1996) reported that the shape of SSA particles is not spherical which caused negative influence on workability and strength of cement concrete due to high water demand of SSA.

The initial and final setting results are given in Table 4-2 and graphically presented in Figure 4-5. The results are consistent and show the retardation effect of SSA on the setting time of mortars. Increasing SSA replacement level resulted in a delay in both initial and final setting times. The initial and final

setting times of the control (100PC) were 140 and 195 minutes, respectively. Replacing 25% of PC with SSA increased the initial and final setting times to 310 and 380 minutes, almost double the control mortar. Increasing the replacement level to 100%, 100SSA mixture, showed initial and final setting times greater than 5 times the values of the control mortar. Similar findings on the retarding effect of SSA of setting time have been reported by previous studies (Cyr et al., 2007; Dyer et al., 2011; Piasta and Lukawska, 2016).

Table 4-2 Summary of paste and mortar results – SSA as cement replacement

Mix	Consistency (%)	Setting time (min)		Density (kg/m ³)	Flow table (mm)	Compressive (MPa)			
		Initial	Final			2d	7d	28d	90d
100PC	26	140	195	2072	148	33.2	36.6	43.4	47.9
75PC-25SSA	32	310	380	2268	134	22.7	26.3	35.1	31.7
50PC-50SSA	35	340	400	2292	139	12.3	13.7	22.2	18.7
25PC-75SSA	49	600	685	2224	112	8.9	9.8	14.9	16.5
100SSA	50	960	1020	2243	125	0.5	1.5	3.5	4.0

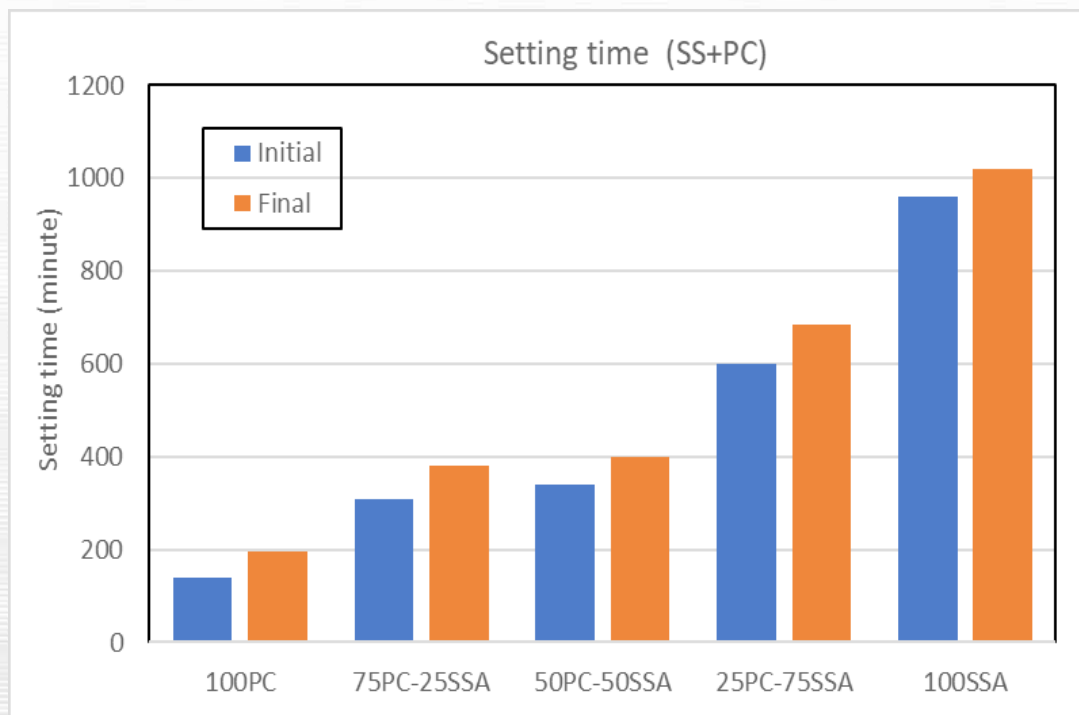


Figure 4-5 Initial and final setting time results

The delay in setting time of SSA mortars could be explained by the presence of considerable amount of phosphorous in the SSA, Table 3-2, which are known to inhibit the growth of crystals.

The results in Table 4-2 show that at the same water to binder ratio (w/b), SSA tends to reduce the workability and increase the density of fresh mortars. The 100PC control mortar exhibited the highest flow table value, whereas the mixtures with the highest content of SSA of 75% and 100% gave the lowest values. Mortars with 25% and 50% SSA gave intermediate values. A nonlinear reduction of workability in mortars is observed with increasing SSA content, and the reduction is less significant at high SSA of 50% and greater. The decrease in workability can be explained by two factors: the irregular morphology of SSA particles and the high absorption on SSA particle surfaces (Paya et al., 2003).

The density results in Table 4-2 show higher density for higher SSA content, despite its lower specific gravity than PC (Table 3-1). The specific gravity of SSA was 2.99, which is lower than the value obtained for PC (3.17). The higher density may be attributed to the finer particle sizes of SSA, as given by the surface area results, and hence improved particles packing and higher density.

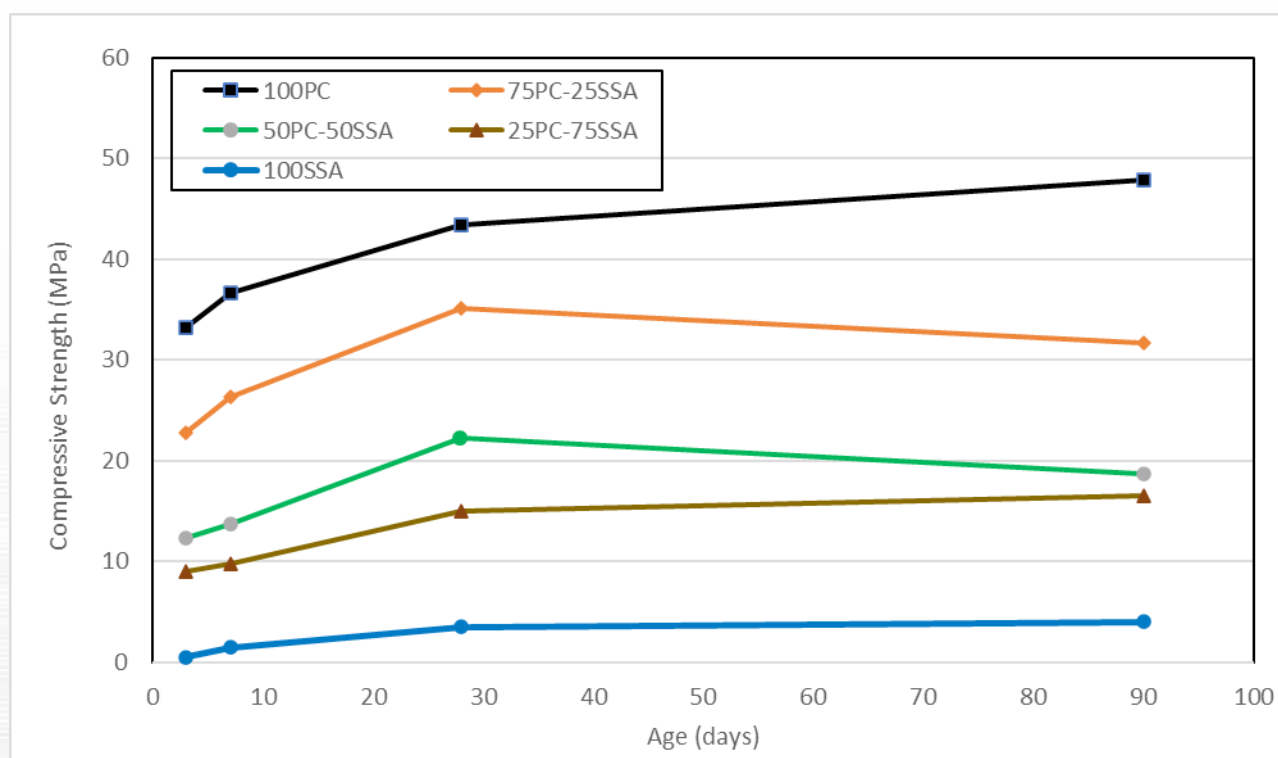


Figure 4-6 Compressive strength results of PC-SSA mixtures

The influence of SSA replacement level on the compressive strength of mortars is given in Table 4-2 and Figure 4-6. Compressive strength testing was conducted at the different ages of 2, 7, 28, and 90 days, with 3 cubes tested at each age and the average value is reported. The compressive strength decreases as the percentage of cement replacement by SSA increases. The 100PC mortar exhibited the highest compressive strength values of 43.3 MPa at 28 days and 47.9 MPa at 90 days. SSA replacement of 25%, 50%, 75% and 100% reduced the 28-day strength by 19%, 49%, 66%, and 92%, respectively. The results also indicate that SSA possess self-hardening properties of low strength mortar as the 100% SSA gave compressive strength values of 1.5 MPa at 7 days, 3.5 MPa at 28 days, and 4.0 MPa at 90 days.

Many researchers found that the compressive strength of mortars made with SSA is lower than that of PC mortars. Ing et al. (2016) reported that replacing 5% of PC with SSA improved the compressive strength up to 10% as compared with the control mixture. However, an adverse effect was noticed at a higher replacement level ($SSA > 5\%$). Rahman et al. (2017) concluded that the content of SSA, as a substitution of PC, decreases the compressive and flexural strength, and increases the water absorption and porosity of mortar and concrete. Chang et al. (2010) reported SSA particles are porous with irregular surface, and its high water-adsorption capability reduces both of mortar workability and compressive strength. The low reactivity of SSA is caused by the low content of CaO and amorphous silica (Pan et al., 2003). In addition, SO_3 contained in SSA may delay the hydration of cement, thereby affecting the formation of hydration products of mortar. Dyer et al. (2011) reported the reaction between PC and SSA is not only pozzolanic as large amounts of hydroxyapatite together with calcium silicate hydrates (CSH) and monosulfate (AFm) were found in the cement paste incorporating SSA.

4.3 Cement Kiln Dust Activation

Cement kiln dust (CKD) was also used in the investigation as a by-product of the cement production process to activate the solid waste materials. CKD has similar particle sizes and composition PC, as major constituents are compounds of lime, silica, iron, and alumina. Despite the similar composition, variability in raw materials, fuel, type of process, and dust collection result in a highly variable material. CKD also has a high alkalinity and LOI compared to PC. Each tonne of PC produces about 3-4 % of CKD (Najim et al., 2014) that needs to be disposed of.

The CKD was blended with SSA at different percentages to produce mortar mixtures, which were tested for fresh and hardened properties. The mortar mixtures were designed to have the same water to binder ratio of 0.5. The mix proportion was 1 part of binder to 3 parts of sand (fine aggregate), by weight.

Table 4-3 Mortar mix proportions for SSA-CKD mixtures (Weight %)

Mix	Binder (%)		Sand (%)	Water	Water/binder
	CKD	SSA			
SSA-5%CKD	5	95	300	50	0.5
SSA-10%CKD	10	90	300	50	0.5
SSA-20%CKD	20	80	300	50	0.5

The mixing, curing and testing of the mortar mixtures followed the same procedure described in Section 4.2. Details of the mix proportions are given in Table 4-3, whereas the flow table and compressive strength results are shown in Table 4-4. The CKD addition was limited to 20% maximum by weight of binder, as increasing the CKD content increases the water demand to achieve the same workability and raised the temperature of the blended binder.

Table 4-4 Properties of SSA-CKD mortar mixtures

Mix	Flow table (mm)	Compressive (MPa)			
		2d	7d	28d	90d
SSA-5%CKD	145	5.2	6.4	6.8	7.1
SSA-10%CKD	136	5.5	6.9	7.4	7.6
SSA-20%CKD	130	5.6	6.4	7.2	7.5

The CKD, as a source of calcium, was used at 5%, 10%, and 20% by weight of binder to activate SSA at a constant water/binder ratio of 0.5. The results indicate that increasing the CKD content decreases the workability of the mortar. At 5% CKD, the flow table measurement was 145mm, as shown in Table 4-4. Increasing the CKD % to 10% and 20% decreased the flow table to 136mm and 130mm, respectively. The effect of CKD on the compressive strength of the SSA-CKD mortars is also given in Table 4-3. For all mixtures, the CKD activation results in early strength gain at the age of 2 days to exceed 5.0 MPa, however the rate of strength development decreased with time to over 7.0 MPa at 90 days. The best strength result is found for the SSA-10% CKD mixture.

4.4 Lime Activation

Lime stabilisation is a common practice in the construction industry, where lime is added to soil to improve its bearing capacity. It is achieved with the addition of quicklime (calcium oxide, CaO) or hydrated lime (calcium hydroxide, CH) in a controlled dose to produce low strength materials. Lime has also been used for activating pozzolanic materials, such as fly ash and blast furnace slag, which are widely used in road construction as base and subbase layers.

Hydrated lime (CH) was sourced from a local supplier in Qatar, which is mainly composed of quicklime and water, with 72.5% CaO. Lime has been used in mortars and renders for thousands of years (BLA, 2022), and its incorporation benefits the fresh and hardened properties of the materials and associated construction. Incorporating an appropriate proportion of lime into a cementitious mixture improves plasticity and workability, making the mixture easy handle.

CH was used for the activation of SSA. Three mixtures were considered to include 10%, 20% and 30% of CH blended with SSA, as given in Table 4-5. The mortar mixtures were designed to have the same water to binder ratio of 0.5. The mix proportion was 1 part of binder to 3 parts of sand (fine aggregate), by weight.

Table 4-5 Mortar mix proportions for SSA-CH mixtures (Weight %)

Mix	Binder (%)		Sand (%)	Water	Water/binder
	CH	SSA			
SSA-10%CH	10	90	300	50	0.5
SSA-20%CH	20	80	300	50	0.5
SSA-30%CH	30	70	300	50	0.5

Table 4-6 Properties of SSA-CH mortar mixtures

Mix	Flow table (mm)	Compressive (MPa)			
		2d	7d	28d	90d
SSA-10%CH	147	0.6	2.0	2.8	3.8
SSA-20%CH	162	1.2	2.3	3.6	4.3
SSA-30%CH	180	1.1	2.1	3.0	4.5

The results in Table 4-6 show that CH improves the workability of fresh mortar. The flow table increases from 147mm for the 10% CH activator to 180mm for the 30% CH activator. Unlike other calcium-rich materials of PC and CKD, the CH resulted in slow strength gain at early age but enhanced rate of strength development with age. At the age of 2 days, the 10% CH gave the lowest strength of 0.6 MPa, whereas the 20% CH and 30% CH gave values slightly higher than 1.0 MPa. The strength continued to develop with age to reach 2.8 MPa at 28 days for the 10% CH, and 3.6 MPa for the 20% CH.

In general, the SSA-20% CH system showed the best performance in terms of workability and strength development, as the strength development for the CH to 30% is not proportional for the increased CH content. Zhou et al. (2020b) showed larger amounts of heat of hydration and higher reactivity of the SSA-lime system compared to SSA-PC system. They identified crystalline phases in the SSA-lime system, mainly brushite and calcium phosphate hydrates, which are responsible for the strength development and concluded the potential use of SSA-lime for the development of controlled low-strength materials.

4.5 Alkali Activated SSA

The use of alkali-activated binders, also known as geopolymers, has been considered widely during the recent century as a promising alternative to PC concrete. Geopolymers belong to the group of aluminosilicate materials that are synthesised in an alkaline environment. The improved sustainability of alkali-activated binders is based on the utilisation of waste and by-product materials, rich in alumina and silica, which would otherwise be landfilled, and the anticipated reduction of carbon emissions associated with the production of PC. Waste products that contain a high content of silicate and aluminate can be activated to produce alkali-activated binders and fully replace PC in concrete.

SSA contains considerable amounts of alumina and silica, Table 3-2, and is considered in this section for the development of alkali-activated green binder. The effects of different alkali activation on the fresh and hardened properties of SSA mortars are investigated.

Chemical activators commonly used to produce activated binders are sodium hydroxide (NaOH), sodium silicates (Na_2SiO_3), sodium carbonate (Na_2CO_3) and sodium sulphate (Na_2SO_4) (Shi et al., 2019), and their effectiveness are mainly associated with the elevated pH and reactive species. When considering the strength development and economic efficiency of alkali-activated concrete, the most used activators are Na_2SiO_3 (sodium silicate) and NaOH (sodium hydroxide) (Choi and Lee, 2019). Blending two types of alkaline activators has been reported to improve the performance of alkali-activated concrete, as each alkaline activator can be complementarily utilised (Pacheco et al., 2008). For example, NaOH is known to promote the initial reaction of alkali-activated materials and Na_2SiO_3 is more effective in strength development (Mangat and Ojedokun, 2018; Haha et al., 2011).

Two chemical solutions were used in this investigation to include sodium hydroxide and sodium silicate. The two solutions were blended in different proportions to study effects of alkali concentration (Na_2O) and silicate modulus (Ms) on the performance of alkali-activated SSA. The two chemical solutions were initially mixed and left overnight before blending with SSA. The sodium hydroxide solution was prepared from commercial grade pellets with a purity of 99%. The sodium silicate solution was locally sourced, and it has the chemical composition of 63% water and 37% solids (26.7% silicate oxide and 10.2% sodium oxide), with a silicate modulus (molar ratio of $\text{SiO}_2/\text{Na}_2\text{O}$) equal to 2.62.

Table 4-7 Mortar mix proportions of alkali activated SSA

Mix	SSA	Sand	Na_2O (%)	Ms ($\text{SiO}_2/\text{Na}_2\text{O}$)	Liquid/binder
SSA 8-1.5	1000	3000	8	1.5	0.75
SSA 6-1.5	1000	3000	6	1.5	0.75
SSA 4-1.5	1000	3000	4	1.5	0.75
SSA 8-1.0	1000	3000	8	1.0	0.75
SSA 6-1.0	1000	3000	6	1.0	0.75
SSA 4-1.0	1000	3000	4	1.0	0.75
SSA 8-0.5	1000	3000	8	0.5	0.75
SSA 6-0.5	1000	3000	6	0.5	0.75
SSA 4-0.5	1000	3000	4	0.5	0.75

Nine mortar mixtures of alkali activated SSA were prepared and tested. The composition of the different mixtures is given in Table 4-7. The binder was 100% SSA and the alkali concentration and silicate modulus varied for the different mixtures. The mortar mixtures were prepared with SSA to sand ratio of 1 to 3 (by weight). A fixed liquid-to-binder ratio of 0.75 was used for all mixtures. The alkali (Na_2O) content and silicate modulus (M_s) of alkaline activator were varied. The silicate modulus (M_s) is the weight ratio of ($\text{SiO}_2/\text{Na}_2\text{O}$). It is important to highlight that the water content of Na_2SiO_3 was included in the total liquid content.

NaOH was added as an alkali activator to adjust M_s according to the dosage of Na_2SiO_3 . Krizan and Zivanovic (2002) reported high strength when the M_s is within the range 0.6 to 1.5. Zuo et al. (2008) showed that the reaction degree increases as the amount of alkaline activator increases, but the reaction degree is no longer increased when the alkaline activator is greater than 6 % by weight of binder. In this investigation, three alkali (Na_2O) contents of 4%, 6%, and 8% were used for alkali concentrations and three levels of M_s were considered at 0.5, 1.0, and 1.5. Details of the alkali activated SSA mixtures are given in Table 4-7.

SSA paste and mortar mixtures were prepared and tested following the procedures described in Section 4.2. Table 4-8 provides a summary of the test results of the paste and mortar mixtures with different alkali contents and silicate modulus. Testing of standard consistence and setting times were conducted on paste specimens as per BS EN 196-3 (2016).

Table 4-8 Properties of alkali activated SSA mixtures

Mix	Consistency (%)	Setting time (min)		Density (kg/m^3)	Flow table (mm)	Compressive (MPa)			
		Initial	Final			2d	7d	28d	90d
SSA 8-1.5	75	50	80	2.145	138	6.0	7.0	7.3	6.8
SSA 6-1.5	72	55	90	2.092	171	6.8	8.2	8.4	8.6
SSA 4-1.5	59	90	135	2.088	135	3.3	3.6	5.8	6.1
SSA 8-1.0	60	80	100	2.234	130	5.3	6.3	8.7	8.6
SSA 6-1.0	61	65	85	2.198	161	3.1	3.7	5.3	5.8
SSA 4-1.0	59	70	85	2.243	160	1.9	2.3	3.3	5.4
SSA 8-0.5	58	120	135	2.221	133	2.7	2.7	4.3	4.8
SSA 6-0.5	59	110	125	2.229	148	2.0	2.2	3.5	5.0
SSA 4-0.5	57	120	135	2.178	111	1.4	1.8	2.0	2.8

The standard consistency results are given in Table 4-8 and shown in Figure 4-7, with values ranging from 57% to 75%. The consistency values of alkali activated mixtures are high compared to the standard consistency value of PC (26%) and could be attributed to the finer and more porous SSA particles and more viscous chemical activator compared to water. The highest liquid demand was for the SSA 8-1.5 mixture, with the highest alkali content of 8% and Ms of 1.5. The lowest consistency of 57% was found for the SSA mixture with minimum alkali content of 4% and lowest Ms of 0.5. The consistency results of the alkali activated SSA are found to be more influenced with Ms rather than the alkali content, as the sodium silicate solution was found to be more viscous than the sodium hydroxide solution. At the highest Ms values of 1.0 and 0.5, there is a small variation of the consistency results at different alkali contents of 4% to 8%.

The effect of alkali activation on the setting time of SSA pastes is shown in Figure 4-8. The alkali activated SSA pastes exhibited setting time values within the range of 50 minutes to 135 minutes. The greatest variation between initial and final setting times was associated with the high Ms of 1.5 and varied between 35 to 45 minutes. The lowest value of initial setting of 50 minutes was found for the mixture with highest alkali content (mix SSA 8-1.5) and highest value of final setting of 135 minutes was for the lowest alkali content of 4% (mix SSA 4-1.5). At high Ms of 1.5, the setting time is reduced with increased alkali content from 4% to 8%. However, the effect of alkali concentration on the setting times is less pronounced at lower Ms values of 1 and 0.5.

The setting times of mixtures with Ms of 1.0 and 0.5 showed small variation at different alkali contents. It is important to highlight non-activated SSA, only blended with water, gave initial and final setting values of 960 and 1020 minutes, respectively, much higher than the setting value results obtained for the alkali activated SSA. The range of setting time found for the SSA with and without alkali activators provides flexibility for use in various construction applications with controlled setting time.

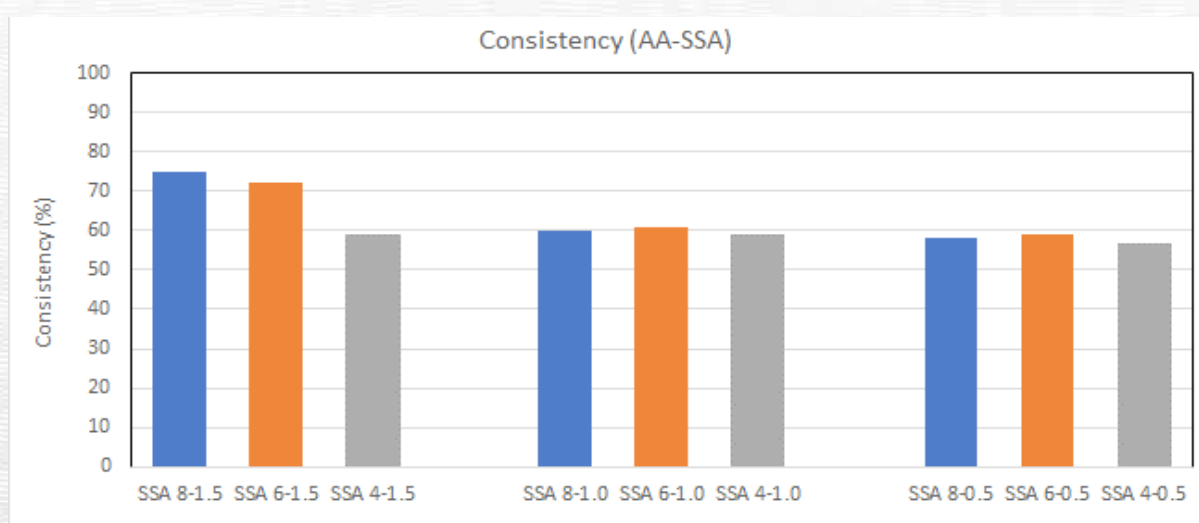


Figure 4-7 Standard consistency of alkali-activated SSA

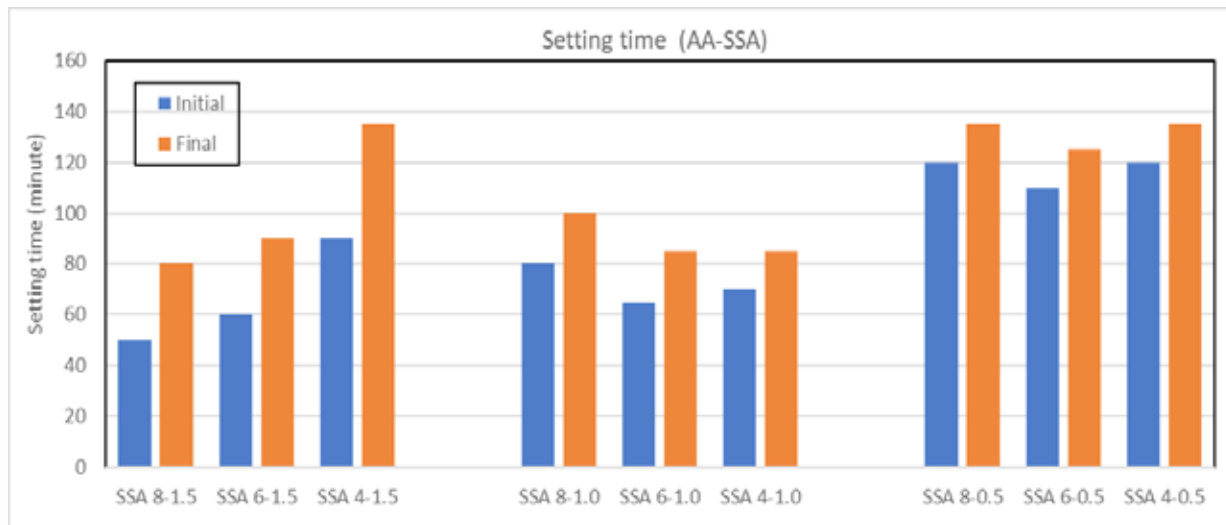


Figure 4-8 Initial and final setting of Standard consistency of alkali-activated SSA

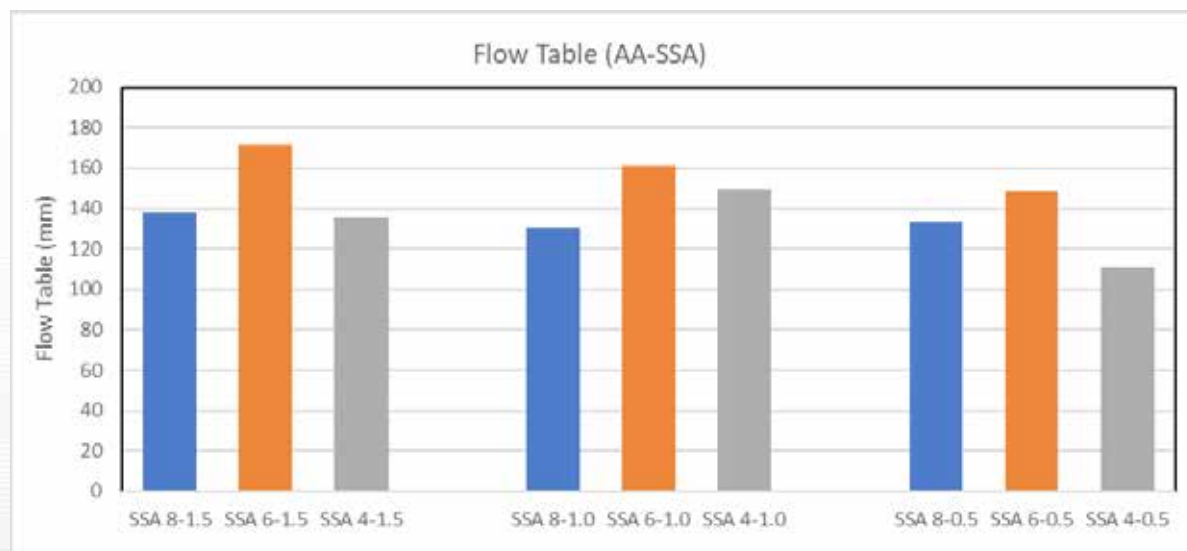


Figure 4-9 Flow table results of alkali-activated SSA mixtures

Figure 4-9 presents the flow table results of the mortar mixtures made with different alkali contents and silicate modulus. At a fixed liquid to binder ratio (0.75), no clear difference was observed for the different mixtures, apart from the slight improvement of workability at alkali content of 6% for the SAA mixtures made with different Ms. Figure 4-10, Figure 4-11, and Figure 4-12 show the flow table for the different alkali activated SSA mortar mixtures. All the mixtures look homogeneous and cohesive with clear retention of the SSA to liquid alkalis.



Figure 4-10 Flow table of SSA 8-1.5 (left) and SSA 6-1.5 (right)



Figure 4-11 Flow table of SSA 8-1.0 (left) and SSA 6-1.0 (right)



Figure 4-12 Flow table of SSA 8-0.5 (left) and SSA 6-0.5 (right)

The compressive strength results of the alkali-activated SSA mortar mixtures are given in Table 4-8, and graphically presented in Figure 4-13. The compressive strength testing was conducted at 2, 7, 28 and 90 days for the different alkali activated SSA mortars, and the results ranged from 1.4 MPa to 8.7 MPa. Knowing that the compressive strength of SSA without alkali activation was 3.5 MPa at 28 days and 4.0 MPa at 90 days, so the results indicate up to 100% improvement in strength with the chemical alkali activation.

The results also indicate that the best strength results are obtained for the SSA mixtures with high Ms (1.5 and 1.0). Increasing the alkali content from 4% to 8% generally increased the strength of SSA, except for SSA 8-1.5 (alkali of 8% and Ms of 1.5). While the early age results showed the general trend of increased strength with age, mixtures with high Ms (1.0 and 1.5) and high alkali content (6% and 8%) showed opposite trend at later ages. For example, SSA 8-1.5 showed strength reduction at 28 and 90 days, in comparison to the 7 days compressive strength. Similarly, mixtures of SSA 8-1.5 and SSA 8-1.0 showed lower strength at 90 days than the 28 days strength.

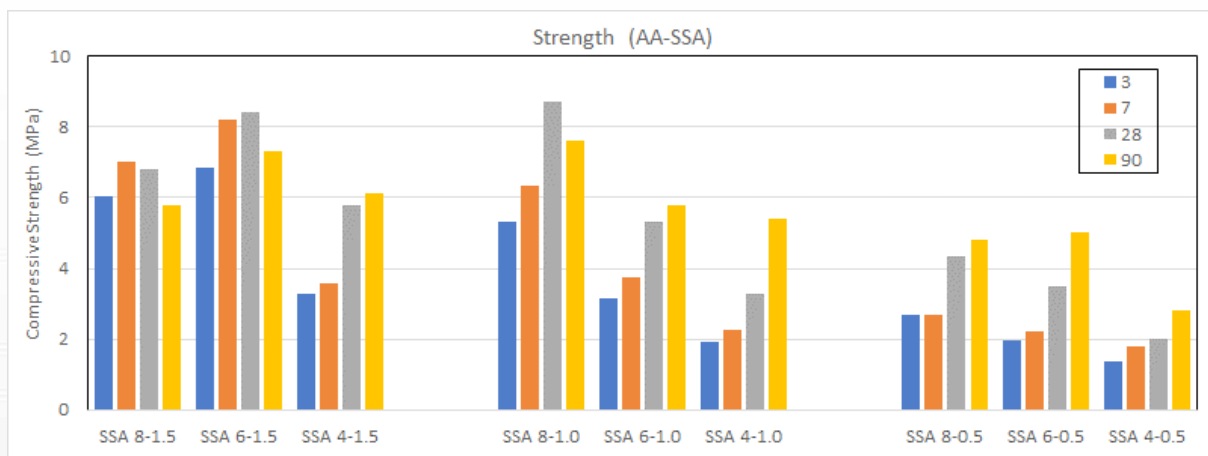


Figure 4-13 Compressive strength results of alkali-activated SSA mortars

Limited work was found in the literature on the alkali activated SSA. Sitarz et al., (2020) investigated alkali-activated materials containing SSA, ground granulated blast furnace slag (GGBS) and coal fly ash (FA). They reported 28-day compressive strength values ranged from 5 to 45 MPa, with the lowest value for the alkali-activated SSA, and the highest for the GGBS, and reported the most efficient use of SSA in geopolymers technology is when mixed with GGBS.

4.6 Alkali-activated SSA blended with SCM

Supplementary cement materials (SCM), such as ground granulated blast furnace slag (GGBS) and coal fly ash (FA), are commonly used to partially replace PC without the need of chemical activators, but they usually exhibit lower strength development than PC especially at high replacement levels. However, alkali-activated materials are effectively used to convert waste and by-product into green cement, and accelerated strength development and reduced greenhouse gas emissions compared to conventional cements.

SSA was blended in this investigation with GGBS and FA. The GGBS was supplied by Al-Jabor Trading company in Qatar and complies with BS EN 15167-1 (2006), and the FA was supplied by Gulf Additive Factory and complies with BS EN 450-1 (2012). The fine aggregate was local washed sand and complies with the Qatar Construction Specification (QCS 2014).

The sodium hydroxide pellets were dissolved in water and added to sodium silicate solution to adjust the alkalinity and silicate modulus of the alkali activator. Three different mixtures were made for each SSA+SCM blends to have alkali concentrations of 4%, 6% and 8% (Na_2O % by of mass of SSA) and silicate modulus (M_s) of 1.5. Table 4-9 gives the composition of mortar mixtures together with the alkali concentration and M_s for each mix. The blended binder of SSA-GGBS was made by the weight ratio of 50% SSA and 50% GGBS, whereas the SSA-FA binder was made at the proportion of 70% SSA and 30% FA. The total liquid to binder ratio was kept constant at 0.75 for all mixtures.

Table 4-9 Mortar mix proportions of alkali activated SSA and SCMs

Mix	SSA	GGBS	FA	Sand	Na_2O (%)	M_s ($\text{SiO}_2/\text{Na}_2\text{O}$)	Liquid/binder
SSA-GGBS 8-1.5	500	500	-	3000	8	1.5	0.75
SSA-GGBS 6-1.5	500	500	-	3000	6	1.5	0.75
SSA-GGBS 4-1.5	500	500	-	3000	4	1.5	0.75
SSA-FA 8-1.5	700	-	300	3000	8	1.5	0.75
SSA-FA 6-1.5	700	-	300	3000	6	1.5	0.75
SSA-FA 4-1.5	700	-	300	3000	4	1.5	0.75

Table 4-10 Summary results of alkali activated SSA and SCMs

Mix	Consistency (%)	Setting time (min)		Density (kg/m^3)	Flow table (mm)	Compressive (MPa)			
		Initial	Final			2d	7d	28d	90d
SSA-GGBS 8-1.5	51	100	145	2142	136	27.0	29.3	25.4	24.1
SSA-GGBS 6-1.5	46	90	110	2159	189	21.3	23.2	20.3	19.7
SSA-GGBS 4-1.5	45	60	65	2160	183	12.7	13.6	16.9	19.8
SSA-FA 8-1.5	60	30	40	2128	150	9.7	10.5	16.3	20.0
SSA-FA 6-1.5	56	45	50	2099	190	7.9	8.5	12.9	17.4
SSA-FA 4-1.5	56	40	60	2197	181	2.9	3.3	7.2	7.5

A summary of the paste and mortar results of the alkali-activated SSA-GGBS and SSA-FA mixtures are given in Table 4-10. The consistency of the SSA-GGBS and SSA-FA mixtures showed similar trend of higher water demand for increased alkali concentration. At the same silicate modulus (M_s of 1.5), the SSA-GGBS consistency increased from 45% at 4% alkali concentration to 51% at 8% alkali concentration. Similarly, the SSA-FA consistency increased from 56% at 4% alkali concentration to 60% at 8% alkali concentration. Considering the high consistency values of the SSA at M_s of 1.5 of 59 to 75% (Table 4-8), the replacement of 50% with GGBS reduced the consistency of the mixtures. The SSA-FA mixtures showed lower consistency values than the alkali-activated SSA alone, but higher consistency values than the GGBS mixture. The higher consistency for the SSA-FA mixtures could be attributed to the increased content of SSA (70%) with its irregular shape and high surface area particles.

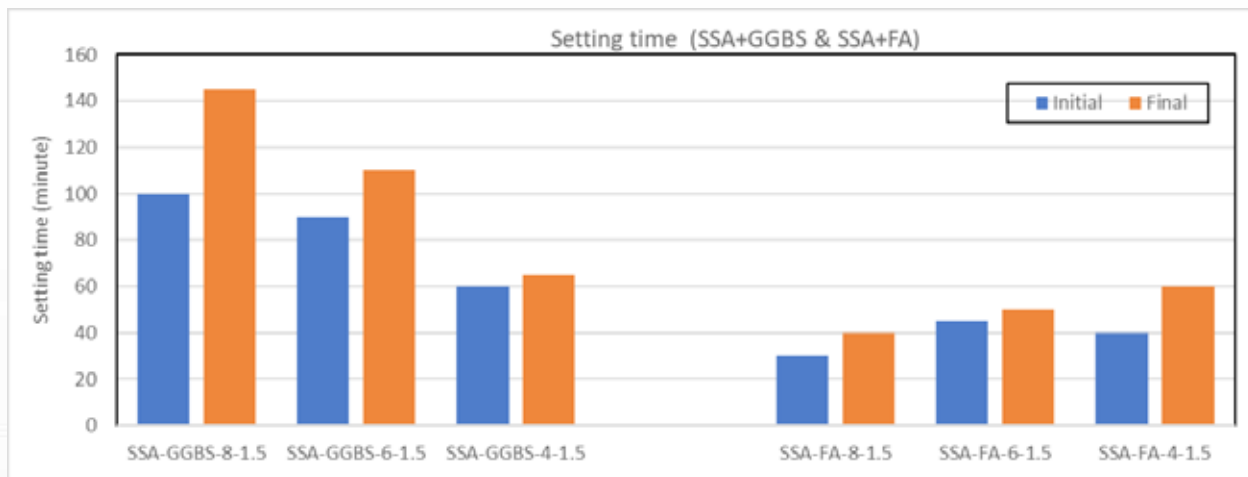


Figure 4-14 Setting time of alkali activated SSA+GGBS and SSA+FA mixtures

The setting time results of the SSA blended with SCMs are given in Table 4-10 and graphically presented in Figure 4-14. The SSA-GGBS alkali-activated mixtures showed increased setting time with higher alkali concentration, whereas the SSA-FA gave opposite trend of decreased setting time for increased alkali concentration. The setting times of the SSA-FA mixtures are greatly reduced in comparison to the SSA-alkali activated and SSA-GGBS alkali activated mixtures, which could be attractive for the precast concrete industry. The maximum setting time value was 145 minutes for the SSA-GGBS-8-1.5, compared to 135 minutes for the SSA-4-1.5, and 60 minutes for the SSA-FA-4-1.5.

Previous work on the alkali-activated slag concrete showed that the setting time is decreased with increasing the silicate modulus and the alkali concentration, but for mixtures with high alkali concentrations and for a silicate modulus greater than 1.2, the setting time should be increased (Atiş et al. 2009; Bakharev et al. 1999).

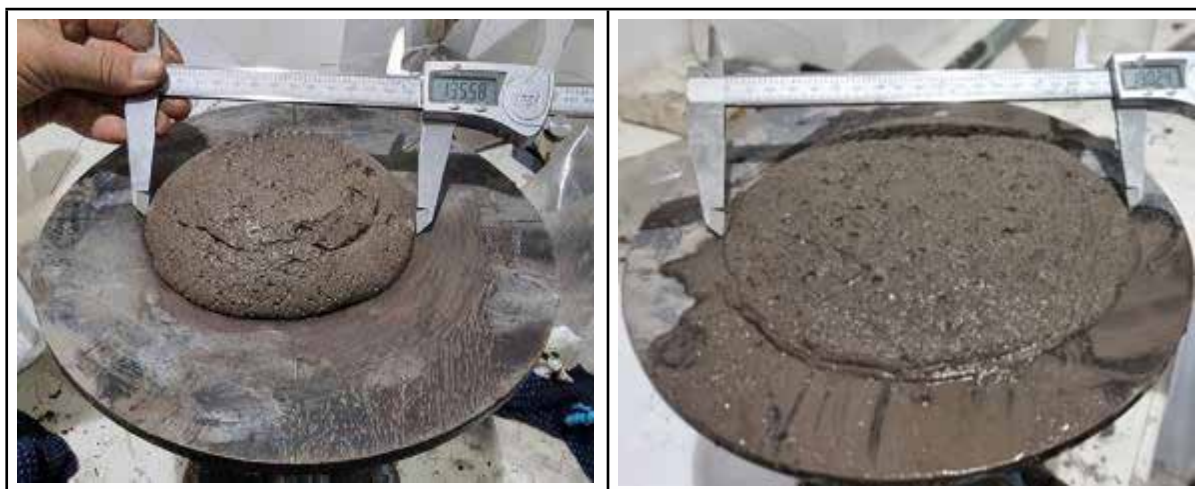


Figure 4-15 Flow table of SSA-GGBS-4-1.5 (left) and SSA+GGBS-6-1.5 (right)

The workability of the mortar mixtures was assessed using the flow table test as per BS EN 4551-1 (1998) and ASTM C1437 (2020), and the results are given in Table 4-10. The flow table results for the low and high alkali concentrations are also presented in Figure 4-15 for the SSA-GGBS mixtures and Figure 4-16 for the SSA-FA mixtures. At the same silicate modulus of 1.5, the highest workability values were obtained at 6% alkali concentration for both SSA-GGBS and SSA-FA mixtures. Interesting, the same behaviour was observed for the alkali activated SSA at the same alkali concentration of 6%.

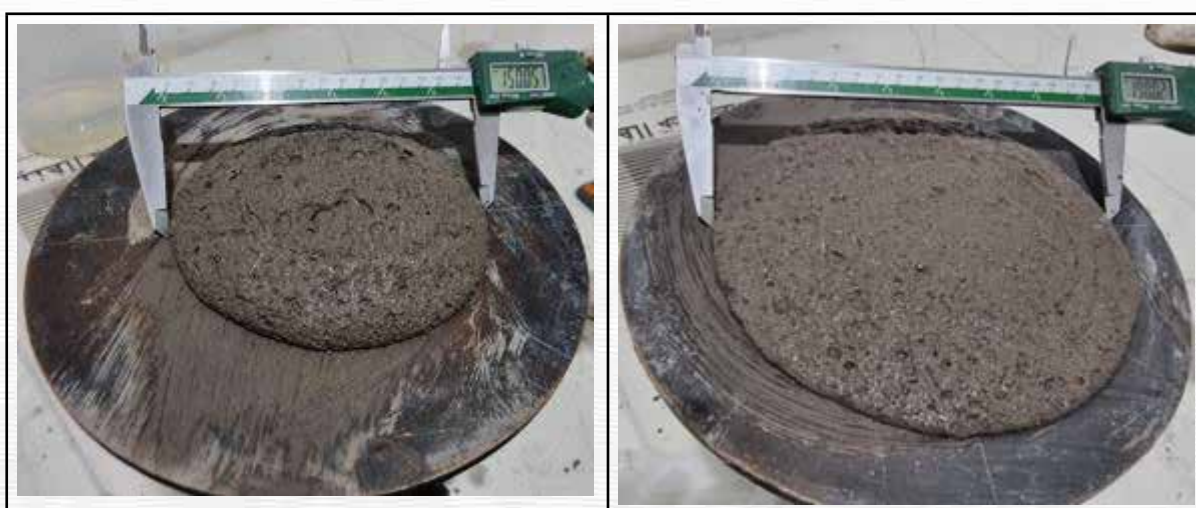


Figure 4-16 Flow table of SSA-FA-4-1.5 (left) and SSA+FA-6-1.5 (right)

The compressive strength results of the alkali activated SSA+GGBS and FFA-FA at Ms of 1.5 and different alkali concentrations are given in Table 4-10 and shown in Figure 4-17. At the same Ms and alkali concentration the SSA-GGBS mixtures exhibited higher compressive strength values than the SSA-FA mixtures.

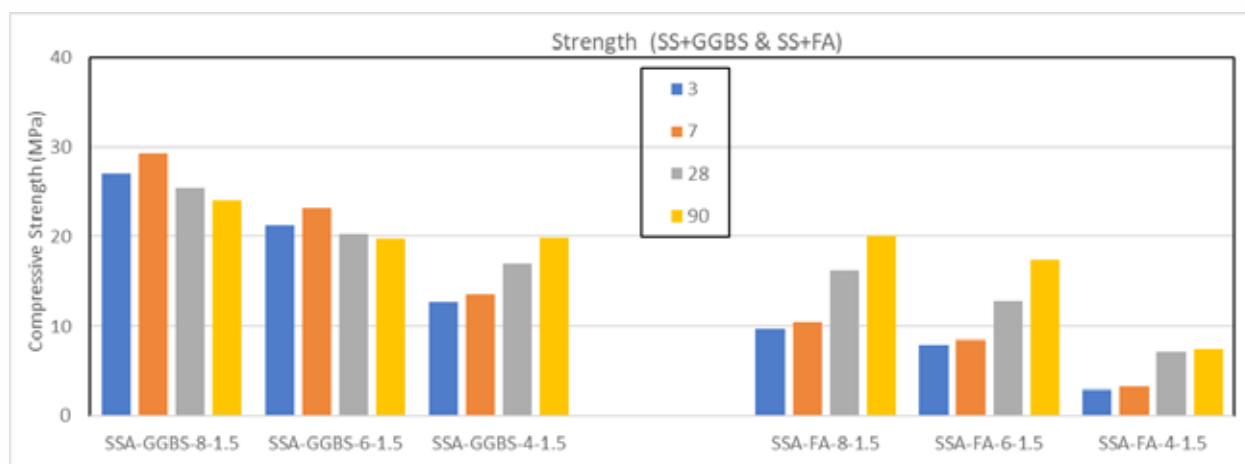


Figure 4-17 Compressive strength of alkali activated SSA+GGBS and SSA+FA

GGBS is one of the high calcium systems compared to the low calcium system of FA used in this investigation. Whilst the SSA contains >28% calcium but it seems the calcium is not as reactive as the GGBS system. The SSA-FA system showed increased compressive strength with age, with most of the strength development after 7 days.

The SSA-GGBS alkali activated system showed a different behaviour in strength development. For the SSA-GGBS systems with alkali concentration of 6% and 8%, the strength increased from 2 to 7 days but reduced at the age of 28 and 90 days. At the low alkali concentration of 4%, the SSA-GGBS showed the expected strength increment with age. Other researchers reported similar strength reduction of alkali activated slag (AAS) system. Atis et al. (2009) reported that the compressive strength of AAS paste decreased as the silicate modulus increased from 0.75 to 1.50 for Na_2O contents of 6% and 8%, respectively. The same conclusion was obtained by Garcia et al. (2008) who found that the compressive strength of AAS decreased as the Na_2O content increased from 4% to 8% for the silicate modulus between 0 and 2.0. Taghvayi et al. (2018) reported that increasing the alkali concentration and Ms up to 6.5% and 0.85, respectively, could increase the compressive strength of the AAS. However, in most of the mixtures, higher alkali and Ms had no positive effect on the increase of the compressive strength. Other researchers also reported a loss in the compressive strength for the mixtures with a silicate modulus of more than 1. Whilst the compressive strength is enhanced with increasing the alkali concentration, high alkali concentrations can weaken the gel structure of the binder (Shojaei et al. 2015; Wang et al. 2005).

4.7 Microstructure Analysis

Microstructural analysis was conducted on the mortar cubes after 90 days of curing to examine the microstructure of the SSA activated samples as revealed during optical microscopy as well as to analyse the composition of different products on a micro-scale. The microstructural testing was conducted at the Core-Labs at the Qatar Environment and Energy Research Institute (QEERI). A scanning electron microscopy (SEM) is used for the microstructure analysis, and associated energy-dispersive X-ray spectroscopic microanalysis (SEM-EDS) is employed for compositional analysis.

Small pieces were chipped off from the mortar cubes and mounted on the SEM stub using conductive glue. As concrete does not conduct the electron ray, the samples were coated with a conductive material of gold for electrical conductivity. FEI Quanta650FEG SEM is used for imaging and Bruker Quanta400 EDS for Microanalysis. High voltage of 5KV is used for SEM imaging and 15KV for EDS analysis. The EDS scan was conducted on an area of 4mm² of the mortar samples.

In addition, X-ray diffraction (XRD) was used to identify and measure the mass fractions of various crystalline phases of the activated SSA mixtures. XRD was also used for the quantitative characterisation of microstructural features of the SSA mixtures. The XRD testing was performed on selected samples using the Rigaku's SmartLab system. Figure 4-18 shows the SEM and XRD equipment used for the investigation.



Figure 4-18 Quanta650FEG SEM (left) and Rigaku's SmartLab XRD (right) equipment

4.7.1 Scanning Electron Microscopy – Energy-Dispersive X-ray spectroscopic

SEM/EDS is an analytical technique used for the elemental analysis or chemical characterisation of a sample. It relies on an interaction of an electron beam and the mortar/paste sample, and its characterisation capabilities are based on the fundamental principle that each element has a unique atomic structure, allowing a unique set of peaks on its electromagnetic emission spectrum (which is the main principle of spectroscopy). The SEM-ESD results are presented in Figure 4-19 to Figure 4-23 for the various mortar mixtures investigated.

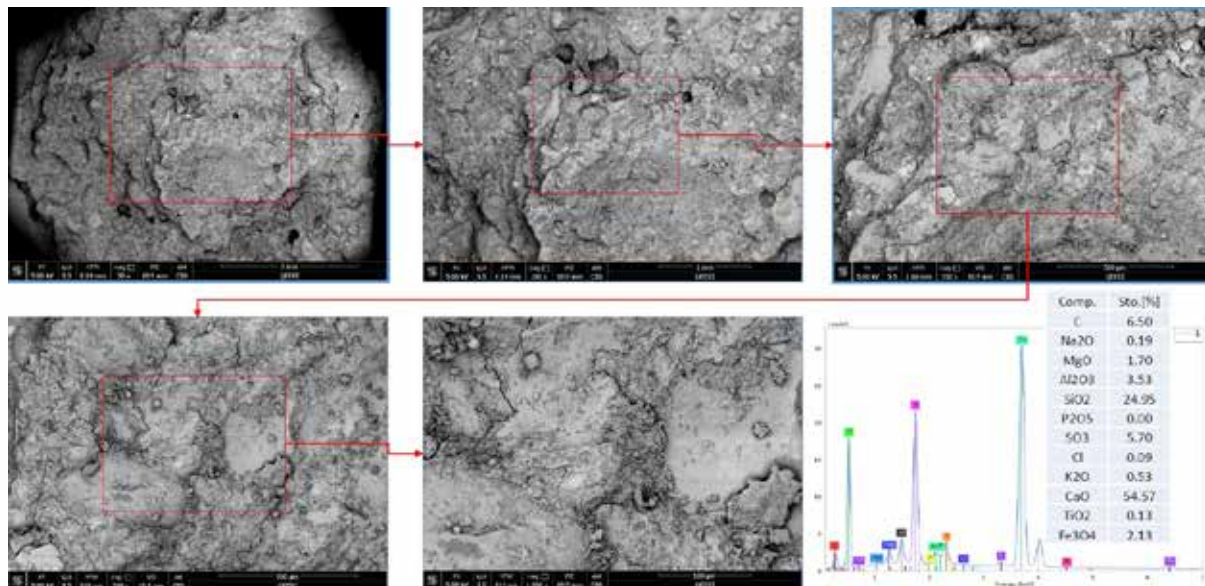


Figure 4-19 SEM-EDS analysis of the PC mortar

Figure 4-19 shows the SEM analysis of the PC mortar mixture, which is characterised by its dense microstructure. A fine crack was observed in the SEM which could be attributed to the elevated curing at 40°C for the initial 24 hours of age or to the sample preparation. The EDS analysis identifies the main components of calcium and silica with smaller peaks of carbon, aluminium, magnesium, iron and sulfur.

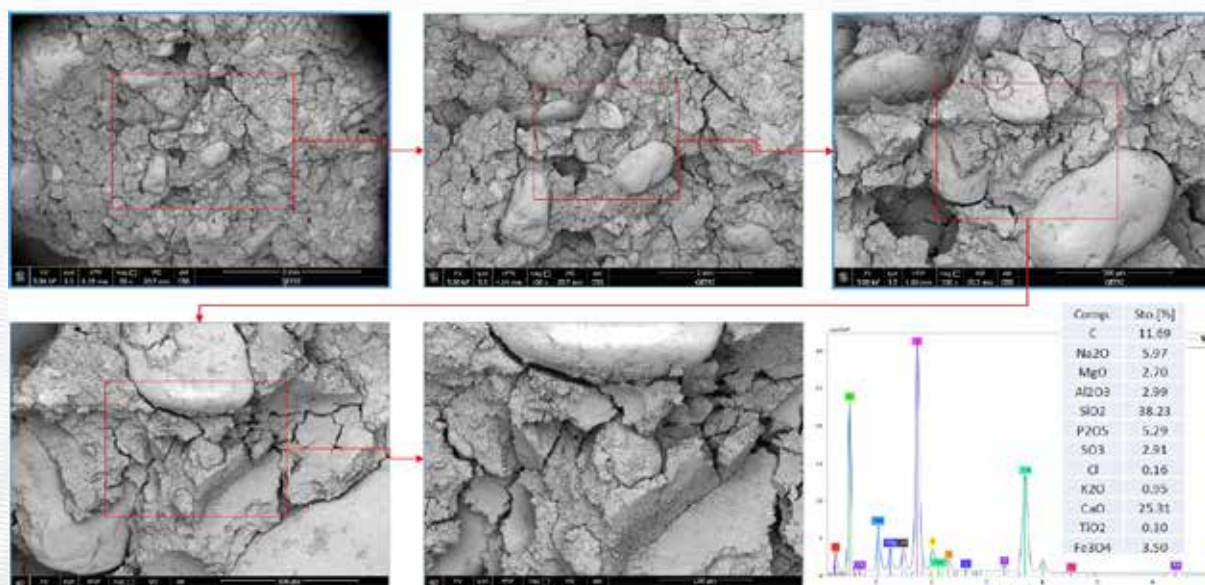


Figure 4-20 SEM-EDS analysis of the SSA high alkali (8%N-1.5Ms) mortar

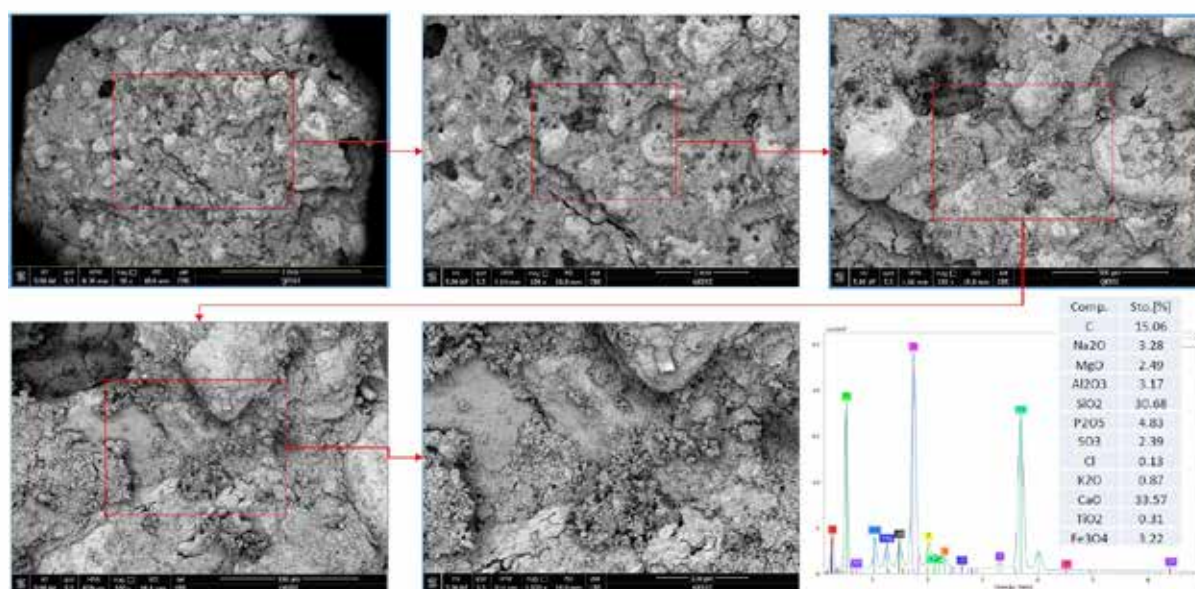


Figure 4-21 SEM-EDS analysis of the SSA low alkali (6%N-1.0Ms) mortar

The SSA activated with high alkali (8% N and 1.5 Ms) showed different microstructure to the PC mortar, as shown in Figure 4-20. The sample exhibited more porous structure and cracks than the PC mortar. The cracks are closely located and spread across the tested sample. The two main components of silica and calcium, found in PC mortar, are also identified in the high-alkali SSA mortar but with lower calcium content. However, the sample is characterised with its high alkali as reflected from the sodium content and the presence of phosphorous products.

Lower alkali resulted in improved microstructure of the SSA mortar as shown in Figure 4-21 for the SSA low alkali (6% N and 1.0 Ms). The lower alkali SSA mortar inhibited less cracking and denser microstructure compared to the high-alkali SSA mortar. The EDS analysis showed similar components to the high-alkali SSA mortar, but with a lower sodium content.

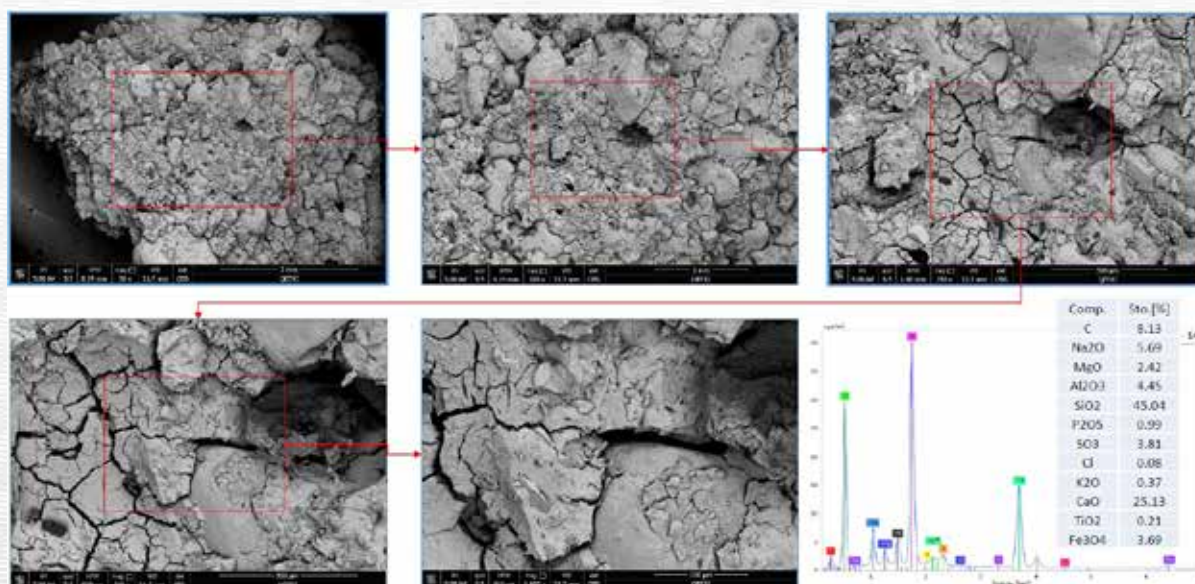


Figure 4-22 SEM-EDS analysis of the alkali-activated SSA-GGBS (8%N-1.5Ms) mortar

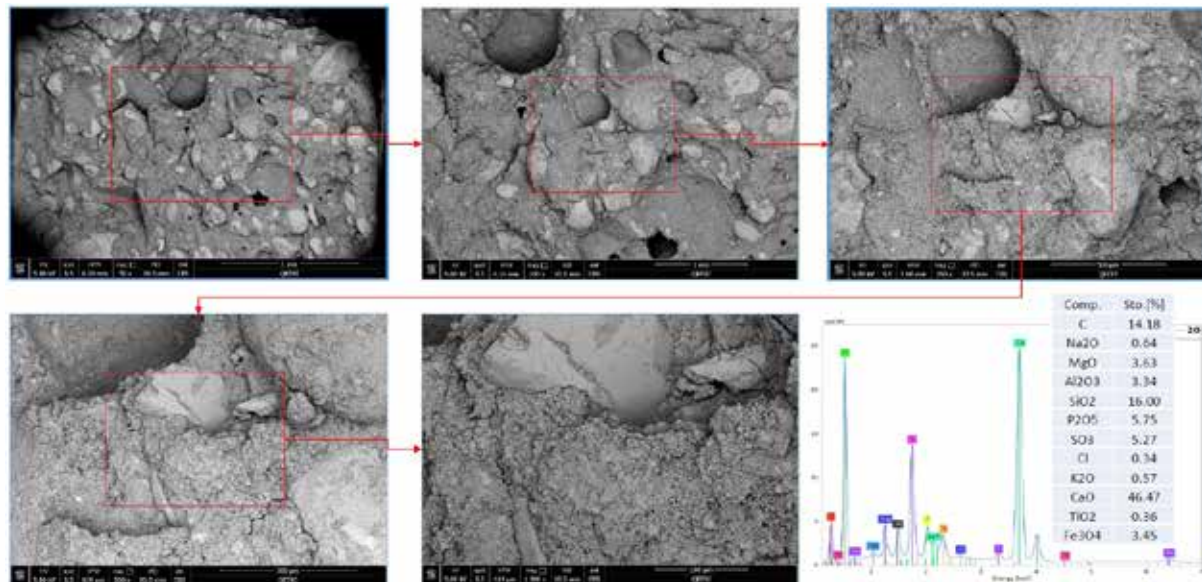


Figure 4-23 SEM-EDS analysis of the SSA-lime activated mortar

The high-alkali SSA-GGBS mortar exhibited similar crack patterns and porous microstructure to the high-alkali SSA, as shown in Figure 4-22. The results clearly show the effect of high alkali (N of 8% and Ms of 1.5) and elevated curing at 40°C for the first 24 hours on the microstructure after 90 days. It seems the combination of high-alkali and elevated temperature cause self-desiccation of the SSA mortars and result in microcracking and porous microstructure. The EDS analysis of the SSA-GGBS high-alkali showed similar composition to the SSA high-alkali mortar but with higher contents of silica and aluminium, from the addition of GGBS, and a lower content of phosphorous. The change of mineral composition indicates additional hydration products for the SSA-GGBS in comparison to the SSA, when both are alkali-activated.

Figure 4-23 shows the SEM of the SSA activated with lime, with a dense microstructure similar to that of the PC mortar. The EDS analysis of the SSA-lime mortar showed the second highest content of calcium, after PC, and the lowest content of silica. The high calcium is mainly from the addition of lime and the low silica may be attributed to the selected sample with less aggregate.

Table 4-11 EDX data of SSA activated mortars.

	PC		SSA (high alkali)		SSA (low alkali)		SSA/GGBS		SSA/Lime	
	M [%]	A [%]	M [%]	A [%]	M [%]	A [%]	M [%]	A [%]	M [%]	A [%]
C	4.70	8.45	8.61	14.24	11.13	18.38	5.58	9.36	8.95	14.91
O	45.52	61.45	46.08	57.25	44.60	55.32	48.93	61.65	49.48	61.88
Na	0.12	0.11	3.92	3.39	2.22	1.92	3.73	3.27	0.37	0.32
Mg	0.94	0.83	1.43	1.17	1.38	1.13	1.26	1.05	1.69	1.39
Al	1.62	1.30	1.52	1.12	1.38	1.01	1.97	1.47	1.28	0.95
Si	10.25	7.88	16.82	11.91	12.50	8.83	17.98	12.90	5.66	4.03
P	0.00	0.00	2.00	1.28	1.67	1.07	0.34	0.22	1.75	1.13
S	1.83	1.23	0.98	0.61	0.77	0.48	1.22	0.77	1.49	0.93
Cl	0.04	0.03	0.13	0.07	0.15	0.09	0.06	0.03	0.27	0.15
K	0.34	0.19	0.63	0.32	0.60	0.31	0.27	0.14	0.32	0.17
Ca	33.68	18.15	16.20	8.03	21.97	10.88	16.86	8.48	27.19	13.57
Ti	0.03	0.01	0.14	0.06	0.15	0.06	0.10	0.04	0.15	0.06
Fe	0.93	0.36	1.56	0.55	1.46	0.52	1.71	0.62	1.40	0.50

M: Mass

A: Atom

Table 4-11 summarises the EDS analysis of main components with the various SSA mixtures. The highest alkali content of sodium is associated with the alkali activated chemicals of 8% N and 1.5 Ms, used for the mixture of SSA 8-1.5, SSA-GGBS 8-1.8 followed by the chemicals of 6% N and 1.0 Ms used with the mixture of SSA 6-1.0. All the SSA mixtures exhibited high phosphorus content, except the SSA-GGBS. The SSA-GGBS mixture has the lowest content of 50% SSA, indicating the partial consumption of phosphorus with the reactive calcium of GGBS. The PC and SSA-Lime mixtures gave the highest contents to calcium, compared to the chemically alkali-activated SSA mixtures.

X-ray elemental mapping is a powerful technique to show the ESD compositional distribution and the correlations among elements present in the different SSA activated mixtures. Figure 4-24 and Figure 4-25 show the backscatter electron imaging (BSE) of the alkali activated SSA 8-1.5 at two different locations, whereas the BSE of the SSA-Lime activated sample is shown in Figure 4-26. Correlated elemental components within the EDS analysis appear brighter in the BSE, where the dark elements are not correlated.

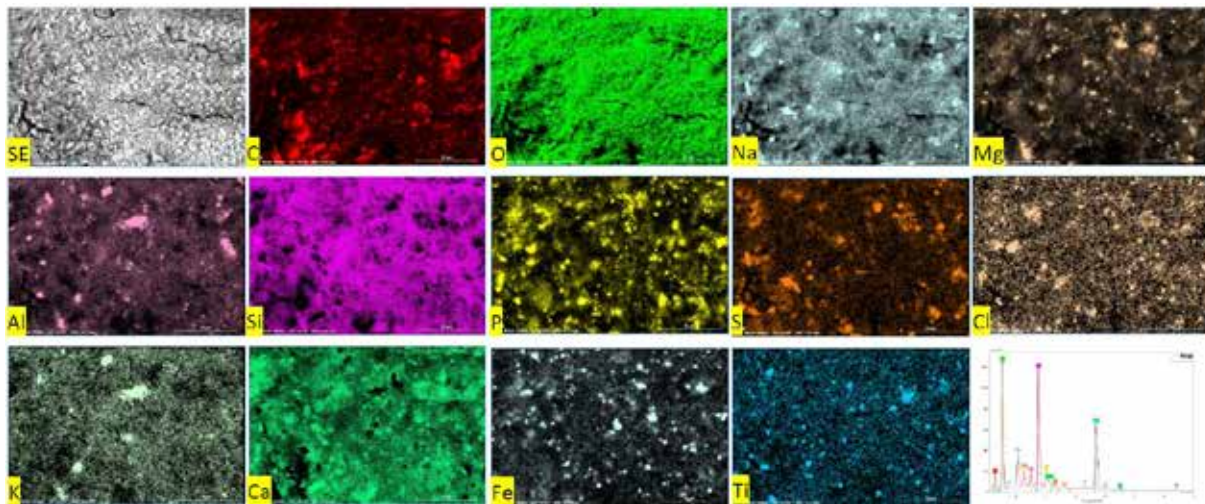


Figure 4-24 Backscattered electron imaging of SSA 8%N-1.5Ms mortar – Location 1

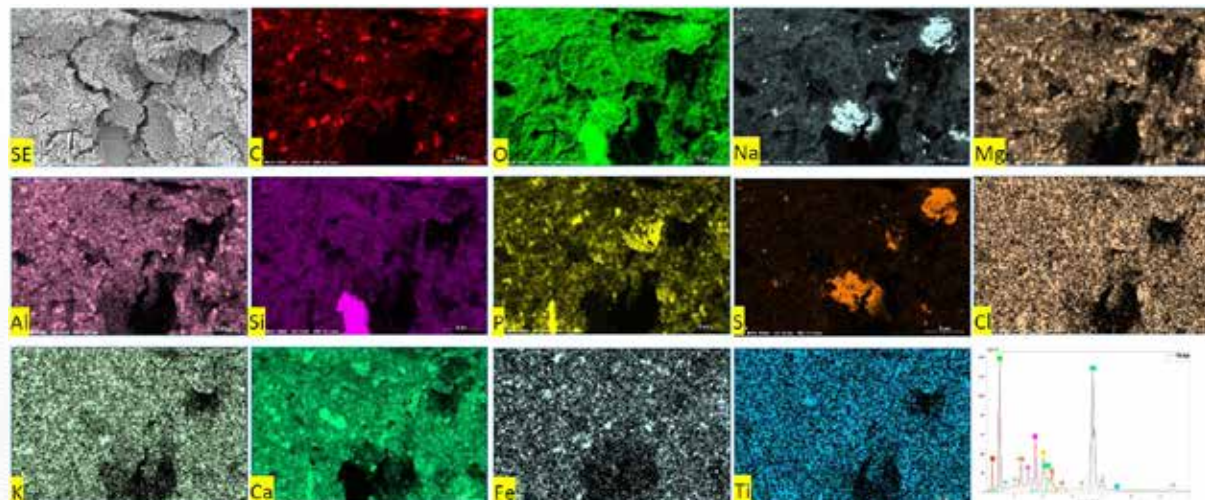


Figure 4-25 Backscattered electron imaging of SSA 8%N-1.5Ms mortar – Location 2

The main elements present in SSAs as reported in Table 3-2 are calcium, silicon, phosphorus, magnesium, iron and aluminium. The two locations of the high alkali SSA mortar (SSA-8-1.5) is show Figure 4-24 and Figure 4-25 indicate nicely distributed phosphorus across the mortar, mainly correlated to the calcium element and indicating more likely the formation of calcium phosphates (Mejdi et al., 2020). Calcium carbonate is also noticed in both locations, which probably contributed to the strength development of the alkali activated SSA. The EDS elemental analysis also shows crosslinks between alkali, in the form of sodium and potassium, and calcium with aluminium and silicon to form a mineral. This is likely to be a feldspar mineral found in the fine aggregate, as compared to reaction products such as calcium-alumino-silicate-hydrate (C-A-S-H) or sodium/potassium-alumino-silicate-hydrate (N-A-S-H). Both samples also show the correlation of sodium and sulfate to form sodium sulfate.

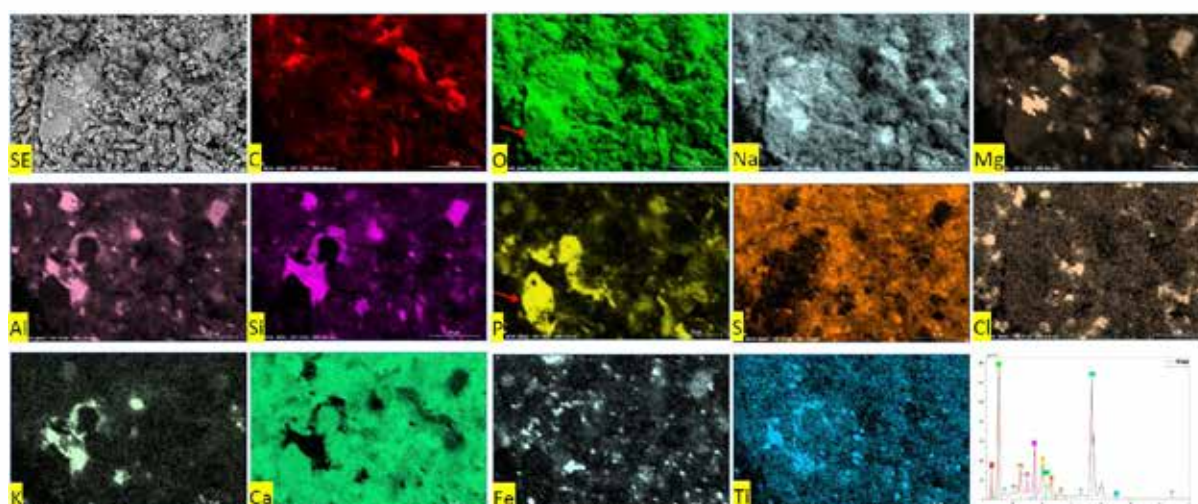


Figure 4-26 Backscattered electron imaging of SSA-Lime mortar

Figure 4-26 shows the EDS compositional distribution correlations between the different elements of the SSA-Lime activated mortar. The results show the formation of calcium phosphate. Zhou et al. (2020) identified crystalline phases in the SSA-lime system, mainly brushite and calcium phosphate hydrates, which are responsible for the strength development and concluded the potential use of SSA-lime for the development of controlled low-strength materials.

4.7.2 X-Ray Diffraction (XRD) Results

The XRD pattern list of the PC and SSA-activated mortars are summarised in Table 4-12 and shown in Figure 4-27. The XRD patterns show that the major crystalline phase is Quartz (SiO_2), which is attributed to the fine aggregate used in the mortar together with the relatively high content of SiO_2 in the SSA. The PC mixture showed the conventional XRD peaks of Portlandite $\text{Ca}(\text{OH})_2$, Calcite $\text{Ca}(\text{CO}_3)$, and Albite $\text{NaCaSi}_3\text{Al}_3\text{O}_8$ minerals. The latter is a plagioclase feldspar mineral, which is likely to have originated from the fine aggregate.

All the activated SSA samples shows Quartz (SiO_2) and Calcite (CaCO_3). The SSA-activated mixtures also showed XRD pattern of Anorthoclase $(\text{Na,K})\text{AlSi}_3\text{O}_8$ or Albite $\text{NaCaSi}_3\text{Al}_3\text{O}_8$ minerals (Table 4-12). In PC the Albite mineral is found to be Ca rich, whereas in all alkali/lime activated SSA mixtures, the mineral is found to be a low Ca version with higher quantities of Na. These are likely to be variations from the analysis and it is likely that the mineral is a version of Feldspar found in fine aggregate. From the XRD analysis, the main binding agent seems to be calcite, which can be formed through the carbonation of Calcium Oxide or Calcium Hydroxide. In SSA/GGBS mix it is highly likely that C-A-S-H/N-A-S-H minerals are forming, however, not evident in the analysis due to diffraction caused by sand minerals. In further studies SEM and XRD analysis will be performed on paste samples without the fine aggregate to ascertain more details about the binding mechanism.

Table 4-12 XRD pattern list of the PC and SSA-activated mortars

Mix	Visible	Ref. Code	Score	Compound	Scale
PC	*	01-086-1560	68	Quartz low	0.959
	*	01-086-2334	28	Calcite $\text{Ca}(\text{CO}_3)$	0.029
	*	00-044-1481	19	Portlandite $\text{Ca}(\text{OH})_2$, syn	0.016
	*	00-041-1480	13	Albite, Ca-rich, ordered $(\text{Na,Ca}) \text{Al} (\text{Si,Al})_3 \text{O}_8$	0.037
SSA-8-1.5		01-078-1252	51	Quartz (SiO_2) \$GA, syn	0.989
	*	01-086-2339	40	Calcite $\text{Ca}(\text{CO}_3)$	0.081
		00-009-0478	31	Anorthoclase, disordered (Na, K) $(\text{Si}_3 \text{Al}) \text{O}_8$	0.107
		00-029-1073	21	Texasite [NR]	0.146
		00-011-0293	19	Brushite	0.043
SSA-6-1.0	*	01-078-1252	54	Quartz (SiO_2) \$GA, syn	0.969
	*	01-086-2334	34	Calcite $\text{Ca}(\text{CO}_3)$	0.073
	*	01-076-0927	13	Albite calcian low (Na0.84 Ca0.16) Al1.16 Si2.84 O8	0.027
SSA-GGBS-8-1.5	*	01-083-0539	53	Quartz (SiO_2)	0.970
	*	01-072-1937	39	Calcite $\text{Ca}(\text{CO}_3)$	0.078
	*	00-034-0180	32	Rutile (Ti O_2) , syn	0.024
	*	01-076-0927	24	Albite calcian low (Na0.84 Ca0.16) Al1.16 Si2.84 O8	0.066
SSA-Lime	*	01-078-1252	61	Quartz (SiO_2) \$GA, syn	0.946
	*	01-081-2027	48	Calcite $\text{Ca}(\text{CO}_3)$, syn	0.107
	*	01-076-0927	26	Albite calcian low (Na0.84 Ca0.16) Al1.16 Si2.84 O8	0.035

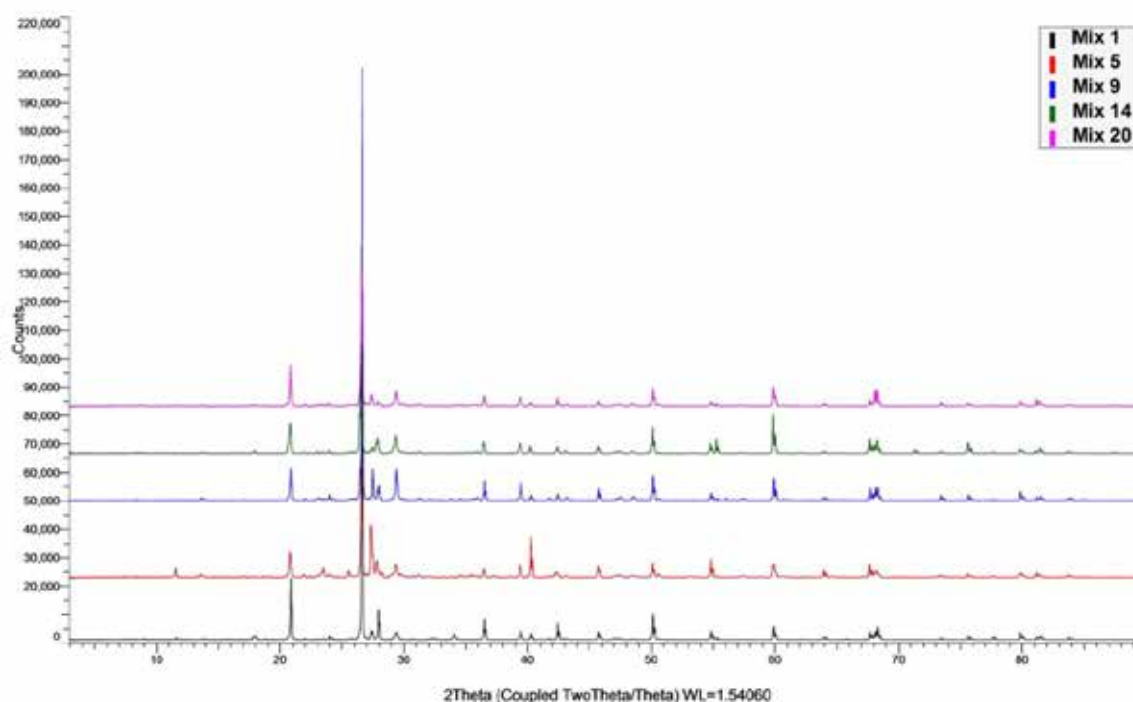


Figure 4-27 XRD traces of the activated SSA mixtures

4.8 Summary

SSA was activated using different techniques for the development of low-strength concrete products. The techniques considered are blending with PC, CKD, hydrated lime and alkali solutions.

SSA was used to replace up to 100% of PC in mortar mixtures. The higher surface area of SSA, compared to PC, resulted in increased water demand and reduced workability but contributed to improved particle packing and higher density. Higher SSA content increased the setting time and reduced the compressive strength of mortars.

SSA was also activated through blending with CKD. The CKD content was limited to a maximum of 20% due to its adverse effect on the workability of concrete as well as raising the temperature of the fresh mixture. CDW resulted in accelerated strength at 2 days, but the rate of strength development was relatively low up to 90 days of age. The best strength result is found for the SSA-10% CKD mixture, which achieved 7.4 MPa and 7.6 MPa at 28 and 90 days, respectively.

Quicklime (CaO) was used to activate SSA. Increasing the CaO content improved the workability but reduced the setting time and strength of mortars. The strength reduction at high CaO content is attributed to the potential increased heat of hydration and microcracks associated with the fast-reacting CaO. Hydrated lime was found to improve the strength development of SSA mortars, at 7 days and beyond, and is safer to handle compared to quicklime.

Alkali-activated SSA mixtures were made with varying alkali concentration and silicate modulus. The high surface area of SSA and viscous nature of sodium silicate resulted in increased activator content to achieve similar workability values. Alkali content was found to influence the setting time with high alkali results in accelerated setting, and the effect is more pronounced at a high silicate modulus value. The highest 28-day strength of the alkali-activated mortars is 8.7 MPa for the SSA-6-1.0, compared to 3.5 MPa for the 100 SSA mortar.

The best strength result of the alkali-activated SSA mortars was achieved with the highest silicate modulus value of 1.5. However, a strength reduction was observed for the SSA mortars activated by high alkali concentration and high silicate modulus at 28 and 90 days.

Different behaviour of setting time is observed for the alkali-activated SSA blended with GGBS and FA. At the same silicate modulus of 1.5, the SSA-GGBS mixtures showed increased setting time with higher alkali concentration, whereas the SSA-FA gave reduced setting time.

GGBS, with its high calcium content, exhibited the highest strength of 29.3 MPa after 7 days, compared to 10.5 MPa for the low calcium FA and when alkali-activated with SSA. However, the alkali-activated SSA-GGBS showed strength reduction with high alkali concentrations, 6% and above, after 7 days.

SEM analysis indicated porous microstructure and microcracks, respectively in the SSA and SSA-GGBS systems activated with high alkali concentration and silicate modulus (8% N and 1.5 Ms). The accelerated reaction of alkali-activation together with the initial heat curing at 40°C resulted in self-desiccation and microcracking within the mortar structure.

5 Development of SSA Concrete Mixtures

Three construction products were developed from the green cement and tested for compliance with relevant specifications. SSA-activated systems were used to produce non-structural concrete products of blocks, foam concrete and cement bound materials. The laboratory development of the SSA low-strength concrete mixtures were made to simulate existing procedure used in the industry. The development products were tested and assessed for compliance with national and international specifications for use in the desired applications.

5.1 SSA Concrete Blocks

Concrete blocks are one of several precast concrete products used in construction industry in Qatar. The annual production is expected to exceed 500 million blocks and composed of hollow and solid blocks. The QCS 2014 is mainly based on BS EN 771-3 (2011) for specifying concrete blocks. Current practice is based on Portland cement (PC) as the main binder to produce low-strength concrete products, which could be replaced with alternative binders. This section covers the use of SSA green cement in the production of concrete blocks and assess their properties with the performance requirements of the QCS 2014.

5.1.1 Materials and mixtures

Laboratory developed mixtures were made of primary and alternative waste materials. Incinerated sewage sludge ash (SSA) was used as the main binder for the development of concrete blocks. The SSA was activated by Portland cement (PC), cement kiln dust (CKD), and alkali chemical activators. The main binders of SSA, PC and CKD are shown in Figure 5-1. The chemical alkali activator included blended sodium hydroxide and sodium silicate solutions, to give a total alkali content (Na_2O) of 6% and 1.5 of silicate modulus (Ms). Ground granulated blast furnace slag (GGBS) was also blended SSA for the development of alkali activated material. The PC and CKD were supplied by the Qatar National Cement Company (QNCC). The PC complies with the requirements of the QCS 2014 and BS EN 197-1 (2011), minimum grade of 42.5.



Figure 5-1 Solid binder materials used for the development of concrete blocks

The aggregate materials used for the block production are washed sand and recycled concrete aggregate (RCA) as fine and coarse aggregates, respectively (Figure 5-2). The washed sand was supplied by QNCC and the RCA was supplied by Qatar Primary Materials Company (QPMC). The washed sand had an apparent particle density of 2.69 gm/cm^3 and water absorption of 1.1%. The RCA had an apparent particle density 2.74 gm/cm^3 and water absorption of 3.8%. The gradings of washed sand and RCA are shown in Figure 5-3. The washed sand grading was between 0-5 mm and the RCA grading was between 5-10 mm.

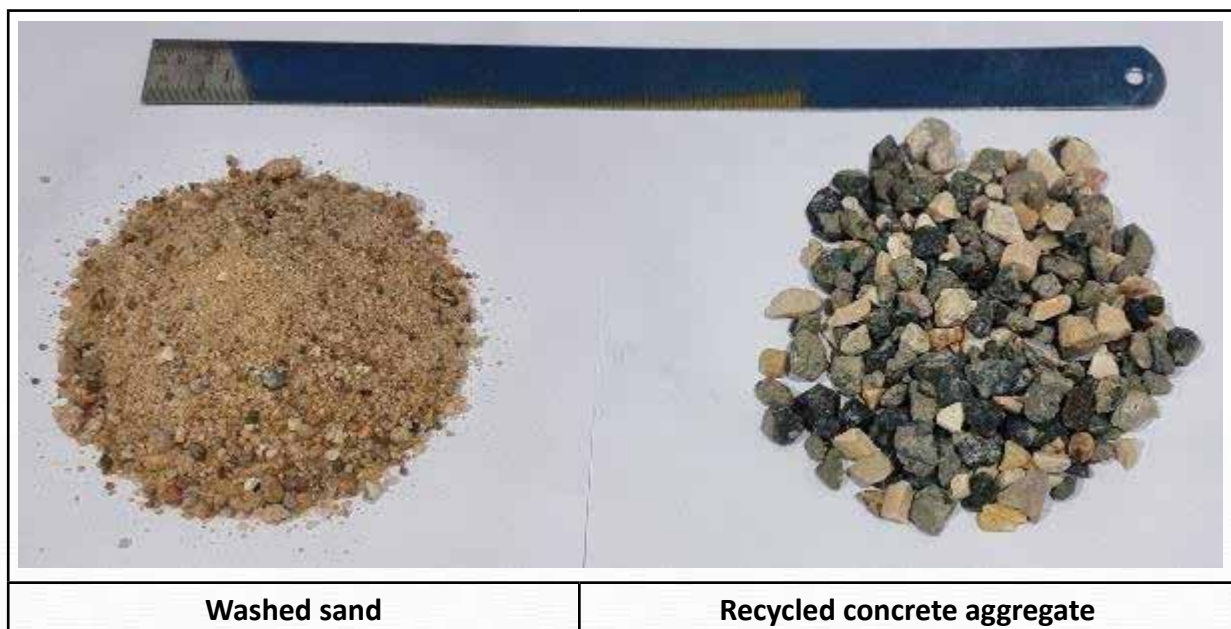


Figure 5-2 Aggregate materials used for the production of concrete blocks

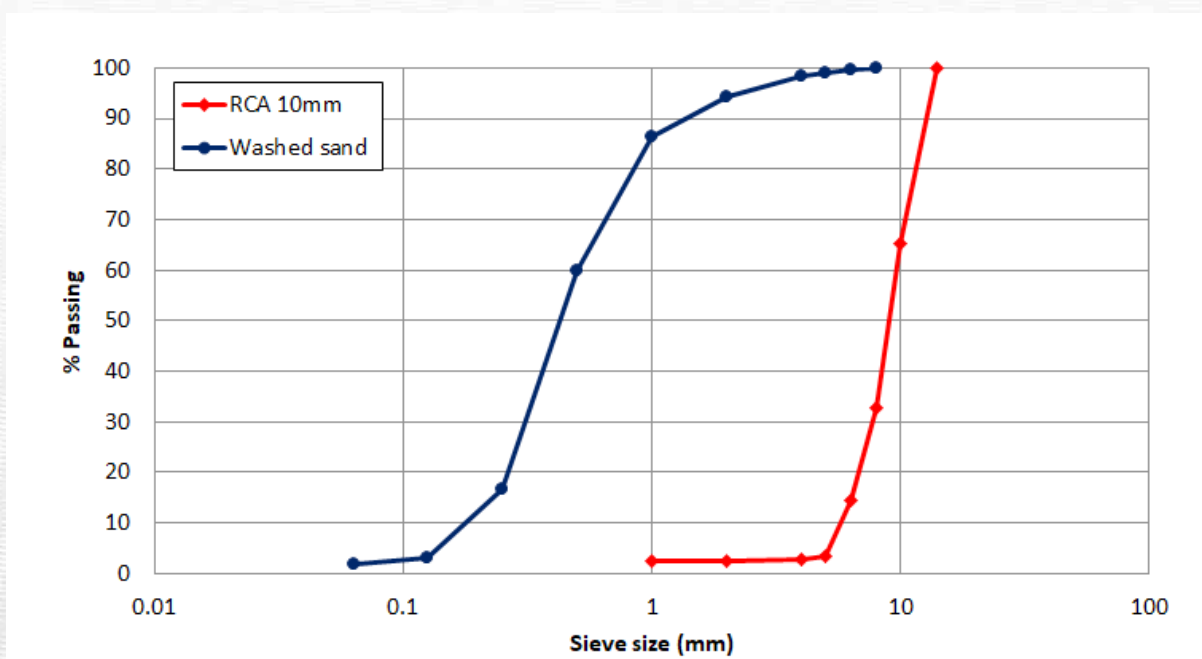


Figure 5-3 Grading curves of washed sand and RCA

A total of nine mixtures were used for the development of hollow concrete blocks. Hollow blocks are generally used in non-load bearing walls and have the typical composition of 270 kg/m³ PC, 1850 kg/m³ of coarse aggregate 5-10mm, 900 kg/m³ of fine aggregate 0-5mm, 150 kg/m³ water, and a chemical admixture (superplasticiser, SS) of 5 l/m³. For the laboratory development of concrete block mixtures, the ratio of binder to fine aggregate to coarse aggregate was maintained at 1: 3: 6 (by weight) with a binder content of 270 kg/m³. Table 5-1 provides the mix proportions of the different mixtures. The control mixture was made with 100% PC binder, whereas the other eight mixtures were made with 50-100% SSA. The fine aggregate (FA), coarse aggregate (CA), and superplasticiser dosage (SS) were fixed for all mixtures. The mixtures were relatively dry, to enable immediate demoulding, with a liquid to binder ratio of 0.5, except for the alkali-activated mixtures of 0.55. The lime used was hydrated lime at 20% by the binder weight. Three different dosages of CKD were used to activate the SSA at 5%, 10%, and 20% by total weight of binder.

Table 5-1 Mixtures of the concrete blocks made with SSA waste material

Mix	SSA	PC	CKD	Lime	GGBS	Alkalis	FA	CA	Liquid/ binder	SS
PC	-	1	-	-	-	-	3	6	0.50	2%
SSA	1	-	-	-	-	-	3	6	0.50	2%
SSA-PC	0.75	0.25	-	-	-	-	3	6	0.50	2%
SSA-Alkali	1	-	-	-	-	6%N, 1.5Ms	3	6	0.55	2%
SSA-GGBS Alkali	0.5	-	-	-	0.5	6%N, 1.5Ms	3	6	0.55	2%
SSA-Lime	0.8	-	-	0.2	-	-	3	6	0.50	2%
SSA-5CKD	0.95	-	0.05	-	-	-	3	6	0.50	2%
SSA-10CKD	0.9	-	0.1	-	-	-	3	6	0.50	2%
SSA-20CKD	0.8	-	0.2	-	-	-	3	6	0.50	2%

The mortar materials were mixed mechanically, using an electrical mixer. The solid binder and mixing liquid were mixed initially for 30 seconds before adding the SS followed by the fine and coarse aggregate. The washed sand was already supplied in saturated surface-dry (SSD) due to its washing in the plant. The RCA was also saturated before mixing and used as SSD. The concrete ingredients were mixed for additional 90 seconds, to have a total mixing time of 2 minutes. The concrete mixtures were relatively dry, due to the low liquid to binder ratio and high aggregate content, to simulate the dry mixtures generally used to produce concrete blocks. Figure 5-4 shows the different fresh concrete mixtures before moulding. The PC concrete appeared with a grey colour similar to the PC colour. The SSA mixtures appeared darker than PC in colours due to the darker colour of SSA compared to PC. The concrete mixtures looked homogeneous with the binder coating the fine and coarse aggregate particles.

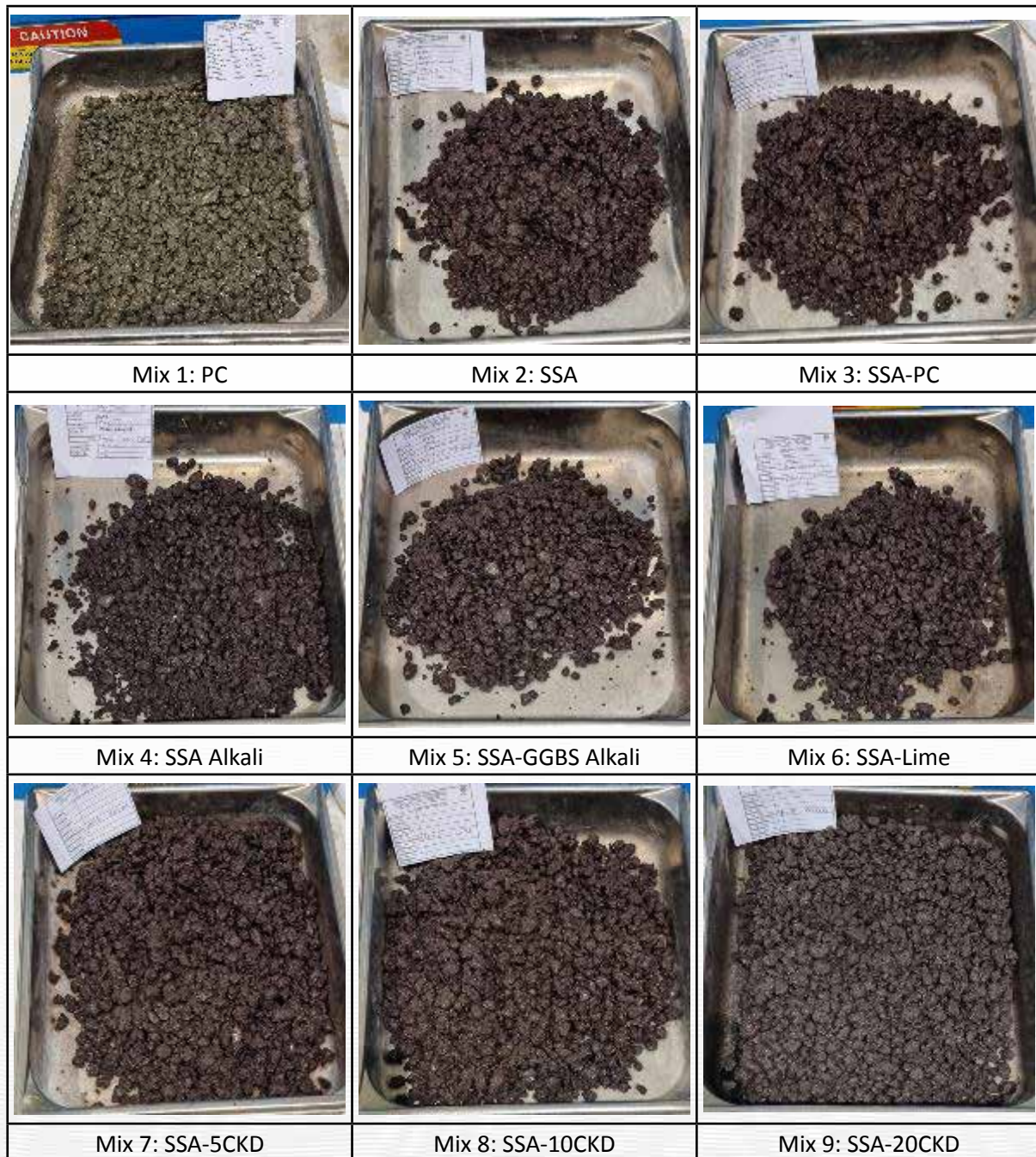


Figure 5-4 Dry concrete mixtures for the production of concrete blocks

The fresh concrete was cast into steel moulds of the dimensions of 50x50x50 mm. The fresh concrete was compacted, using a vibrating hammer, in 2 layers with 10 seconds compaction for each layer as shown in Figure 4-1. The compacted cubes were immediately demoulded after compaction, transferred onto a wooden plate, and cured in a controlled chamber at $40\pm 2^{\circ}\text{C}$ and 80% relative humidity (RH) for 24 hours. On the following day, the concrete cubes were demoulded and cured at $25\pm 2^{\circ}\text{C}$ and 65% RH until testing. The curing adopted in the laboratory development simulates current practice for the production of concrete blocks.



Figure 5-5 Compaction of the concrete cubes using a vibrating hammer

For the laboratory development of concrete block mixtures, the ratio of binder to fine aggregate to coarse aggregate was maintained at 1: 3: 6 (by weight) with a binder content of 270 kg/m^3 , and water to binder ratio of 0.5. Table 5-1 provides the binder proportions of the different mixtures, together with the results of compressive strength and water absorption. The control mixture was made with 100% PC binder, whereas the other mixtures were made with 25-90% SSA. Washed sand was used as fine aggregate (FA), whereas recycled aggregate was used as coarse aggregate (CA). A superplasticiser dosage of 2% was used for all mixtures. The mixtures were relatively dry, to enable immediate demoulding after compaction.

5.1.2 Testing, results, and compliance

The QCS 2014 specifies requirements for the ingredient materials, cement and aggregate, as well as the final product of concrete blocks. The QCS 2014 specifies a minimum average compressive strength of 10.4 MPa for load bearing walls, 7.0 MPa for external non-load bearing walls, and 4.0 MPa for internal non-load bearing walls. Current practice in Qatar is to use 7.0 MPa for both external and internal non-load bearing walls, which was considered in this investigation for the utilisation of SSA products. The QCS also specifies a maximum average water absorption of 7.0 % as per the CML Method 9-97 (1997). The method is based on oven drying the blocks for 72 hours at 105°C to remove the free water followed by immersion in water for 30 min. The average strength and water absorption values shall be based on the testing of 3 individual blocks for each test.

Figure 56 shows the 7-day cured cubes before testing for compressive strength and water absorption for mixtures of SSA-25%PC and SSA-10% CKD. The cubes appeared in good condition with minor damage of the aggregate particles on the surface, shown in grey or white colour on the cube surface in Figure 5-6. The slight aggregate damage is probably caused by the effect of vibrating compaction, with increased stresses on the surface, but it is unlikely to impact the bulk properties of the cubes.

The average compressive strength and water absorption results are given in Table 5-2, with each value representing of the average of 3 tested cubes. Compressive strength testing was conducted at 2 and 7 days, whereas water absorption testing was carried out at 7 days.



Figure 5-6 Cured cubes after 7 days, SSA-PC (left) and SSA-10CKD (right)

Table 5-2 Properties of concrete mixtures for blocks

Mix	2-day Compressive Strength (MPa)	7-day Compressive Strength (MPa)	7-day Water Absorption (%)
PC	22.9	23.0	3.5
SSA	6.3	6.1	5.2
SSA-PC	8.1	9.3	5.1
SSA Alkali	3.3	3.8	4.7
SSA-GGBS Alkali	2.6	2.7	4.7
SSA-Lime	4.8	5.8	5.6
SSA-5CKD	5.2	7.4	5.1
SSA-10CKD	6.5	7.5	5.1
SSA-20CKD	5.6	6.4	5.0

The compressive strength results are given in Table 5-2 and the 7-day results are plotted in Figure 5-7 together with the QCS 2014 minimum strength requirement of 7.0 MPa. The 100% PC mixture gave compressive strength values of 22.9 and 23.0 MPa at 2 and 7 days, respectively. The effect of initial heat curing at 40°C is reflected in the early high strength of 22.9 MPa at 2 days followed by almost no further strength development at 7 days to reach similar strength of 23.0 MPa. Elevated heat-curing temperature is known to promote rapid cement hydration and enhance the early strength of concrete but adversely affect the late strength development. The 100% SSA mixture exhibited similar performance to the PC concrete in terms of strength development, but at lower strength values. The 7-day compressive strength of the SSA mixture was 6.1 MPa, 27% of the PC mixture. Blending 75% SSA with 25% PC results in relatively high strength of 8.1 MPa at 2 days, with further strength development

at 7 days to achieve 9.3 MPa, 40% of the PC mixture. The continuous strength development at 7 day indicates the possibility of additional hydration products from the blending of PC and SSA.

The alkali activated mixtures were prepared with the addition of alkali solutions. Sodium hydroxide solution and sodium silicate were preblended to give a total alkali content 6% (Na_2O) and a silicate modulus value (M_s) of 1.5. These values were found to provide the optimum performance of the alkali-activated SSA mixtures (Hassan et al., 2022). The alkali-activated SSA and SSA-GGBS exhibited the lowest compressive strength values within the developed mixtures. The 7-day strength of the alkali-activated SSA and SSA-GGBS were 3.8 and 2.7 MPa, respectively.

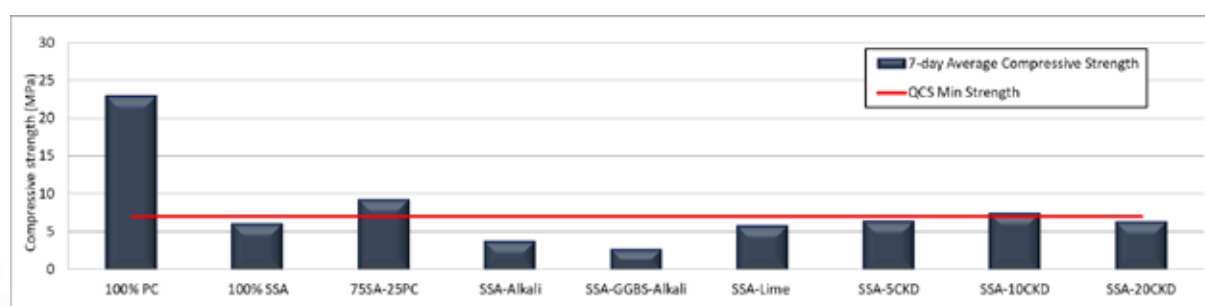


Figure 5-7 Compressive strength of the concrete mixtures at 7 days



Figure 5-8 Water absorption of the concrete mixtures at 7 days

The use of 20% hydrated lime to activate SSA was found to delay the early strength but contributes more to the late strength development (Hassan et al., 2022). The results in Table 5-2 and Figure 5-7 show that the SSA-Lime mixture attained 5.8 MPa at 7 days, 25% of the PC mixture. CKD was used to activate the SSA at different levels of 5%, 10%, and 20% by weight of binder. The best strength results were found for the SSA-10CKD, which gave a 7-day strength of 7.5 MPa, 33% of the PC mixture. Similar to the SSA-PC mixture, the SSA-CKD mixtures exhibited strength development from 2 to 7 days, which may indicate further hydration between the cement hydration products and SSA particles.

The results of 7-day water absorption of the different mixtures are given in Table 5-2 and graphically presented in Figure 5-8. All the mixtures gave values of less than 7%, the maximum permissible limit by the QCS 2014 for use in concrete blocks.

Based on the obtained results, the SSA mixtures activated with PC and CKD are the only mixture satisfying the strength requirement of the QCS 2014 for use in concrete blocks, whereas all the investigated mixtures satisfied the water absorption requirement. Mixtures of SSA-PC and SSA-10CKD are therefore selected for the full-scale production of the concrete blocks.

5.1.3 Optimised SSA Mixture

SSA was used for the development of dry concrete mixtures to simulate the production of concrete blocks. The SSA was used as the sole binder and activated with PC, CKD, lime and alkalis. The dry concrete mixtures were compacted using a vibrating hammer and initially cured at elevated temperature of 40°C to match current production.

SSA mixtures activated with PC (75% SSA + 25% PC) and CKD (90% SSA + 10% CKD) achieved 7-day average compressive strength and water absorption values that satisfy the QCS requirements for concrete blocks. Unlike the PC control mixture, the SSA exhibited strength development between 2 and 7 days, indicating the development of further reactions between SSA and alkali cement hydration products. The alkali activated SSA with sodium hydroxide and sodium silicate solutions, N of 6% and Ms of 1.5, gave the least strength values. The SSA-Lime activated concrete exhibited relatively low strength but is expected to attain more strength with age.

All the developed mixtures satisfied the water absorption requirement of the QCS 2014, with average values lower than the maximum specified value of 7%. The mixture of PC (75% SSA + 25% PC) will be used for the full-scale production of concrete blocks in the next stage.

The QCS 2014 allows the use of recycled materials in the production of concrete blocks as follows:

- Up to 50% recycled aggregate in the production of blocks with an average compressive strength ≥ 7.0 MPa.
- Up to 100% recycled aggregate in the production of blocks with an average compressive strength < 7.0 MPa.

The QCS 2014 also limits the aggregate sulfate (acid soluble sulfate) and chloride contents to 0.8 % and 0.2 % by weight of aggregate, respectively.

It is important to highlight that the QCS 2014 limits the use of binder in concrete blocks to PC, unless the blocks are used below the ground level where sulfate-resistance PC shall be used. The successful development of new SSA concrete blocks would therefore require amendment of the QCS 2014 for implementation in practice. Recommendations for updating the QCS 2014 are considered within the scope of this project to support the implementation of the newly developed green construction products.

5.2 Foam Concrete

Foam concrete (FC) is a cementitious mortar in which air-voids are entrapped in the mortar by suitable foaming agent. FC has many advantages compared to conventional concrete in terms of high flowability, lightweight, controlled low strength, minimal consumption of aggregate, and good thermal insulation properties. FC can be produced with a range density from 400 to 1900 kg/m³ with proper controlling amount of foam. SSA was used in this section, together with CKD, for the production of foamed concrete and their properties were compared to that of PC foamed concrete and compliance with national specifications.

5.2.1 Materials and Mixtures

SSA and CKD were used as solid waste materials for the replacement of PC in the production of controlled low strength foamed concrete (FC). FC is a lightweight mixture composed of a cementitious binder, fine aggregate, water and a stable preformed foam. A synthetic foam was used, which is based on sodium laureth sulfate, and supplied by CHRYSO Gulf LLC. The foam is as a matrix of stable, evenly distributed air bubbles, for the generation of stabilized air-entrainment during the production of low-density concrete and mortar. A high-performance superplasticiser (SP), based on polycarboxylic polymers, was supplied by Don Construction Products Qatar and used to enhance the workability of flowable concrete.

Three FC mortar mixtures were considered in this investigation, with the compositions given in Table 5-3. PC was used for the production of the control FC mixture with a cement content of 235 kg/m³. SSA and CKD, with the weight ratio of 80% to 20%, were used for the full replacement of PC in the second FC mixtures. The third FC mixture was also made with 80% SSA and 20% PC, as an activator to the SSA. The sand and water contents were fixed for all mixtures to have a water to binder ratio of 1.0.

Table 5-3 Mortar mix proportions of foamed concrete (kg/m³)

Mix	Binder			Sand	w/binder	(SP (l/m ³	Foam
	PC	SSA	CKD				
Control-PC	235	-	-	1530	1.0	2.1	1.93
80SSA-CKD	-	188	47	1530	1.0	4.0	1.5
80SSA-PC	47	188	-	1530	1.0	2.6	1.6

The mixtures were designed to have density values in the range of 1500 to 1600 kg/m³, through the use of SP and foaming agent. The SP dosage varied for the different mixture between 2.1 and 4.0 l/m³, with the lowest dosage for the PC and the highest value for the SSA-CKD mixture. In contrast the highest foam content of 1.93 kg/m³ was associated with the PC mixture, and the lowest foam content of 1.5 kg/m³ was found with the SSA-CKD mixture. It seems both SP and foam contributes to the air content of FC as increasing the SP dosage results in lower foam content to achieve similar density. Figure 5-9 shows the preformed foam used in the production of FC mixtures



Figure 5-9 Synthetic preformed foam

The FC mixtures were prepared by initially mixing sand and binder with water for approximately 1 minute. The SP was added to the mortar mixture and mixed again for another minute. Finally, the foam was added to the mixture with varying content to achieve the desired density of 1500 to 1600 kg/m³. Figure 5-10 shows the adding of foam to the mortar mixture (left photo) and finished foamed concrete mixture (right photo). The FC mixtures showed high stability with good distribution of the air bubbles and no evidence of segregation or bleeding.



Figure 5-10 Adding foam to mortar (left) and mixed foamed concrete (left)

The fresh FC mixtures were tested for wet density, as per BS EN BS EN 12350-6 (2019), air content to BS EN 12350-7 (2019), slump to BS EN 12350-2 (2019) and flow table to BS EN 12350-5 (2019). The wet density and air content testing are shown in Figure 5-11, whereas Figure 5-12 shows the workability of the fresh FC mixture. As shown in Figure 5-12, the FC mixture is a highly workable free flowing concrete that levels under its own weight without compaction. Concrete cubes of 150mm, by pouring the FC without compact and left to cure in their moulds for 24 hours at 25°C. The cubes were demoulded on the following day and cured in sealed plastic bags at the same temperature of 25°C until testing.



Figure 5-11 Wet density (left) and air content (right) testing



Figure 5-12 Workability of foamed concrete



Figure 5-13 Cube preparation for the different FC mixtures

5.2.2 Results of FC testing

The fresh FC properties of wet density, air content, slump, and flow table are presented in Table 5-4. The density values were similar for all mixtures, within the range of 1576 and 1586 kg/m³, within the desired range of 1500 to 1600 kg/m³. The air content results were also similar for the mixtures of 25% for the control PC and SSA-CKD and a slightly higher value of 26% for the SSA-PC mixture. The flowability of the FC mixture is reflected in the workability results of slump and flow table. The mixtures exhibited similar slump values between 260 to 270 mm. A slight variation was obtained in the flow table results with the control-PC exhibiting the highest value of 750 mm and the SSA mixtures giving lower values of 560 and 610mm. Nevertheless, all the FC mixtures were highly flowable with high air content and stability, with no segregation or bleeding.

Table 5-4 Properties of the fresh FC mixtures

Mix	Wet density (kg/m ³)	Air content (%)	Slump (mm)	Flow table (mm)
Control-PC	1586	25	270	750
80SSA-CKD	1576	25	260	560
80SSA-PC	1581	26	270	610

The cubes were cured in sealed plastic bags at 25°C and tested for compressive strength, as per BS EN 12390-3 (2002), at the ages of 3, 7, and 28 days. Three cubes were used for each testing age and the average values are reported in Table 5-5 and Figure 5-14. Table 5-5 also presents the retained strength, determined from the ratio of the average compressive strength after immersion in water two weeks to the average 28-day strength. The retained strength is used as a durability indicator test to assess the resistance of low-strength concrete to water and a value of 80% and greater indicating good durability and resistance to water damage.

Table 5-5 Compressive strength (MPa) and retained strength of FC mixtures

Mix	Control-PC	80SSA-CKD	80SSA-PC
3 days	2.0	-	-
7 days	2.4	-	0.3
28 days	4.3	0.5	0.7
Retained strength (%)	97%	89%	84%
Density (kg/m ³)	1691	1601	1472

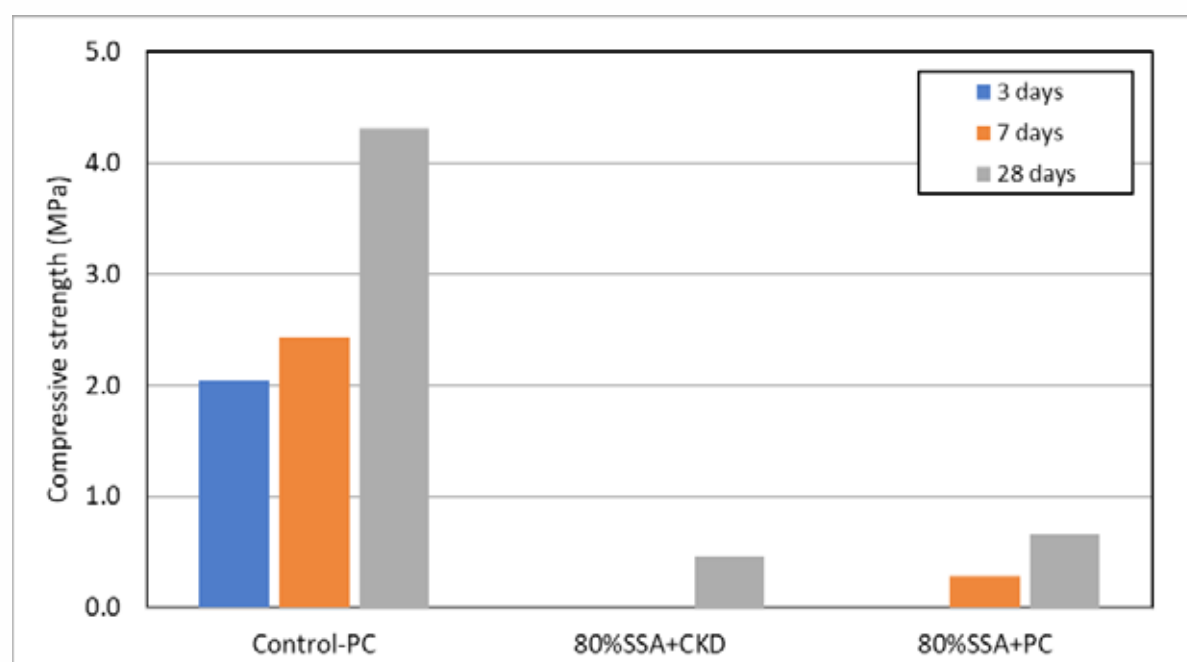


Figure 5-14 Compressive strength of foamed concrete (80% SSA)

The QCS 2014 specifies foamed concrete for backfill applications to be flowable with a 28-day strength of 5.0 MPa and a density of between 1600 to 2000 kg/m³. The results in Table 5-5 show that none of the FC mixtures achieved the QCS strength requirements. The PC control mixture showed a slow strength development at 3 and 7 days, and achieved an average 28-day strength of 4.3 MPa, lower than the QCS specified value. The 80%SSA+CKD was hardened within 24 hours, but did not achieve any measurable compressive strength up to 7 days. The 28-day compressive strength was 0.5 MPa. The SSA activated with PC (80% SSA + 20% PC) also hardened after 24 hours and did not achieve strength at 3 days. The compressive strength results after 7 and 28 days were 0.3 and 0.7 MPa, respectively.

Whilst the FC mixtures failed to achieve the QCS strength requirement, the SSA should very low strength values compared to the control PC mixtures. FC are generally produced with a range of densities (500-2000 kg/m³) and strength values of 1.0 to 5.0 MPa (DfT, 2019; HK Highways Department, 2019), which are less onerous than the QCS 2014. The FC mixtures exhibited retained strength values greater than 80% and indicating good resistance to water damage. The density values ranged between 1472 and 1691 kg/m³, with the highest value for the control-PC and the lowest for the 80SSA+PC.

Further work was conducted on the development of FC mixtures to increase the strength at least greater than 1.0 MPa to satisfy the requirements of international standards while utilising a large proportion of SSA.

5.2.3 Improved SSA FC mixtures

Improved FC mixtures were developed by increasing the binder content and reducing the amount of mixing water. Table 5-6 gives the mix composition of the improved FC mixtures. The binder content has increased to 260 kg/m³ and the w/binder ratio is reduced to 0.88. The amount of SSA was kept at 50% and activated by either PC or CKD. A 3rd mix made with 50% PC + 50% CKD for comparison. The sand and SP contents were kept constant, and the amount of foam varied to achieved the desired density of 1500 to 1600 kg/m³. Table 5-6 also gives the similar fresh density of the FC mixtures, ranging between 1576 and 1586 kg/m³. The 50% PC – 50% SSA mixture required the least foam content of 1.40 kg/m³ whereas the 50% PC – 50% CKD consumed the highest foam content of 1.82 kg/m³ to achieve similar density values.

Table 5-6 Mix proportions of improved SSA FC mixtures (kg/m³)

Mix	Binder			Sand	w/binder	SP (l/m ³)	Foam	Fresh density (kg/m ³)
	PC	SSA	CKD					
PC-50SSA	130	130	-	1515	0.88	4.3	1.40	1586
CKD-50SSA	-	130	130	1515	0.88	4.3	1.73	1576
PC-50CKD	130	-	130	1515	0.88	4.3	1.82	1581

The fresh and hardened properties of the FC mixtures were also investigated, and the results are presented in Table 5-7. The FC mixtures were flowable with slump values of 260 to 270 mm and flow table values of 520 to 610 mm. The best workability was found for the PC – 50SSA. The FC mixtures exhibited similar high air content values between 23 % and 25 %. The PC activated mixtures of PC–50SSA and PC-50CKD mixture exhibited the highest compressive strength to reach 2.4 MPa at 28 days, compared to 0.7 MPa for the SSA mixture activated with 50% CKD (Mix: CKD-50SSA). The density of FC at the age of 28 days ranged from 1639 to 1669 kg/m³.

Table 5-7 Fresh and hardened properties of improved FC mixtures

Mix	PC-50SSA	CKD-50SSA	PC-50CKD
Slump (mm)	270	270	260
Flow table (mm)	610	570	520
Air content (%)	25	23	25
3-day strength (MPa)	0.86	-	1.02
7-day strength (MPa)	1.4	-	1.4
28-day strength (MPa)	2.4	0.7	2.4
28-day density (kg/m ³)	1669	1639	1657

The above results show that increasing the binder content has positive effect on the strength of FC mixtures, and also PC was the best activator for such mixtures.

5.2.4 Optimised FC mixtures

Optimised FC mixtures are developed through the use of PC as an activator for SSA and slightly reduce the foam content to achieve optimised strength results. Table 5-8 presents the mix composition of the optimised FC mixtures. The control mixture was made with 100% PC, whereas the SSA mixtures were made by replacing 50% and 25% of PC. The sand content, superplasticiser dosage, and water/binder were maintained the same for all mixtures at 260 kg/m³, 2.5 l/m³, and 0.88, respectively. The amount of foam was reduced between 1.2 to 1.4 kg/m³ to enhance the compressive strength of FC mixtures.

Table 5-8 Mortar mix proportions of optimised foamed concrete (kg/m³)

Mix	Binder		Sand	w/binder	SP (l/m ³)	Foam
	PC	SSA				
Control-100PC	260	-	1530	0.88	2.5	1.4
SSA-50PC	130	130	1530	0.88	2.5	1.3
SSA-75PC	195	65	1530	0.88	2.5	1.2

Before the addition of foam, mortar cubes were cast and used for comparing the compressive strength of mixtures with and without foam.

Table 5-9 Fresh properties of optimised FC mixtures

Mix	With Foam				Without Foam	
	Wet density (kg/m ³)	Air content (%)	Slump (mm)	Flow table (mm)	Wet density (kg/m ³)	Air content (%)
Control-100PC	1760	20	270	660	2080	7.5
SSA-50PC	1730	20	260	550	2070	8.0
SSA-75PC	1610	25	270	590	2080	8.0

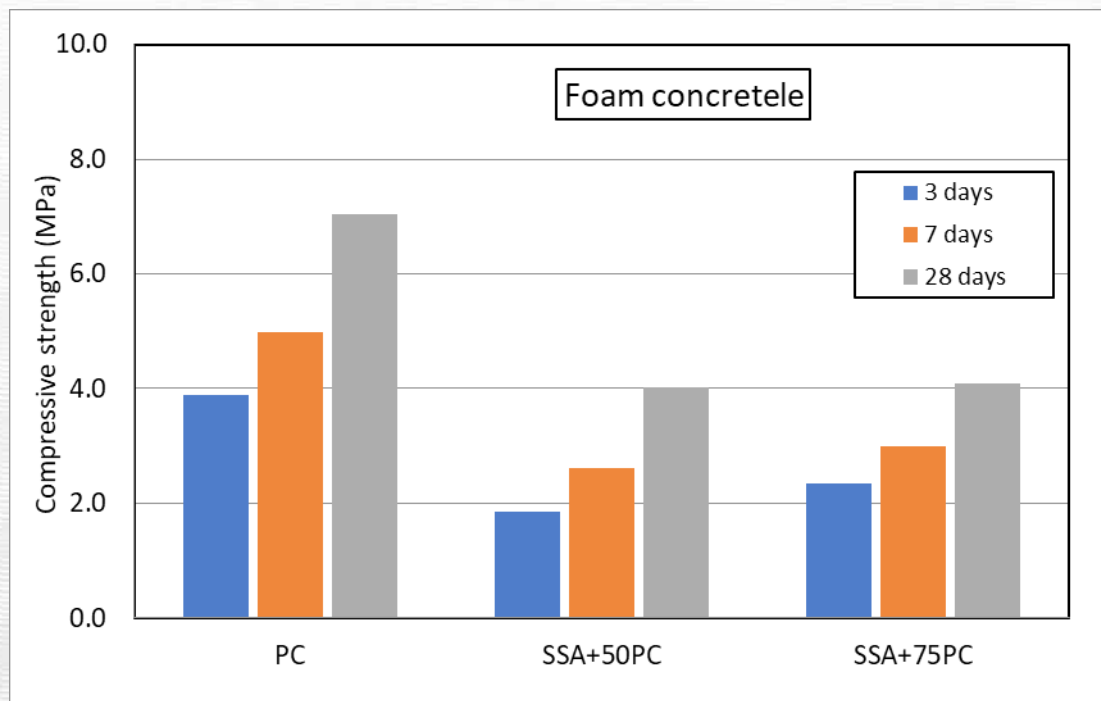
The fresh properties of optimised FC mixtures are given in Table 5-9 for the wet density, air content, slump and flow table. Table 5-9 also presents the wet density and air content of the same mortar mixture before the addition of foam. The wet density and air content values of the mortar mixtures without foam ranged between 2070-2080 kg/m³ and 7.5-8.0 %, respectively. The addition of foam reduced the wet density range to 1610-1760 kg/m³ and increased the range of air content to 20-25%.

The high flowability of the FC mixture is shown in the workability results of slump and flow table given in Table 5-9. The mixtures exhibited similar slump values between 260 to 270 mm. A slight variation was obtained in the flow table results with the control-PC exhibiting the highest value of 660 mm and the SSA mixtures giving lower values of 550mm for the SSA-50PC mixture, and 590mm for the SSA-75PC. The flow table results clearly show the effect of SSA on reducing the workability of the FC mixtures. Nevertheless, all the FC mixtures were highly flowable with high air content and stability, with no segregation or bleeding.

Table 5-10 Density and compressive strength of optimised FC mixtures

Mix		Compressive Strength (MPa)			Density (kg/m ³)		
		3 days	7 days	28 days	3 days	7 days	28 days
With Foam	Control-100PC	3.9	5.0	7.1	1806	1809	1836
	SSA-50PC	1.9	2.6	4.0	1726	1732	1725
	SSA-75PC	2.4	3.0	4.1	1574	1577	1567
Without Foam	Control-100PC	8.8	11.2	13.6	2039	2021	2013
	SSA-50PC	5.0	6.9	10.7	1988	2005	2003
	SSA-75PC	8.2	9.8	13.9	2027	2032	2010

The hardened properties of density and compressive strength of the optimised foam concrete and the other mixtures made without foam are given in Table 5-10. The control mixture made with 100% PC achieved compressive strength values of 3.9 MPa at 3 days, 5.0 MPa at 7 days, and 7.1 MPa at 28 days. The FC mixture made with 50% SSA (SSA-50PC) reached 1.9 MPa at 3 days and 4.0 MPa at 28 days, whereas the FC mixture made with 25% SSA (SSA-75PC) achieved slightly higher values of 2.4 MPa at 3 days and 4.1 MPa at 28 days. The results clearly show the possible use of SSA in the production of FC mixture of 4.0 MPa. The 25% SSA mixture (SSA-75PC) exhibited the lowest density values 1567-1577 kg/m³ compared to the PC mixtures with the highest values of 1725-1732 kg/m³.

**Figure 5-15 Compressive strength of optimised FC mixtures**

When comparing the mixture made with foam, Table 5-10 show that the SSA-75PC mixture exhibited similar compressive strength to the Control 100% PC mixture at 3 and 28 days. They also exhibited similar density values ranging between 2010 and 2040 kg/m³. The SSA-50PC mixture showed lower strength and density results compared to the other two mixtures.

Foamed concrete (FC) provides a range of density and strength properties, and has the properties of porousness, light weight, heat preservation, heat insulation, and sound absorption, and it use has received wider interest in Qatar and internationally. The UK Department for Transport DfT (2020) specifies FC for reinstatement works as the material is flowable, self-levelling and does not require compaction when placed. The layer thickness could vary from 150 to 450 mm, and the 7-day strength shall be $C_{1.5/2}$ or $C_{3/4}$ with the lower strength when used as subbase and below. When FC is used for backfilling excavations and trenches under carriageway, the DfT specifies the following strength requirements:

- A minimum cube compressive strength of 4 MPa at 7 days.
- A maximum cube compressive strength of 10 MPa at 7 days.

The results obtained for the optimised SSA mixtures SSA+50PC and SSA+75PC exhibited average 7-day strength values of 2.6 and 3.0 MPa, respectively higher than the UK specified value of 2.0 MPa for cubes. The results clearly show the developed optimised SSA FC mixtures are in compliance with the UK specifications for use in road reinstatement as subbase layer and below.

The Hong Kong Highway Department (2019) specifies lower strength requirement of ≤ 1.0 MPa at 28 days, and not less than 0.3 MPa before the application of the overlying pavement layer. The density shall be between 800 and 1800 kg/m³, slump flow ≥ 200 mm without segregation, and setting time between 8 and 24 hours. The FC developed in this report complies with the strength and density requirement of the HK Highway Department.

The low strength of FC provides consistent foundation support, much better than unbound backfill materials to support the pavement structure, but more importantly allows easy re-excavation. The main advantages associated with the use of FC include less on-site labour and equipment requirements, due to its flowable nature and easy placement with no vibration or compaction, and fast construction speed in terms of delivery of materials and site cleaning.

The QCS 2014 permits the use of FC in backfill applications and specifies (Section 8: Part 2) specifies a 28-day compressive strength of 5 MPa with a unit density of between 1600 – 2000 kg/m³. There is no requirement for the flowability, and the specified strength is relatively high for easy re-excavation. The optimised FC mixtures in this investigation achieved compressive strength of at least 4.0 MPa at 28 days. It is recommended to update the QCS 2014 to include a range of density and strength for FC for use in the backfill for different road categories of primary, secondary and local roads.

5.3 Cement-bound materials

Cement bound materials (CBMs) are part of hydraulically bound materials (BS EN 14227-1, 2013), defined as a mixture of granular aggregate or soil material mixed with cement or other binders, and compacted at optimum moisture content as a subbase or base layers in pavement construction. The QCS 2014 provides four types of CBMs with varying strength and gradings. The section deals with the use of SSA as a binder, to fully replace Portland cement (PC), in CBM mixtures and the compliance of the developed products with national and international specifications.

5.3.1 Materials and mixtures

CBM mixtures of CBM 1 and CBM 2, as per the QCS 2014, were developed in the laboratories of ReadyMix Qatar. The development was based on fully replacing the PC binder with SSA and other activators and maximizing the use of recycled and local aggregates. The activators used with SSA are hydrated lime and CKD. Details of the CBM mix designs are given in Table 5-11 together with the fresh density values. Two sets of CBM mixtures were developed to include:

- Set 1: CBM1-PC with a binder content of 80 kg/m³, SSA and SSA-Lime with a binder content of 120 kg/m³
- Set 2: CBM 2-PC with a binder content of 120 kg/m³, SSA+10CKD and SSA+20Lime with a binder content of 150 kg/m³

Table 5-11 Mixtures of the CBM mixtures (kg/m³)

Mix	SSA	PC	Lime	CKD	EW (5-40)	RCA (5-20)	Sand	water/ binder	SS	Density (kg/m ³)
CBM1-PC	-	80	-		1100	400	690	1.5	1.4	2390
SSA	120	-	-		1100	400	690	1.5	2.0	2393
SSA-Lime	96	-	24		1100	400	690	1.5	2.0	2400
CBM2-PC	-	120	-		1070	410	710	0.92	2.0	2420
SSA+10CKD	135	-	-	15	1070	410	710	0.8	2.0	2013
SSA+20Lime	120		30		1070	410	710	0.8	2.0	2048

The PC was supplied by the Qatar National Cement Company (QNCC) and complies with the requirements of the QCS 2014 and BS EN 197-1 (2011), minimum grade of 42.5. The CKD was also supplied by QNCC. The coarse aggregate consisted of approximately 75% excavation waste (EW) and 25% recycled concrete aggregate (RCA), supplied by Qatar Primary Materials Company (QPMC). Washed sand from QNCC was

used as fine aggregate. The amount water/binder varied for the different mixtures between 1.5 for the mixture with low binder content to 0.8 for the mixtures with high binder content. A superplasticizer of synthetic polymer was used at the dosage of 1.4 or 2.0 l/m³, as given in Table 5-11. A lower dosage was used for the lowest binder content of 80 kg/m³ for the CBM1-PC mixture.

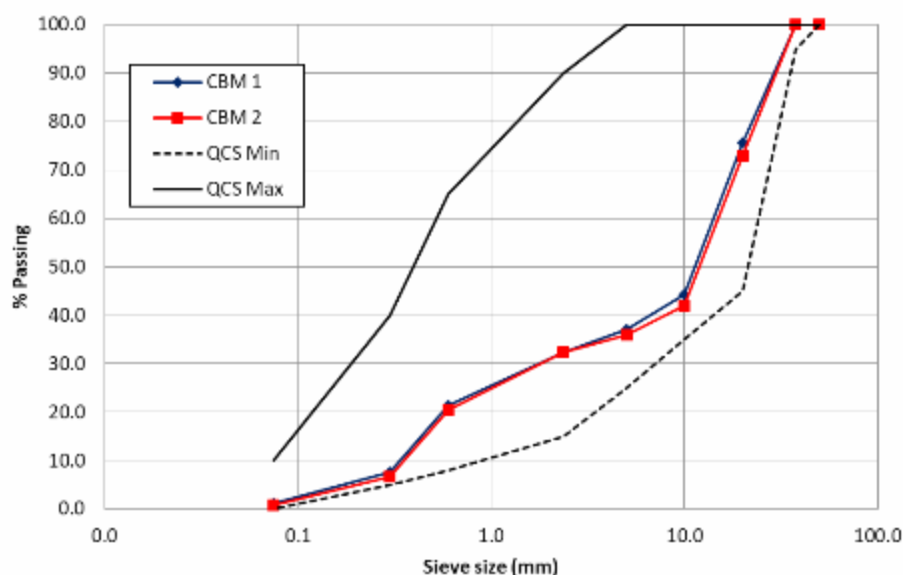


Figure 5-16 Grading of CBM mixtures with QCS 2014 limits

The grading curves of CBM 1 and CBM 2 mixtures, together with the QCS 2014 grading envelope for CBM 2 are presented in Figure 5-16. The QCS 2014 specifies that the CBM 1 grading shall be finer than the QCS Min given in Figure 5-16, and for CBM 2 to be within the provided grading envelope. The results show that both CBM 1 and CBM 2 have almost the same grading, and falling within the specified grading envelope in the QCS 2014.

The CBM mixtures were prepared by initially mixing the aggregate with part of the mixing water, and left for 2 minutes to ensure the aggregate is surface saturated before adding the binder. The PC or SSA binders were then added to the mixer and blended with the aggregate. The remaining mixing water was added followed by the superplasticizer and mixing continued for an additional 2 minutes to ensure consistent mixtures. Four CBM mixtures were prepared, as shown in Figure 5-17. More consistent mixtures were observed for the CBM mixtures with the highest binder content of 150 kg/m³.

After mixing, the fresh CBM mixtures were tested for fresh density following the procedure of BS EN 12350-6 (2019), and as shown in Figure 5-18. The fresh density was determined by weighing a specific container, of known volume, before and after filling with CBM materials, and the weight difference was used to report the CBM density. The density values ranged between 2013 and 2420 kg/m³, with the

lowest values for the SSA mixtures with highest binder content. The CBM materials were then cast into cube moulds (150mm) and compacted in two layers using a vibrating hammer following the procedure described in BS EN 13286-51 (2004). Figure 5-19 shows the compaction and curing of the CBM cubes. The surface of the cast cubes was levelled and covered with wet hessian and polyethylene sheets overnight. The cubes were kept outdoors in the month of February with the average daily temperature between 20 and 30 °C.

On the following day, the cube specimens were removed from moulds and cured in sealed plastic bags until required for testing at 3, 7, and 28 days. Sixteen cubes were prepared for each mix. The cubes were tested for compressive strength as per BS EN 12390-3 (2019) at the age of 3, 7, and 28 days. Three cubes were tested after immersion in water for 2 weeks to assess their durability performance as specified in the QCS 2014.



Figure 5-17 CBM mixtures



Figure 5-18 Fresh density testing of CBM mixtures



Figure 5-19 Compaction and curing of CBM cubes

5.3.2 CBM results

A summary of the cube compressive strength results is given in Table 5-12 for the different CBM mixtures. The QCS 2014 specifies a minimum average 7-day compressive strength for CBM 1 of 4.5 MPa, with the strength of each individual cubes not less than 2.5 MPa. For CBM 2, the minimum average 7-day compressive strength is 7.0 MPa, with the strength of each individual cubes not less than 4.5 MPa. The QCS also specifies a durability requirement after immersion of the CBM cubes in water. The average compressive strength after immersion shall not be less than 80% of the average compressive strength in dry and sealed conditions. After water immersion, the cube specimens shall not show any signs of cracking or swelling.

Table 5-12 Properties of CBM mixtures

Mix	Comp. strength (MPa)			Density (kg/m ³)			Strength after immersion (MPa)	Retained Strength (%)
	3d	7d	28d	3d	7d	28d		
CBM1-PC	4.1	4.7	7.1	2297	2330	2310	6.9	97%
SSA	1.0	0.9	0.9	2258	2197	2160	1.0	111%
SSA-Lime	1.0	2.0	4.1	2278	2276	2242	3.5	87%
CBM2-PC	13.7	16.8	21.2	2385	2405	2414	19.9	94%
SSA+10CKD	1.4	2.7	4.6	2294	2222	2151	4.2	91%
SSA+20Lime	1.3	2.1	3.9	2242	2218	2187	3.7	94%

Table 5-12 gives the compressive strength and density values at the different testing ages of 3, 7, and 28 days, together with the strength values after 2 weeks of immersion in water and percentage of retained strength.

For the first set of CBM mixtures (CBM1-PC, SSA and SSA-Lime) the compressive strength results up to 28 days are shown in Figure 5-20. The CBM 1-PC, with a binder content of 80 kg/m³, gave a 7-day average strength of 4.7 MPa. The SSA CBM mixture made with 120 kg/m³ binder exhibited low compressive strength values, a maximum of 1.0 MPa at the different testing ages of 3, 7, and 28 days. The retained strength after immersion was greater than 100%. Blending the SSA with 20% lime resulted in improved compressive strength up to 4.1 MPa at 28 days, lower than the minimum specified value of 4.5 MPa. The retained strength was 87% exceeding the minimum requirement of 80% and indicating good durability of the SSA-CBM mixtures.

The compressive strength of Set 2 CBM mixtures are presented in Figure 5-21. The CBM2-PC mixture, with 120 kg/m³ binder, exhibited the highest compressive strength values of 16.8 MPa at 7 days and 21.2 MPa at 28 days. These values are relatively high for CBM subbase materials that may cause wide cracks that may reflect through the asphalt pavement. The other SSA mixtures made with a total binder content of 150 kg/m³ gave much lower strength values that are more suitable for use in subbase in road construction. The SSA+10CKD mixture exhibited an average 7-day compressive strength of 2.7 MPa, and 4.6 MPa at 28 days. Slightly lower values are given by the SSA+20Lime of 2.1 MPa at 7 days and 3.9 MPa at 28 days.

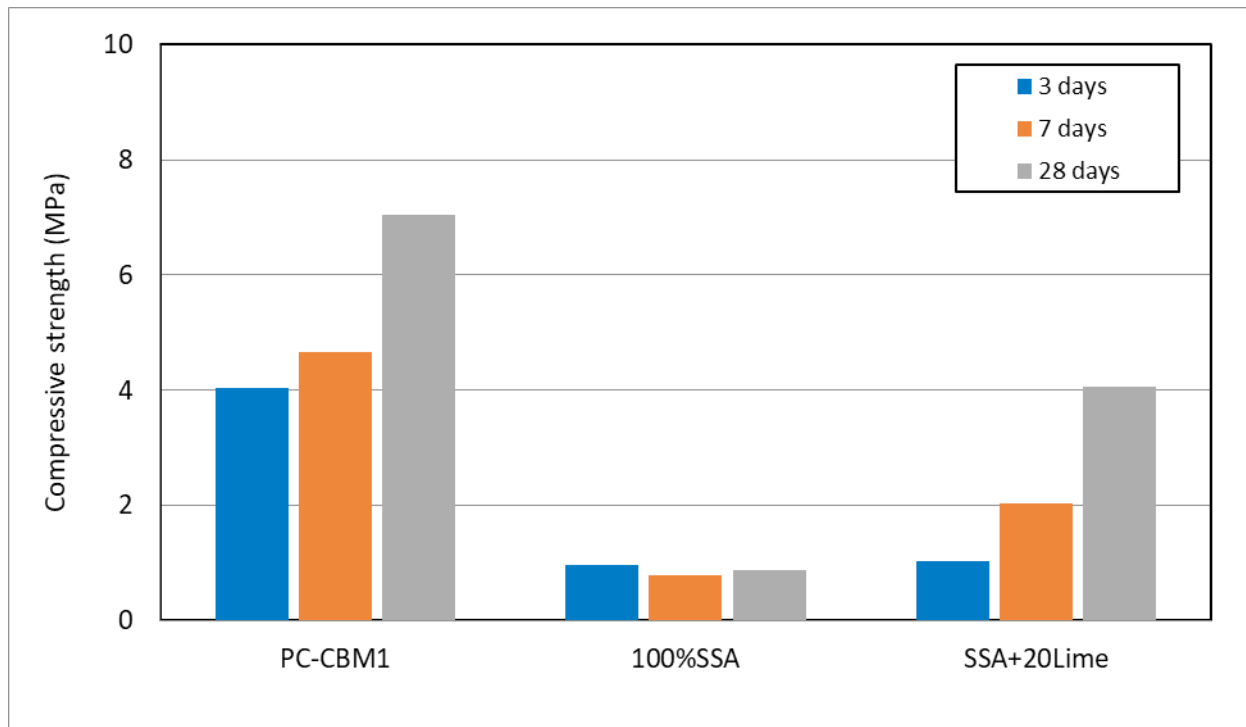


Figure 5-20 Compressive strength of CBM mixtures (Set 1)

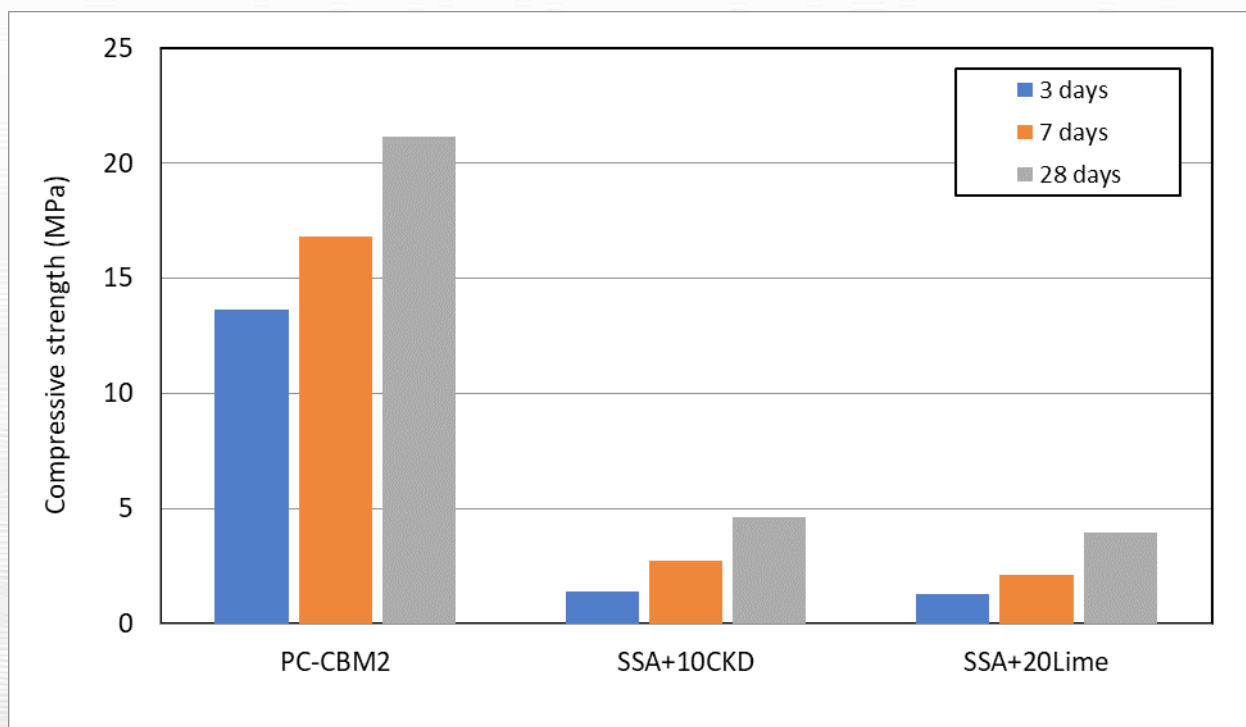


Figure 5-21 Compressive strength of CBM mixtures (Set 2)

The Set 2 CBM mixtures exhibited durable performance with retained strength values greater than 90% for both PC and SSA mixtures, and no signs of cracking or swelling were observed.

The cube density was also calculated from the measurements of weight in air and weight in water before crushing. The density values are also given in Table 5-12 for the different mixtures. The CBM 2 – PC mixture exhibited the highest density values with its high cement content and specific gravity value, followed by the CBM1-PC mixture. The SSA, SSA-Lime, SSA+10CKD and SSA+20Lime mixtures gave the lowest density values due to the low specific gravity values of SSA, compared to PC.

5.3.3 Optimised SSA CBM

The laboratory development of CBMs demonstrated the potential use of SSA to fully replace PC with good compliance with the QCS 2014 requirements. SSA CBM mixtures made with a binder content of 150 kg/m³, SSA+10CKD and SSA+20Lime, could be successfully used to produce CBM mixtures with adequate strength properties and durability. The developed SSA-10CKD mixture exhibited gradual strength development of 1.4 MPa at 3 days, 2.7 MPa at 7 days and 4.6 MPa at 28 days, similar to the performance of other hydraulic bound materials (HBM) such as fly ash and slag bound mixtures (BS EN 14227-1). The materials also exhibited excellent durability performance with a retained stability of 91%. The SSA-20Lime exhibited similar gradual strength development and excellent durability.

CBMs are generally specified based on maximum compressive strength values, with the tendency to produce low strength CBMs to minimise the risk of reflection cracks in the asphalt overlay. The QCS 2014 specifies minimum compressive strength for CBMs, but project specifications tend to specify minimum and maximum strength of 3 and 7 MPa, respectively, to control reflection cracking.

The SSA-10CKD and SSA-20Lime exhibited delayed strength development compared to the CBM mixtures; however, the slow curing allows the material to act initially as unbound materials and to gain strength and stiffness with increasing age and traffic loading. Slow hardening HBMs also have the advantage of extended time for laying and compaction compared to the fast setting of CBMs.

Based on the results obtained in this study, SSA could be successfully activated by 10% CKD or 20% hydrated lime for the production of consistent low strength CBMs materials for use in road construction. Increasing the binder content to 150 kg/m³ (6.3%) will also improve the consistency of mix production with controlled low compressive strength values.

5.4 Summary

Solid waste material of SSA was used for the development of green cement, and the laboratory production of novel construction products of concrete blocks, foamed concrete and cement bound materials. SSA was used to replace PC in these low-strength non-structural concrete products, and their compliance were assessed against national and international specifications.

SSA was activated by different methods including blending with PC, CKD, hydrated lime, and chemical alkalis. SSA mixtures activated with PC (75% SSA + 25% PC) and CKD (90% SSA + 10% CKD) achieved satisfactory 7-day average compressive strength and water absorption values that are complying with the Qatar Construction Specification (QCS) requirements for concrete blocks. Unlike the PC control mixture, the SSA exhibited strength development between 2 and 7 days, indicating the development of further reactions between SSA and alkali cement hydration products. The chemical alkali-activated SSA with sodium hydroxide and sodium silicate solutions gave the least strength values.

SSA was successfully used to produce foamed concrete with air content of 20-25% and density of 1600-1800 kg/m³. The SSA mixtures exhibited excellent fresh properties in terms of workability and flowability with no segregation or bleeding. The best performance of the SSA mixtures was obtained when blending with PC. The SSA-50PC and SSA-75PC gave 28-day strength values of at least 4.0 MPa for use in road construction and reinstatement. The QCS requirements for FC are onerous in comparison to the UK and Hong Kong specifications.

Cement bound material (CBM) mixtures were made with SSA replacing 100% of PC. SSA was activated by 10% CKD or 20% hydrated lime to provide CBM mixtures with adequate strength and excellent durability performance. The SSA-CBM mixtures exhibited delayed strength development, compared to the PC CBM mixtures, to act initially as unbound materials and gain strength and stiffness with increasing age and traffic loadings. Slow hardening HBMs have the advantage of extended time for laying and compaction compared to the fast setting of CBMs and minimizing the risk of reflection cracking.

6 Performance and Microstructure of Optimised Mixtures

Following the laboratory development of SSA concrete mixtures, optimised low-strength SSA mixtures were identified for the full-scale site trials. The identified mixtures were initially assessed for performance, durability and microstructural analysis. Durability assessment was made based on the laboratory testing of compressive strength, drying shrinkage, and immersion in hot water. Microstructure analysis of X-ray diffraction (XRD), Thermogravimetric Analysis (TGA), and Scanning Electron Microscopy (SEM) were used to understand the hydration products of SSA with different activators.

6.1 Performance of durability of SSA mixtures

Optimised low-strength concrete mixtures were made for the durability assessment of SSA products. Five SSA mixtures were used, and their properties were compared to a control mixture of PC. The SSA was used as the sole binder (100% SSA), and activated with different proportions of PC, CKD and hydrated lime. Binder and mortar mixtures were prepared and tested in this section.

Table 6-1 Paste composition and properties at 30°C

Mix	PC	SSA	CKD	Lime	Consistency (%)	Initial setting time (min)	Final setting time (min)
100PC	1	-	-	-	28	150	215
100SSA	-	1	-	-	27	600	695
25SSA-75PC	0.75	0.25	-	-	28	300	385
50SSA-50PC	0.5	0.5	-	-	28	420	500
90SSA-10CKD	-	0.9	0.1	-	34	480	565
80SSA-20Lime	-	0.8	-	0.2	32	360	435

Table 6-1 gives the binder mix composition and test results of consistency and setting time. Testing of standard consistence is made as per BS EN 196-3 (2016), to define the amount of water needed to achieve a comparable workability limit. The consistency of the PC was 28%, within the typical range of cement between 25% and 35%. The 100% SSA binder exhibited a consistency value of 27%, similar to that of the control PC binder. The low consistency value for the SSA, compared to the initial reported high value of 52%, is due to the different grinding using the ball mill grinder to produce more spherical particles. Pan et al. (2003) concluded that an increase in the ash grinding time (from 10 to 360 min) increases the SSA fineness and its pozzolanic activity but does not bear a significant influence on the density and specific surface area of the ash. Milling also can change the colour of the SSA to red if

contains significant amounts of Fe_2O_3 (Kappel et al., 2017). The highest consistency values were found for the SSA blended with CKD (34%) and hydrated lime (32%).

The results in Table 6-1 and Figure 6-1 show clearly that increasing the SSA content in the mix prolongs its setting time. The setting time testing was made as per BS EN 196-3 (2016), with the exception of immersing the sample in a water bath maintained at 30°C instead of the specified value of 20±1 °C. The 30°C was selected as more representative to the climatic conditions in Qatar and the Gulf region than the specified 20°C.

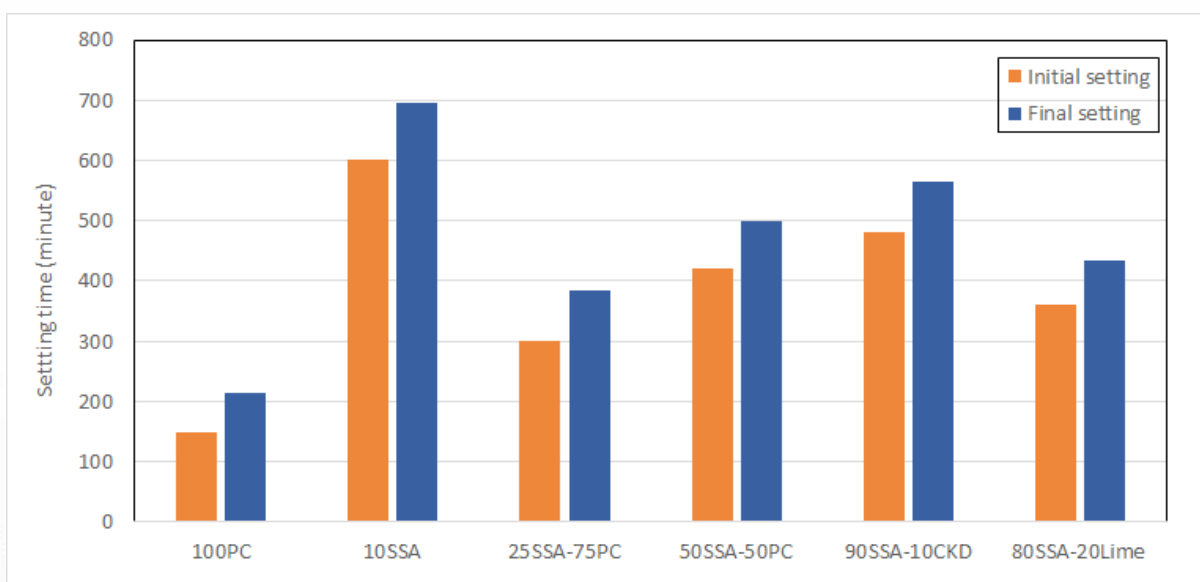


Figure 6-1 Setting time of the optimised SSA mixtures at 30°C

The initial and final setting times of the PC were 150 minutes and 215 minutes, compared to 600 minutes and 695 minutes for the SSA, respectively. The setting time of the SSA paste is prolonged by more than 3 times of the PC setting time. Blending the SSA with other binders of PC, CKD and lime gave intermediate values between the 100% PC and 100% SSA, almost twice the values given from the PC control. The increased setting time of SSA is mainly associated with the increased content of phosphate that reacts with calcium and generates the insoluble calcium phosphate, limiting the access of water to the particles and hindering the hydration reaction (Mejdi et al., 2020; Piasta and Lukawska, 2016). Furthermore, the grinding process for SSA leads to the adsorption of more calcium ions on its surface, and results in a prolonged setting time (Pan et al., 2003).

Optimised SSA mortar mixtures were also made and testing for assessing the fresh and hardened properties. The mortar mix design is prepared in the weight proportions of 1 part binder to 3 parts of fine aggregate of washed sand. The water to binder ratio was fixed for all mixture at a ratio of 0.4, and the flow table test was used for the assessment of mortar workability (BS 4551-1, 1998; ASTM C230, 2020).

Table 6-2 gives the mix compositions together with the fresh properties of wet density and flow table. The fresh mortar was cast into cubes of 50 mm sides and prisms of 200 x 50 x 50 mm and compacted manually in 2 layers with 25 blows on each layer. After compaction, the cast face of the mortar was trowelled and the moulds were cured at 40 ± 1 °C and 95% relative humidity for 24 hours. On the following day, the mortar specimens were demoulded and cured at an environmental chamber maintained at 30 ± 1 °C and 65% relative humidity until testing.

Table 6-2 Mortar composition and fresh properties of the optimised SSA mixtures

Mix	PC	SSA	CKD	Lime	Sand	water	Wet density (kg/m ³)	Flow table (mm)
PC	1	-	-	-	3	0.4	2197	112
SSA	-	1	-	-	3	0.4	2191	137
25SSA-75PC	0.75	0.25	-	-	3	0.4	2195	129
50SSA-50PC	0.5	0.5	-	-	3	0.4	2191	143
90SSA-10CKD	-	0.9	0.1	-	3	0.4	2160	133
80SSA-20Lime	-	0.8	-	0.2	3	0.4	2109	140

The results in Table 6-2 shows that the density values ranged between 2109 kg/m³ and 2197 kg/m³ for all mortar mixtures, with a marginally lower value for the SSA-Lime mixture. The flow table values were almost similar for all mixtures, as shown in Figure 6-2, and ranged from 112 mm for the PC to 143 mm for the 50% SSA and 50% PC mixture.

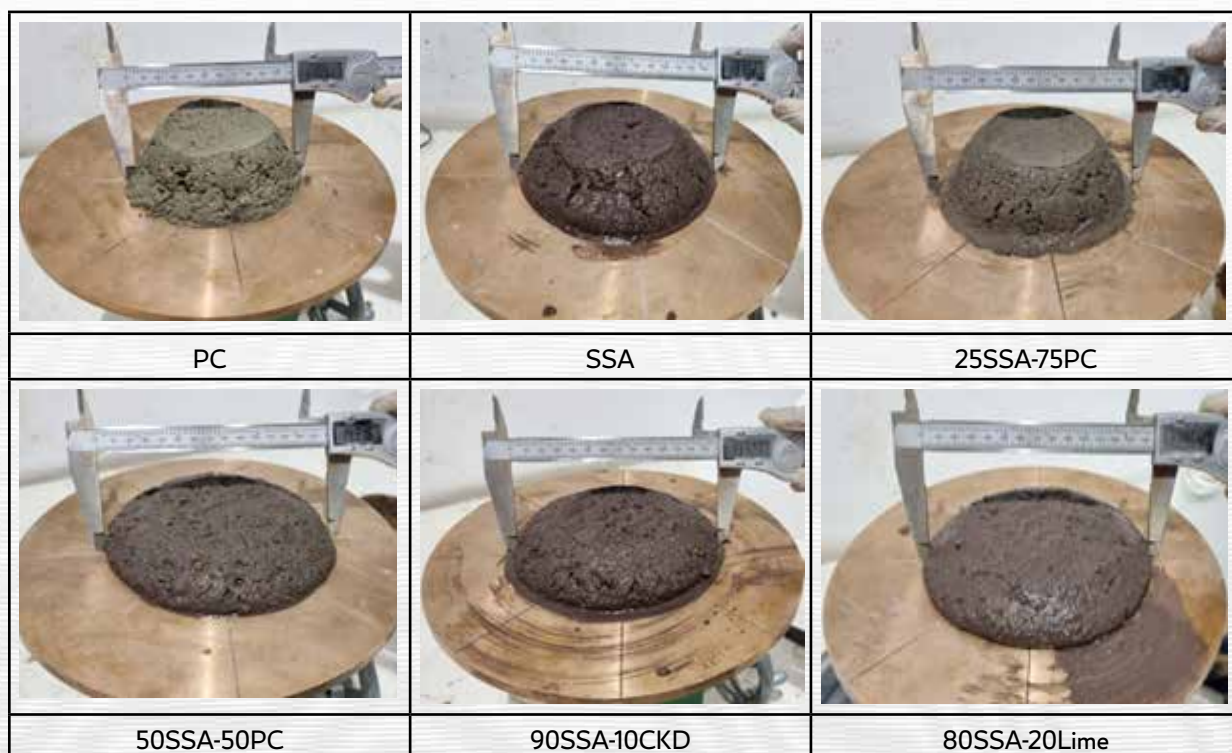


Figure 6-2 Flow table testing of the optimised SSA mortars

6.1.1 Compressive strength

Compressive strength testing was carried out on the mortar cubes at the ages of 2, 7, 28, and 90 days. Three cubes were used for each test at a specific age and the average results are graphically presented in Figure 6-3. The results showed the general trend of increasing compressive strength with age, mainly for the mixtures containing PC. The control PC mortar gave the highest compressive strength values of 25 MPa, 27.2 MPa, 37 MPa, and 40.1 MPa at the testing ages of 2, 7, 28 and 90 days, respectively. The initial hot curing at 40 ± 1 °C and 95% enhanced the strength results at 2 days, but the rate of strength development is reduced with continuous curing at relatively dry environment of 30 ± 1 °C and 65% RH. The 28-day strength of the PC was 37 MPa, which is relatively low for a cement of 42.5 grade. The 100% SSA mortar possessed self-hardening but exhibited very low strength values of approximately 1 MPa at all tested ages.

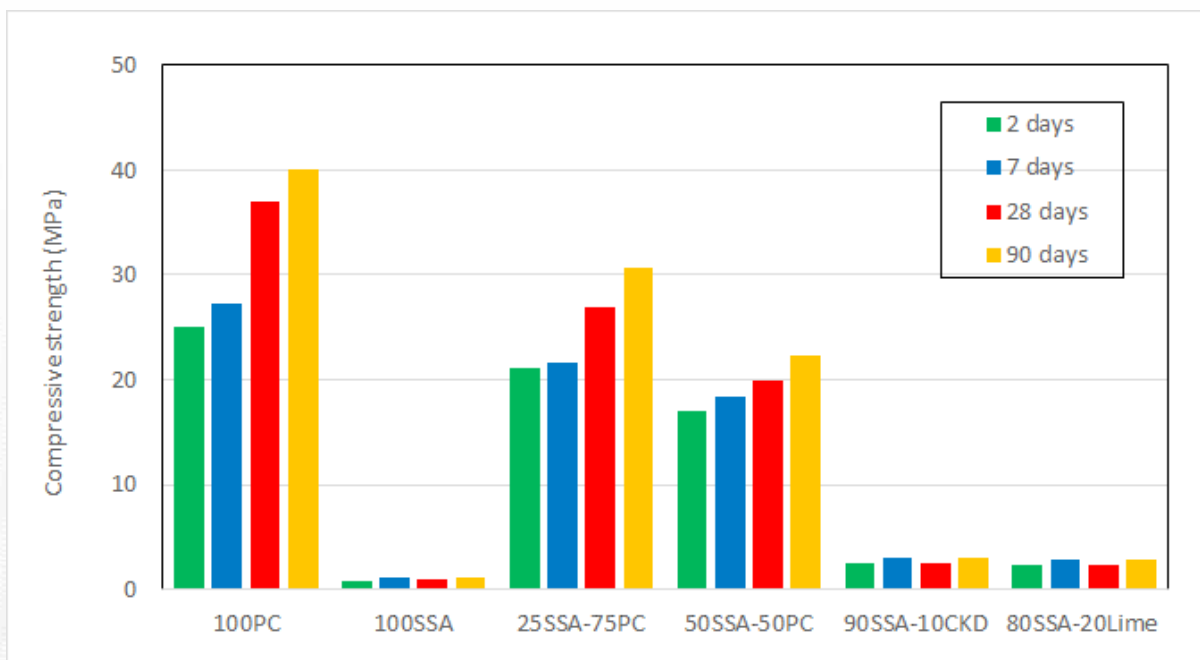


Figure 6-3 Compressive strength of the optimised SSA mortar mixtures

Increasing the SSA content in the mortar mixtures results in reduced compressive strength results. Replacing 50% and 75% of the PC with SSA resulted in 28-day compressive strength values of 27 MPa and 20 MPa, respectively, lower by 46% and 27% when compared to the 100% PC control mortar. Cementless mortar mixtures were made with high contents of SSA. The 90% SSA + 10% CKD and 80% SSA + 20% Lime mortar mixtures gave compressive strength values between 3.5 to 4.0 MPa at 28 days. The strength has mainly developed at 2 days, with marginal improvement in the relatively hot and dry exposure environment.

6.1.2 *Shrinkage*

The shrinkage of cementitious materials is generally depending on a combination of several mechanisms including plastic shrinkage, autogenous shrinkage, drying shrinkage, and carbonation shrinkage (Neville, 2011). For conventional concrete with water-to-cement ratio (w/c) of 0.4 and beyond, the magnitude of drying shrinkage tends to predominate over other shrinkage types and account for the significant proportion of total shrinkage.

Drying shrinkage is an important parameter in relation to concrete durability and dimensional changes. Drying shrinkage is the contraction in the concrete caused by moisture loss from drying concrete and can cause cracking if the concrete is constrained to shrink.

Details of the mortar mixtures tested for shrinkage are given in Table 6-2. Mortar prisms of 200 x 50 x 50 mm were prepared and cured at 40 ± 1 °C and 95% relative humidity for 24 hours. The moulds are provided with 8 mm diameter studs, as per BS EN 1367-4 (2008), for shrinkage measurements. After 24 hours of initial curing, the mortar specimens were demoulded and cured at an environmental chamber maintained at 30 ± 1 °C and 65% relative humidity, to simulate average exposure conditions in Qatar. Figure 6-4 shows the mortar mould, with metal studs fixed on the 50x50mm side, together with the measuring apparatus. The measuring apparatus consists of a gauge with scale divisions of 0.002 mm, mounted into a frame and has a recessed end that can be located on the 8-mm stud bounded into the prism. The other end of the frame has a similar recessed end in the opposite direction of the prism. Figure 6-5 shows the mortar prisms used for the drying shrinkage testing for all mixtures.



Figure 6-4 Shrinkage moulds and testing apparatus



Figure 6-5 Mortar prisms used for the drying shrinkage testing

Shrinkage measurement started at the mortar age of 3 days and continued for 56 days. Measurements were conducted at the specified age by placing each prism in the frame and obtaining the minimum reading while slowly rotating the prism. Calibration was made by checking the length of the reference metal rod, and if greater than 0.002 mm the difference between the rod and prisms was recorded to the nearest 0.002 mm. The length variation of the mortar prisms was recorded and calculated as a percentage of the initial length as the measurement of drying shrinkage.

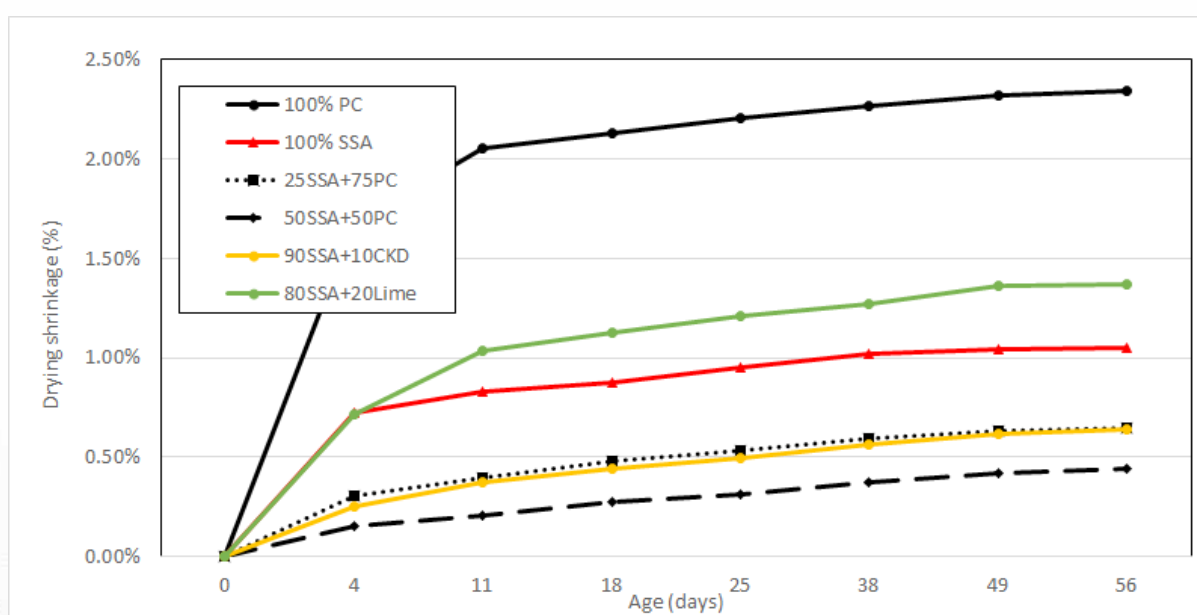


Figure 6-6 Shrinkage of the optimised SSA mixtures

The results of drying shrinkage are presented in Figure 6-6 for the optimised mortar mixtures. All the mixtures exhibited the same trend of increased drying shrinkage values with age of drying. The rate of shrinkage was also high during the initial days of drying and the rate gradually reduced at later stages for all mixtures.

The control 100% PC mixture gave the highest values of drying shrinkage at all testing ages. The 100% PC mixture achieved a drying shrinkage value of 2% after 11 days exposure in a controlled environmental chamber, and the rate of shrinkage reduced dramatically after 11 days to reach 2.4% after 56 days of exposure. All the SSA mixtures exhibited lower shrinkage values than the control 100% PC mixture.

The lowest drying shrinkage values were found for the SSA blended with PC and CKD binders. The 25SSA+75PC, 50SSA+50PC and 90SSA+10CKD exhibited shrinkage values in the range of 0.44% to 0.65%, approximately 25% of the value achieved by the control 100% PC mixture. The two mixtures of 100%SSA and 80SSA+20%Lime gave intermediate values of 1.05% and 1.37%, respectively, approximately 50% of the value given by the control 100% PC mixture.

Drying shrinkage of a porous medium such as cementitious materials is the result of the loss of internal moisture in the porous structure to establish equilibrium with the relative humidity (RH) of the external environment (Neville, 2011). As cement hydration progresses, part of the water is consumed within the hydration products and the remaining water maintains internal moisture against self-desiccation, resulting in the gradual attenuation in the magnitude of autogenous shrinkage. Exposure to hot environment, such as one considered in this research, accelerates the water evaporation from the pore structure and renders concrete susceptible to drying shrinkage, triggered by physical water loss. Drying shrinkage leads to cracking of concrete when the movement of the concrete is constrained and is deemed to be the major driver for physical cracking of concrete over its lifetime (Kayondo et al., 2019).

The reactivity of PC and high early strength resulted in initial high drying shrinkage rate. With more exposure to hot environment the rate of strength development as well as the rate of drying shrinkage have reduced due to the loss of physical water within the pore structure of the PC mortar. The case was different for the SSA mixtures, as the reactivity of SSA is much lower than PC and hence the initial strength gain and drying shrinkage were low. The results also indicate that the binder system of SSA with PC is more effective in reducing the drying shrinkage of concrete compared to the SSA+CKD and SSA+Lime binder systems.

Many researchers have reported higher shrinkage rate for the SSA mixtures compared to the control PC mixture, but mainly associated with increased water demand for the SSA mixtures and consequently higher shrinkage (Gu et al., 2023; Chen and Poon, 2017; Rutkowska et al., 2018). Garcés et al. (2008) investigated the influence of sulphates, in the chemical composition of SSA, on the dimensional stability of the paste due to expansive processes of secondary ettringite formation. They used up to 30% replacement of PC with SSA and the results suggested that the SSA sulphates are not soluble and therefore not have minimum impact on dimensional stability. It seems from the results obtained in this investigation that grinding has a great effect on the performance of SSA in concrete. Grinding the SSA of similar particle sizes to PC has no negative effects on the water demand and workability of concrete. Furthermore, the high water-retention of SSA particles the slow reactivity contributes to reduced drying shrinkage values compared to PC concrete.

6.1.3 *Expansion*

The mortar prisms, 200 x 50 x 50 mm, used for the drying shrinkage were also used for the water immersion and expansion testing. The prisms were immersed in a water path maintained at 60°C, and the dimensional change were measured after different ages of immersion. The water path is provided with a lid cover to minimise the evaporation of hot water during testing. Figure 6-7 shows the water path containing the mortar prisms and with the lid cover.



Figure 6-7 Immersion of mortar prisms in hot water at 60°C.

Concrete curing at elevated temperature can accelerate the early strength development but negatively impact the long-term strength and durability of concrete. How water can also accelerate the reaction of potentially expanding maters, such as sulfate, causing expansion with reduction in strength and durability. The mortar prisms were immersed in water at the age of 60 days and maintained in hot water at 60°C for 56 days. The purpose of water immersion is to assess any potential expansive reaction, from the use of SSA, that can adversely impact the durability and long-term stability of the optimised SSA mixtures.

Figure 68 presents the expansion of the different mortar mixtures after immersion in hot water for 56 days. The rate of expansion followed similar trends for all mixtures, with a high rate after 1 day of immersion. The rate of immersion was reduced from 1 to 28 days, with more reduction between 28 and 56 days.

The highest expansion values were found for the mortar made with SSA and hydrated lime (80% SSA-20% Lime) with an average expansion value of 0.0019% of its original length after 56 days of immersion. On the other hand, mixtures made with 100% SSA and 90% SSA+20%CKD exhibited the lowest expansion values of 0.0008% and 0.0009%, respectively, at 56 days. Mortar mixtures made with 100% PC, 25% SSA + 75% PC, and 50% SSA + 50% PC gave intermediate expansion values within the range of 0.0012% to 0.0014% of original length at 56 days.

No signed of damage or cracks were observed on the mortar prisms after immersion in hot water for 56 days, indicating the dimensional stability of the SSA mixtures and the absence of deleterious reactions that may impact the durability of the mixtures. The expansion results provide assurance on the use of SSA controlled low strength concrete in applications that are exposed to water with less potential to expansion than PC concrete.

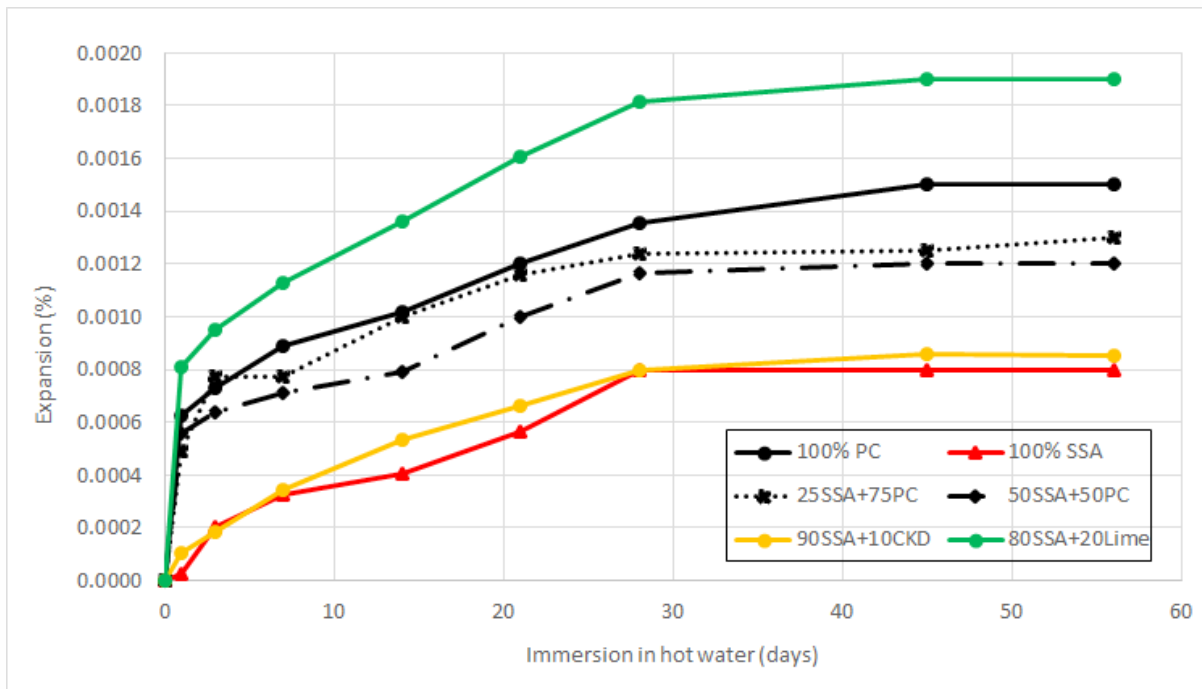


Figure 6-8 Expansion of mortar prisms in hot water at 60°C.

6.1.4 Durability

Durability of controlled low strength concrete products are generally assessed by comparing the strength retention of cubes after immersion in water for a certain duration. For example, the QCS 2014 specifies the durability of cement bound materials based on the retained strength value of a minimum 80%, as determined from the ratio of the average compressive strength after immersion in water to the average control strength.

The durability testing was conducted on the optimised mortar with the mix compositions given in Table 6-2, the same mixtures used for the shrinkage and expansion testing. Mortar cubes of 50 mm sides were prepared and cured at 40 ± 1 °C and 95% relative humidity for 24 hours. After 24 hours, the mortar specimens were demoulded and cured at an environmental chamber maintained at 30 ± 1 °C and 65% relative humidity up to the age of 28 days. After 28 days of dry curing, the mortar cubes were immersed in a water path maintained at 60°C for up to 28 days. Twelve cubes were made of each mix and were tested for water gain and compressive strength after 1, 7, 14, and 28 days of immersion in hot water. Figure 6-9 shows the mortar cubes immersed in the hot water path at 60°C. Immediately after immersion, it was noticed the 100% SSA mortar mixture to crack and disintegrate in the hot water. This was mainly attributed to the weak strength of the 100% SSA mixture, approximately 1.0 MPa, associated with the dry curing that increased the water absorption and weakened the cubes to failure. This observation was only noticed for the weak strength 100% SSA mixture, however, all other mixtures showed good stability in hot water as shown in Figure 6-9.

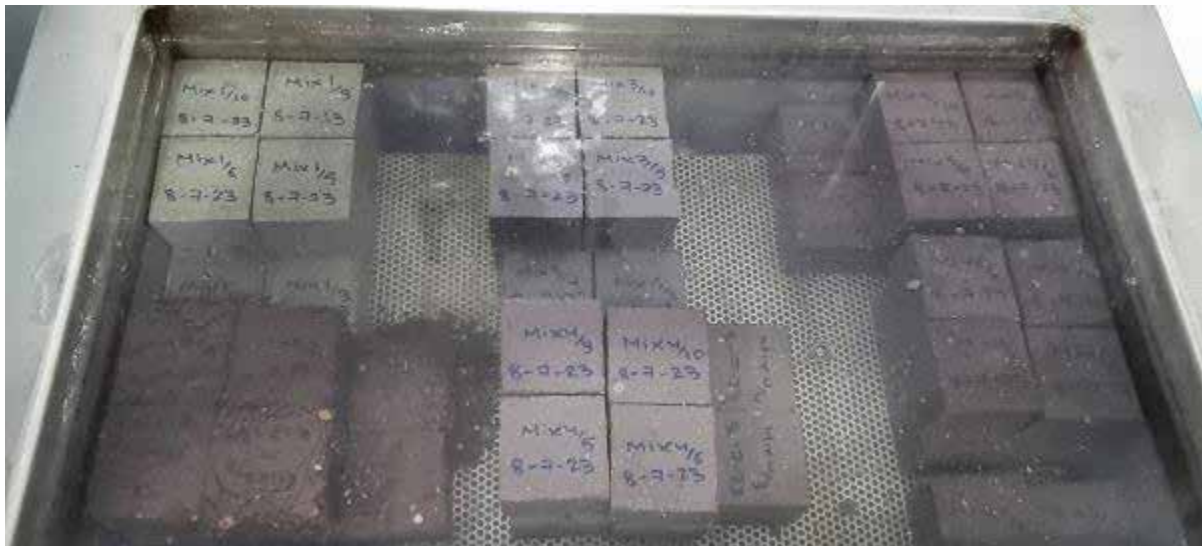


Figure 6-9 Immersion of mortar cubes in hot water at 60°C

Three cubes, from each mixture, were used for the measurements of weight gain and compressive strength after immersion in hot water at 60°C for 1, 7, 14, and 28 days. The average results are presented in Figure 6-10 for the weight gain and Figure 6-11 for the compressive strength. The results exclude the 100% SSA mixture, which were damaged immediately after immersion in water.

Figure 610 shows the weight gain as a percentage of the original weight of the cubes. The results show the general trend of high weight gain after 1 day immersion in hot water, ranging between 3.2% and 6.3% for all mortar mixtures. The rate of weight gain is reduced with increased immersion time and became almost constant after 14 days of immersion, indicating possible full saturation of the mortar cubes. The weight gain after immersion is related to the porosity and pore connectivity of the different mixtures, with high weight gain indicating more porous connected pores whereas low weight gain is associated with improved and tighter pore structure with enhanced durability.

The lowest weight gain results are given for the SSA blended with PC mixtures. The 25%SSA+75%PC mortar mixture exhibited the lowest weight gain at all testing ages from 1 to 28 days. Its weight gain was 3.2% after 1 day and increased to 5.8% after 28 days of immersion. The results indicate more than 50% of weight gain was achieved after 1 day of immersion. The second lowest mortar mixture with weight gain was the 50%SSA+50%PC, which gave weight gain of 3.9% and 6.6% after immersion for 1 and 28 days, respectively. Again, the weight gain after 1 day was greater than 50% of the weight gain after 28 days of immersion.

The highest weight gain of the investigated mortar mixtures was obtained for the 90%SSA+10%CKD mixture. Its weight gain was 6.3% after 1 day, and 8.2% after 28 days of immersion. The weight gain at 1 day of immersion was almost 75% of the weight gain at 28 days. The weight gain at 1 day was also higher than the weight gain of the 25%SSA+75%PC mortar mixture after 28 days of immersion in hot water.

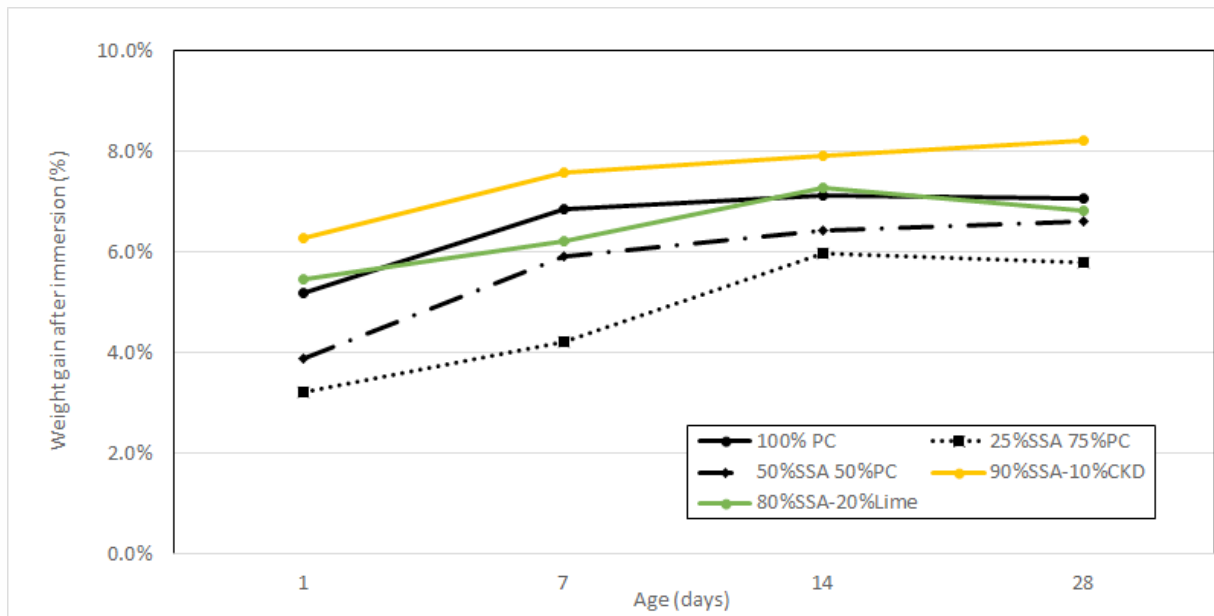


Figure 6-10 Weight gain of mortar cubes after immersion in hot water

The weight gain of the 100% PC and 80%SSA+20%Lime mixtures were almost similar with intermediate values between the lowest, 25%SSA+75%PC, and highest, 90%SSA+10%CKD, mixtures. The 100% PC mixture exhibited weight gain of 5.2% and 7.1% whereas the 80%SSA+20%Lime gave values of 5.5% and 6.8% at 1 and 28 days of immersion, respectively.

The results show that more than 50% of the maximum weight gain is achieved after 1 day of immersion, and the SSA+PC blended mixture gave the lowest value of weight gain. The results indicate improvement of the pore structure of the mortar mixtures made with a blend of SSA+PC with wet curing.

As discussed earlier, the durability of controlled low-strength concrete products is determined from the strength retention after immersion in water. Figure 6-11 shows the compressive strength results after immersion in hot water up to 28 days. The strength at 0 age is related to the 28-day strength after curing in the dry environment at 30 ± 1 °C and 65% relative humidity up to the age of 28 days, i.e., just before immersion in water. The 100% SSA mixture gave a 28-day compressive strength of 1.0 MPa and was disintegrated upon immersion in hot water as the mixture was too weak. The results of the 100%SSA mixture were therefore excluded from Figure 6-11.

The results in Figure 6-11 show two different trends of increased and steady strength after immersion in hot water at 60°C. The SSA-PC blended and PC mixtures exhibited higher strength, than the original 28-day strength, after immersion in water. The strength development commenced immediately after immersion, as reflected in the 1-day results, up to 28 days of immersion.

The highest strength development was achieved by the 50% SSA + 50% PC, from 15.8 MPa at 0 immersion to 41.9 MPa after 28 days of immersion, an increment of 166% from the original 28-day strength. Similarly, the 25% SSA + 75% PC showed a strength increment of 82%, from 30.0 MPa at 0 immersion to 54.5 MPa after 28 days of immersion. The 100% PC also showed increased strength 34.3 MPa to 60.5 MPa from 0 to 28 days immersion, approximately 77% increment from the strength before immersion. In fact, the 25%SSA+75%SSA and the 50%SSA+50%PC mixtures achieved 90% and 69% of the 100% PC mixture, respectively, after 28 days of immersion. The results indicate that immersion in hot water has no detrimental effects on the strength development and durability of controlled low-strength concrete mixtures. The delay of early strength development associated with the use of SSA is much reduced with the availability of water to achieve comparable results to the PC mortar with replacement of 25% of PC with SSA.

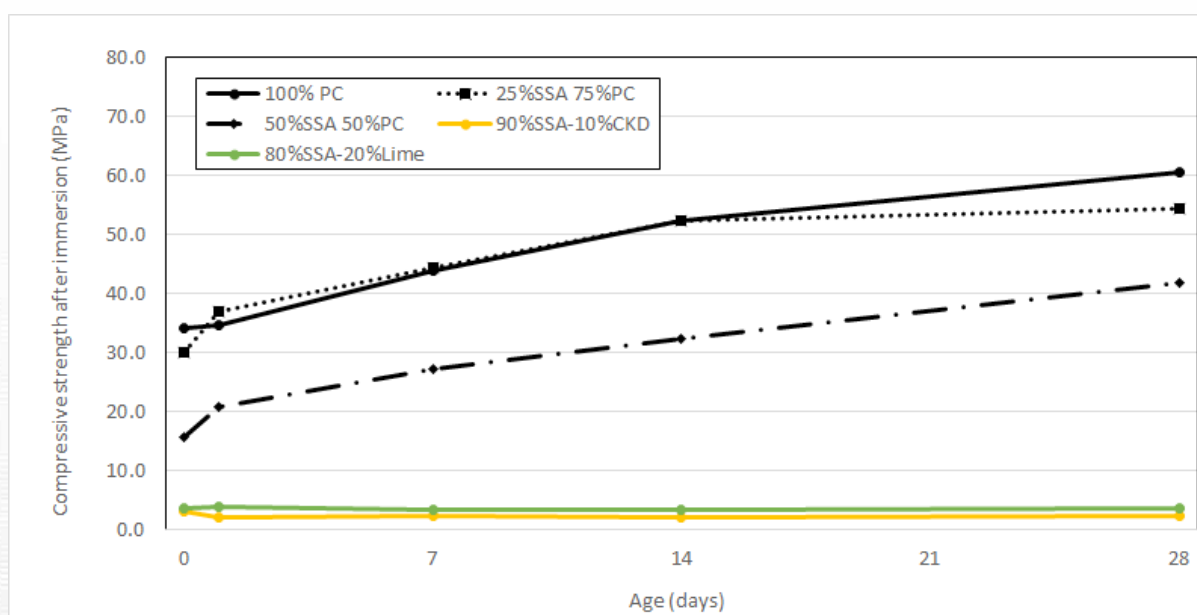


Figure 6-11 Compressive strength of mortar cubes after immersion in hot water

The 90%SSA+10%CKD and 80%SSA+20%Lime mixtures showed almost similar compressive strength values after immersion in hot water. The 28-day strength of the 90%SSA+10%CKD was 70% of the value before immersion, indicating potential reduction in durability with immersion in hot water. The 80%SSA+20%Lime mixture gave the identical strength value of 3.7 MPa after 28 days of immersion and confirming the stability of the mixture in hot water.

6.2 Microstructural Analysis

The microstructural analysis was conducted at the Queens University of Belfast in the UK.

6.2.1 Characterisation of the raw materials

The raw materials used in this study include: sewage sludge ash (SSA), cement kiln dust (CKD), Portland cement (OPC) and hydrated lime (CH), as shown in Figure 6-12. Each raw material has been characterised to determine its chemical and mineralogical composition as well as particle size properties.



Figure 6-12 Raw materials investigated

6.2.1.1 Mineralogical Composition

XRD, a powerful method for determining the mineralogical composition of materials, was used to identify individual crystalline components of the raw materials and the hydrated cements. XRD works on the principle that each cement phase/mineral produces a unique pattern (series of peaks) independent of others, with the intensity of each peak being proportional to the concentration of the phase in a mixture.

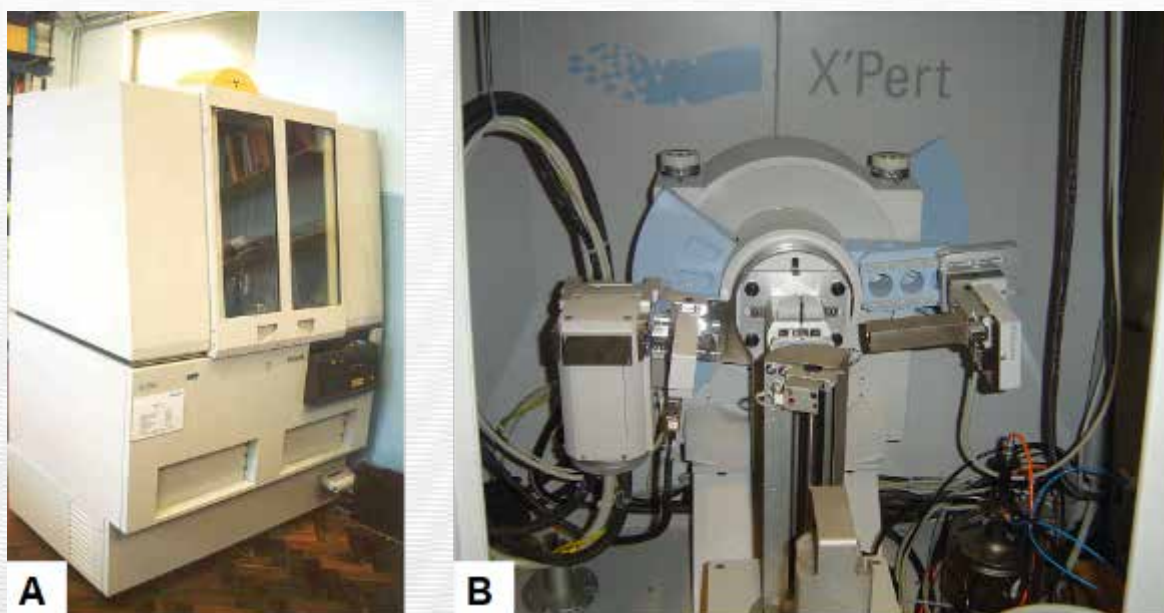


Figure 6-13 PANalytical X'Pert Pro MPD Diffractometer.
(a) whole instrument and (b) Xray emitter and receiver.

Approximately 2 grams of fine powder was placed into a metallic sample holder permitting x-rays to hit the sample and produce a series of diffraction peaks over the 2θ range 5 – 65°. A PANalytical X-ray diffractometer, Figure 6-13, was used and the mineralogy was revealed from the diffraction pattern by using PANalytical's X'Pert Highscore software in conjunction with the Powder Diffraction File database.

The following was the conditions used during tests:

Voltage:	40kV	Antiscatter Slit:	1°
Current:	45mA	Fixed Slit:	½°
Radiation:	CuK α	Step Size:	0.02°
Range (2 θ):	5-65	Filter:	Ni
Stage:	Rotating	Detector:	X'Celerator
Time per step:	75 seconds		

The mineralogical composition of all raw materials was determined by X-ray diffraction (XRD). It is important to highlight that the results provided below are not fully quantitative as they do not take into consideration the amorphous content of the materials.

SSA

Results in Figure 6-14 indicate that SSA consists primarily of the following minerals: whitlockite ($\text{Ca}_{18}\text{Mg}_2\text{H}_2(\text{PO}_4)_{14}$), with smaller quantities of hematite, maghemite, hydroxyapatite, albite, forsterite and quartz.

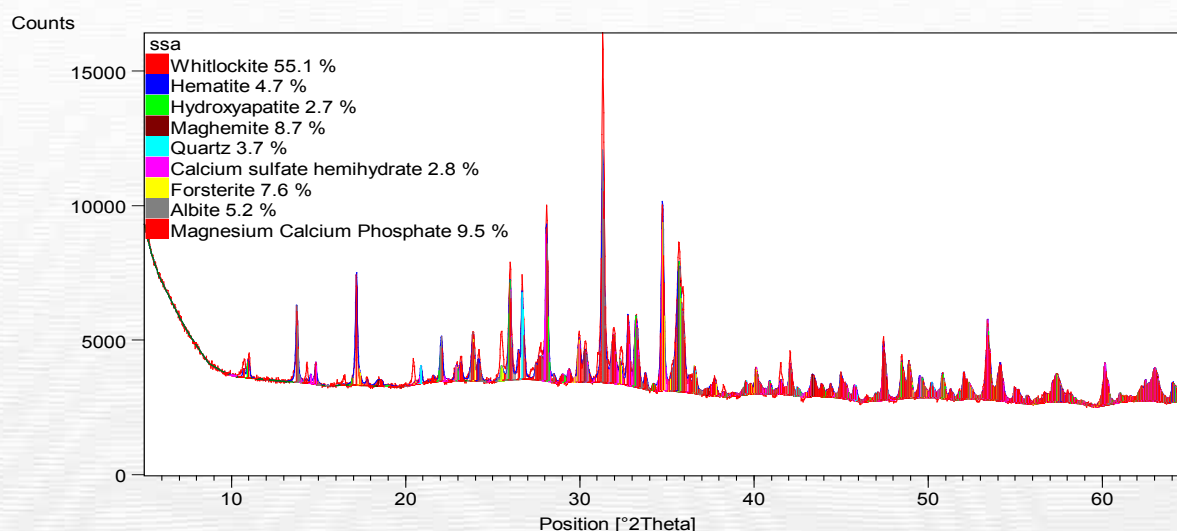


Figure 6-14 XRD of SSA

Portland cement (PC)

As expected, results in Figure 6-15 indicate that PC consists tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite. It also contains various calcium sulphates minerals.

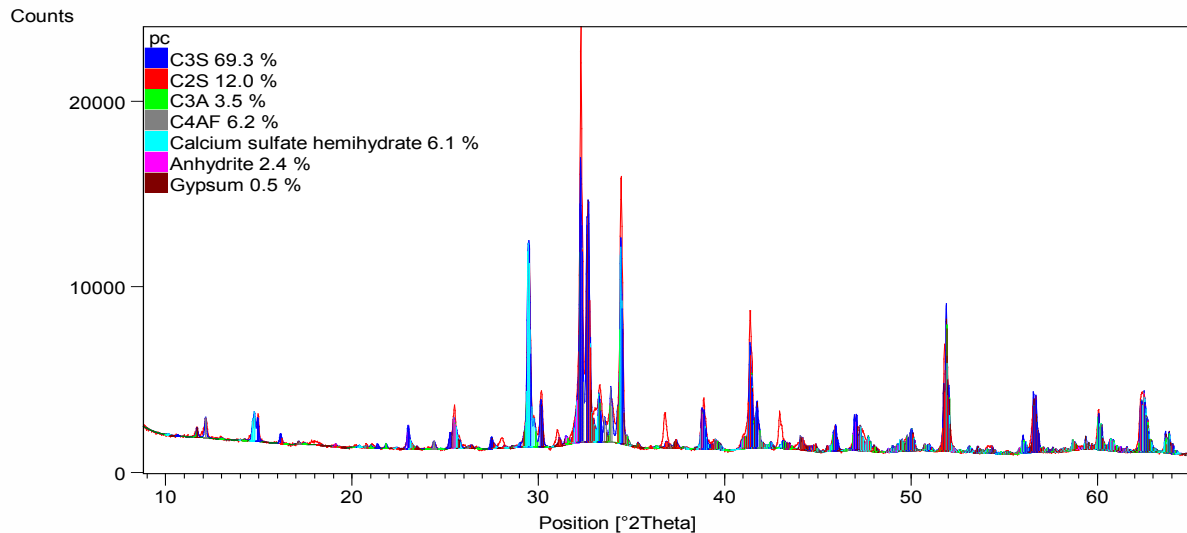


Figure 6-15 XRD of PC

CKD

Results in Figure 6-16 indicate that CKD consists primarily of lime and calcite. The amount of lime will be determined by the age of the CKD and its level of atmospheric exposure. Lime when exposed to the environment will hydrate, producing hydrated lime, and carbonate, producing calcium carbonate.

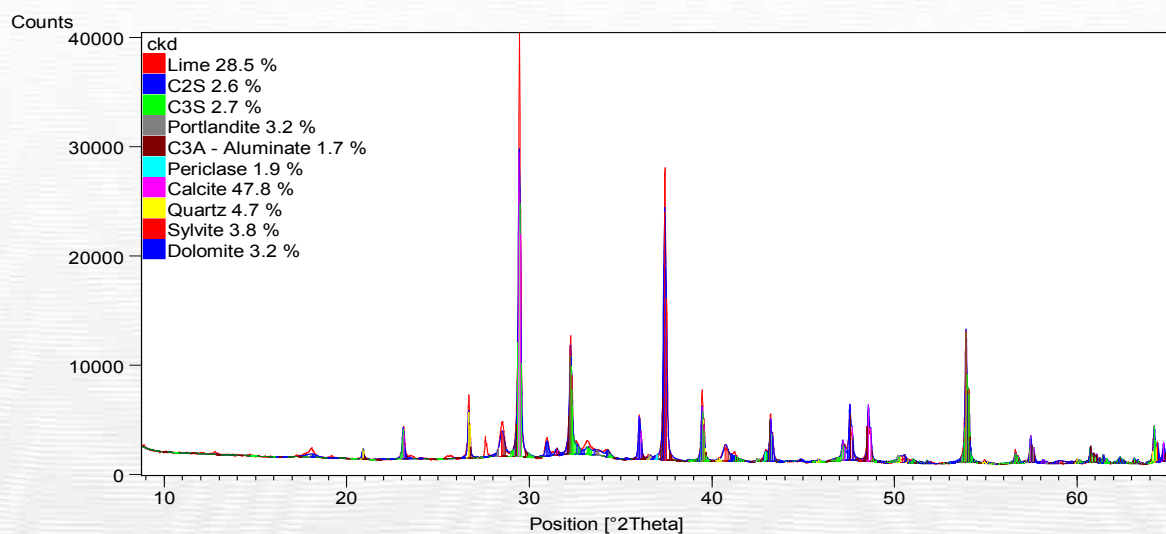


Figure 6-16 XRD of CKD

CH

The hydrated lime (CH) used in this study is very pure and only slightly carbonated as shown in Figure 6-17.

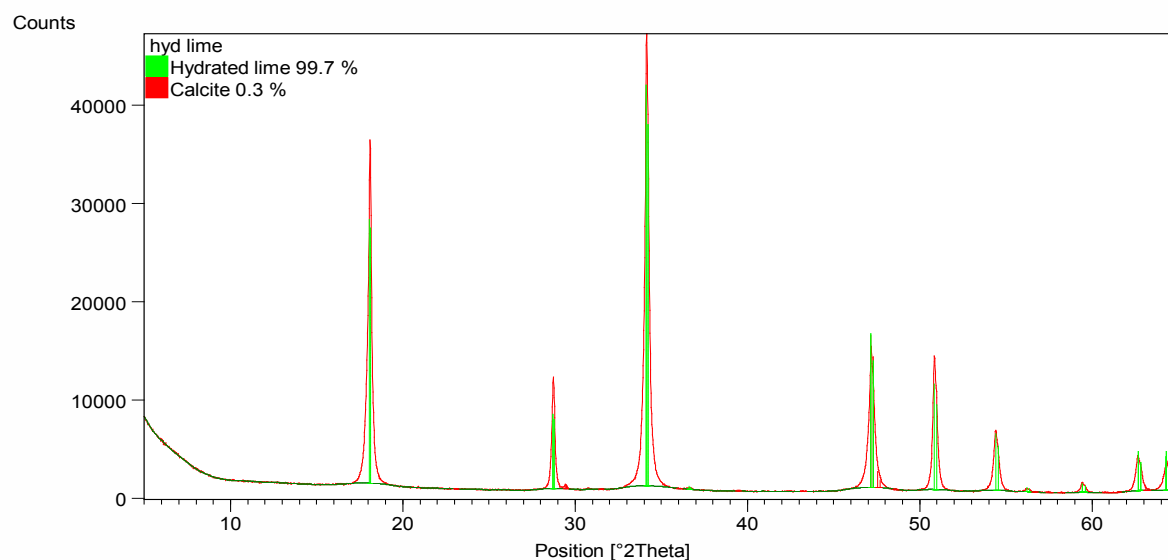


Figure 6-17 XRD of CH

6.2.2 Particle Size Properties

A Malvern's Hydro LV Mastersizer 3000, based upon laser diffraction technology was used to determine the particle size distribution of the various raw materials, Figure 6-18. Laser diffraction technology works "by illuminating particles in a collimated laser beam and measuring the scatter light over a range of angles. Particle size information can be obtained as the angle to which particles scatter light is dependant on their size".

The particle size characteristics of each raw material is detailed in Figure 6-19. The hydrated lime contains finer particles, whereas the CKD and SSA contains coarser sized particles than PC.



Figure 6-18 Mastersizer 3000; application note MAK1262-01

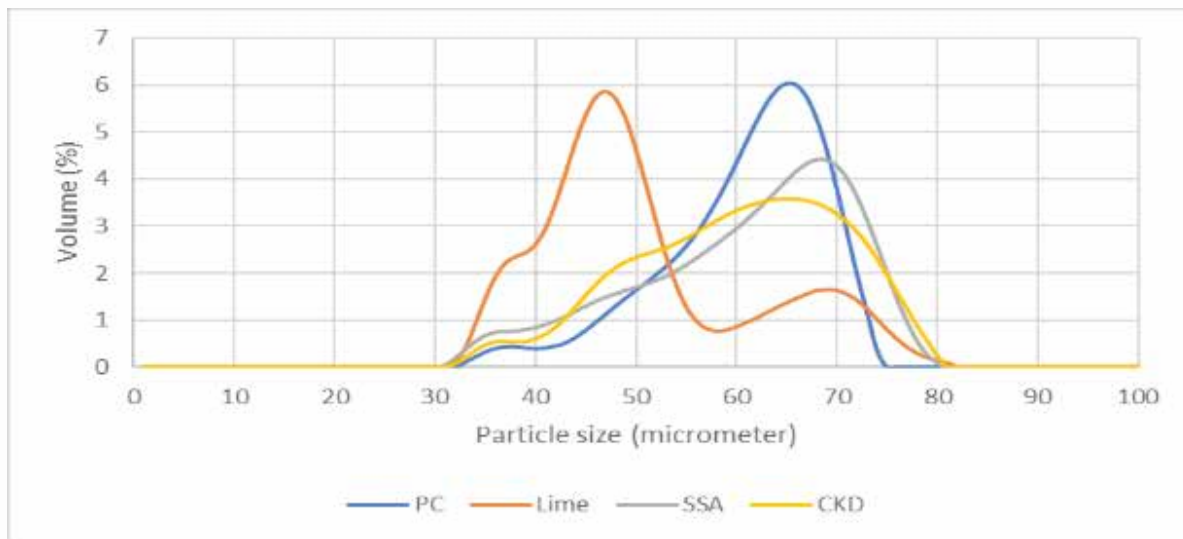


Figure 6-19 Particle size analysis of Raw Materials

6.2.3 *Manufacture and Hydration of Binders*

Five binders, detailed in Table 6-3, were manufactured and hydrated with a 0.5 water to binder ratio. The pastes were cast and cured for 2, 28 and 90 days. The samples were cured by placing the samples in a sealed bag and then placing the sample in a 30°C oven. At the end of the curing period the samples were analysed by XRD, TGA and SEM to determine the mineralogical composition of each mix.

Table 6-3 Mix Design of binders

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
PC	100%			50%	
SSA		100%	80%	50%	90%
CKD					10%
CH			20%		
w/b	0.5	0.5	0.5	0.5	0.5

Each binder was hydrated for 2, 28 and 90 days before analysing for mineralogical composition by XRD. The relative increase and decrease of peaks indicate a respective increase and decrease in the presence of a particular mineral. Results are presented below.

PC

During hydration the cement phases change to hydrates such as calcium silicate hydrate, calcium hydroxide and ettringite. As shown below, Figure 6-20, as hydration progresses, the tricalcium silicate peaks decrease whilst the calcium hydroxide peaks increase.

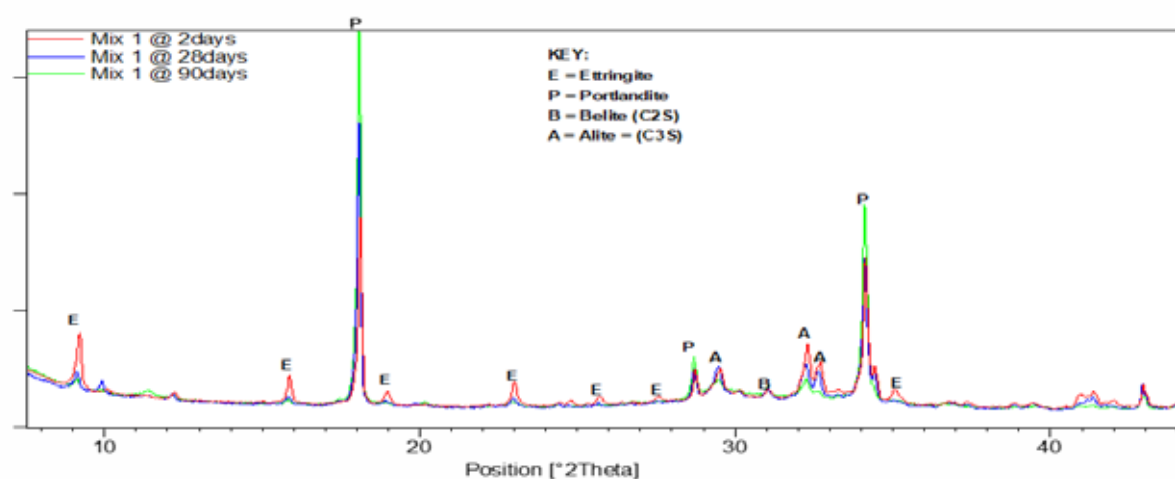


Figure 6-20 XRD of hydrated PC samples

SSA

Figure 6-21 superimposes the raw SSA with the binders containing 100% SSA. As shown below, hydration has had no impact on the minerals and no new phases have been formed. Accordingly, SSA could be considered inert in these conditions.

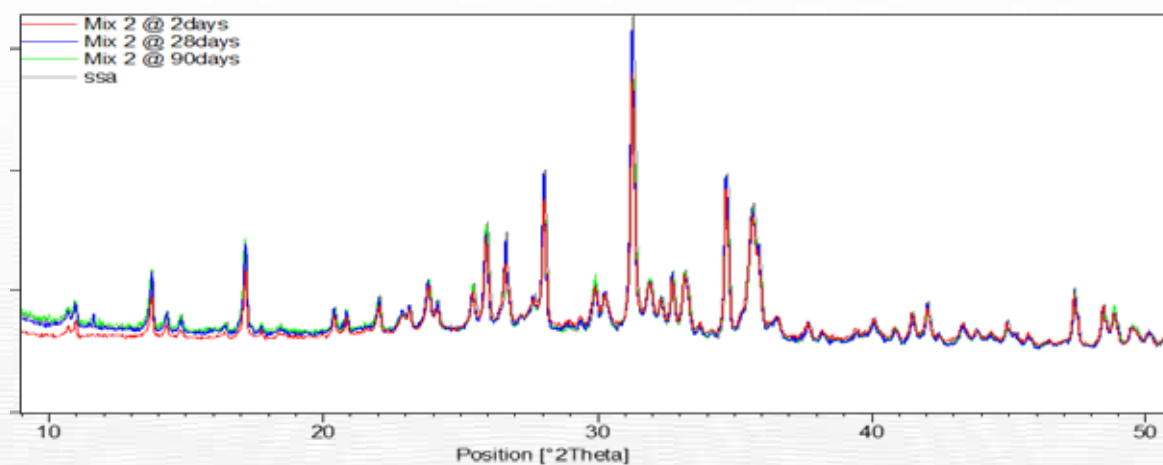


Figure 6-21 XRD of hydrated SSA samples

SSA (80%) and lime (20%) hydration:

Figure 6-22 superimposes the XRD traces of binders containing 80% SSA and 20% hydrated lime. Some of the minerals, such as whitlockite and hematite, remained unchanged. However, some unexpected changes do occur, such as:

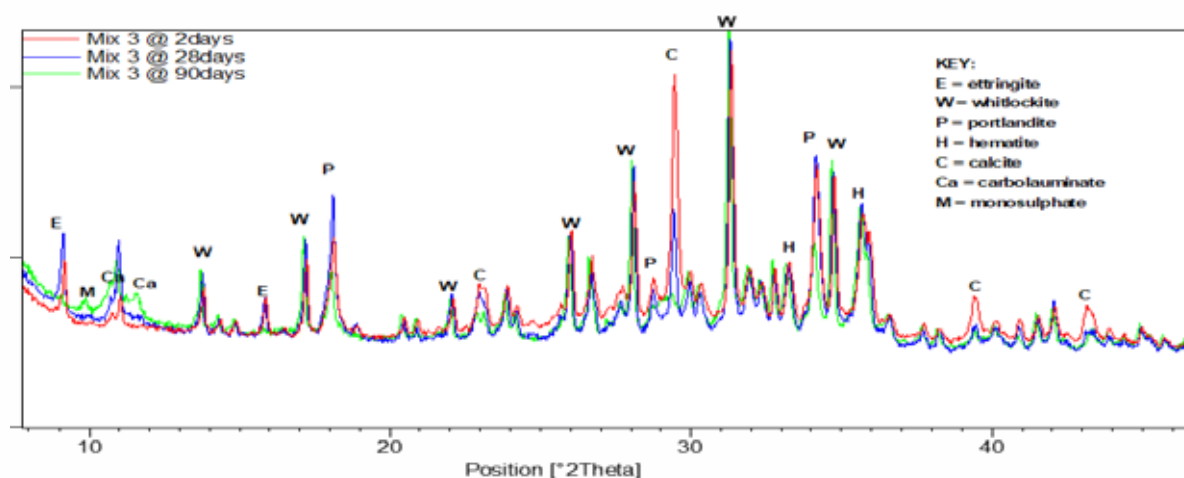


Figure 6-22 XRD of hydrated SSA and hydrated lime samples

Calcite – the amount of calcite significantly decreases from 2 days to 28 days, and almost disappears after 90 days hydration. It seems the calcite has taken part in a reaction to form AFm minerals (e.g. carboaluminates). This indicates the presence of reactive forms of Al_2O_3 in the SSA. XRD didn't pick up the presence of reactive Al_2O_3 phases, hence the Al_2O_3 in SSA must be amorphous.

Monosulphate ($\text{Ca}_4\text{Al}_2(\text{SO}_4)(\text{OH})_{12} \cdot 6\text{H}_2\text{O} = 2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaOH} \cdot \text{CaSO}_4$) – this mineral has formed in small quantities after 90 days hydration. Coupled with the presence of carboaluminates, this indicates the presence of reactive Al_2O_3 phases in the SSA. The sulphate has come from the presence of hemihydrate in the SSA – see Figure 1.

Portlandite – as expected the amount of portlandite/CH increases from 2 to 28 days. However, thereafter, the quantity of CH decreases significantly. This is not due to carbonation but rather likely due to the formation of various AFm types phases.

Ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$) – Ettringite is apparent in the samples hydrated for 2 and 28 days. However, between 28 and 90 days ettringite disappears. The presence of ettringite indicates that SSA contains a source of reactive Al_2O_3 . The disappearance of ettringite after 90 days hydration, will be due to additional aluminate phases reacting with ettringite to form monosulphate and with calcite and calcium hydroxide to form carboaluminates.

SSA (50%) and PC (50%) hydration:

Figure 6-23 superimposes the XRD traces of binders containing 50% SSA and 50% PC. Some of the minerals, such as Whitlockite and hematite, remained unchanged. However, ettringite, which forms after 2 days hydration, is negligible after 90 days hydration. The ettringite converts to monosulphate at 28 and 90 days. Carboaluminates also form. Like the previous section, this result indicates the presence of reactive aluminates in the SSA.

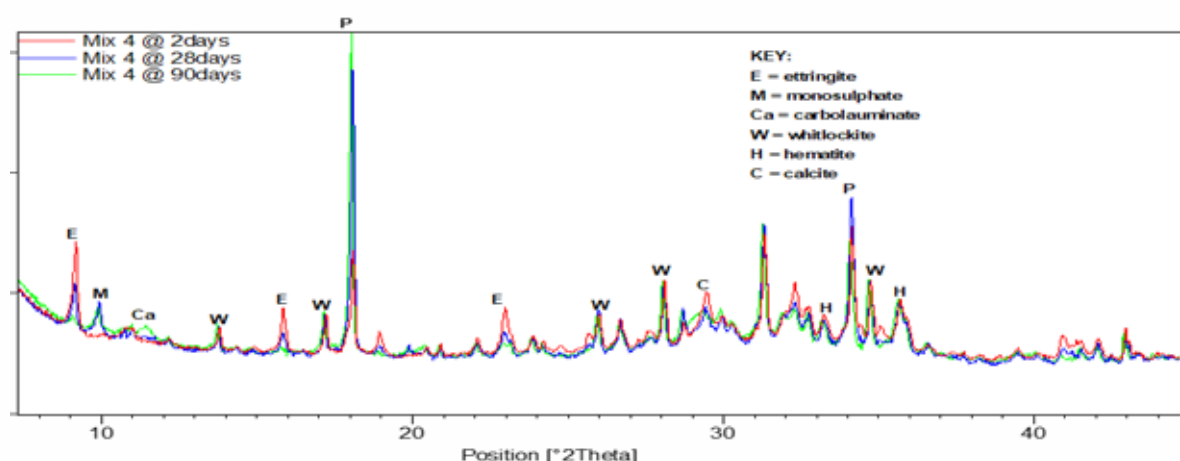


Figure 6-23 XRD of hydrated SSA and PC samples

SSA (90%) and CKD (10%) hydration:

Figure 6-24 superimposes the XRD traces of binders containing 90% SSA and 10% CKD. Some of the minerals, such as whitlockite and hematite, remained unchanged. Ettringite is present in this sample.

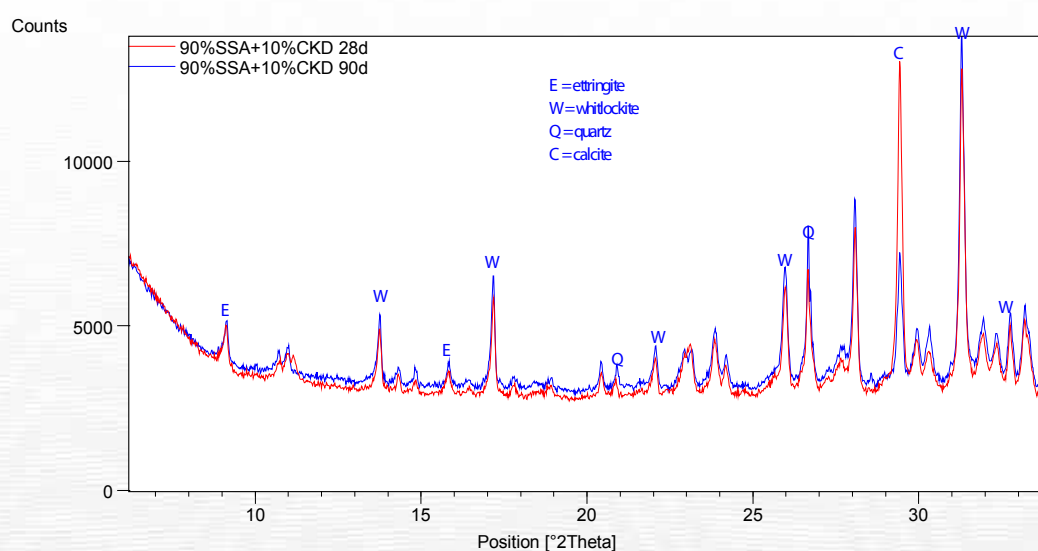


Figure 6-24 XRD of hydrated SSA and CKD samples

6.2.4 Thermogravimetric Analysis (TGA)

TGA was used to identify and, in some instances, calculate the amount of hydrates developed within the different cement pastes. The samples (~30-40mg) were placed into alumina crucibles and heated to elevated temperatures (1000°C) at a controlled rate 20°C/min to 1000°C in a controlled environment (N_2) using a Netzsch TG209 F1 Libra during heating, the mass change in cement was monitored and the resulting data was recorded as sample mass against temperature. The TGA equipment used is shown in Figure 6-25.

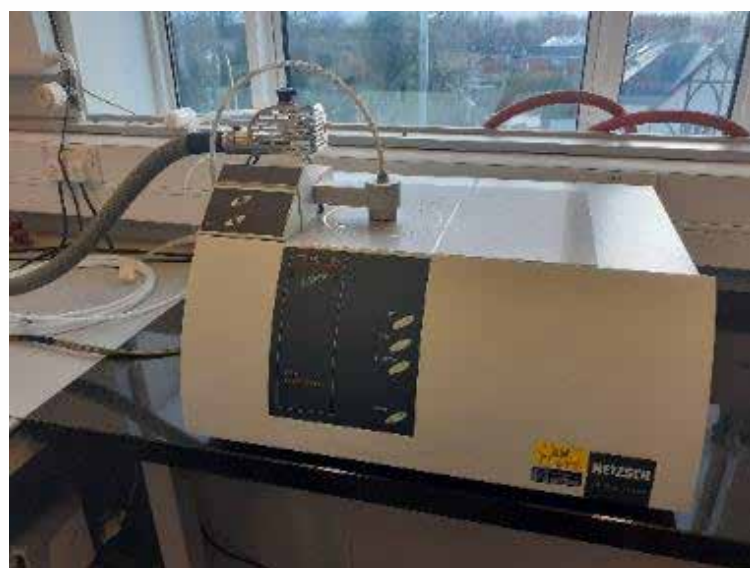


Figure 6-25 Netzsch Thermogravimetric Analyser

TGA was used to determine the presence and abundance of various hydrates (e.g. C-S-H and CH). Figure 6-26 is an example of the TGA trace from the 100% PC mix. Results after analysis of the various TGA traces are presented in Figure 6-27. The CH values are considered to be correct; whereas, the C-S-H values are not absolute values but rather an indication of C-S-H based on the mass loss of water evolved in the temperature range 200-400°C.

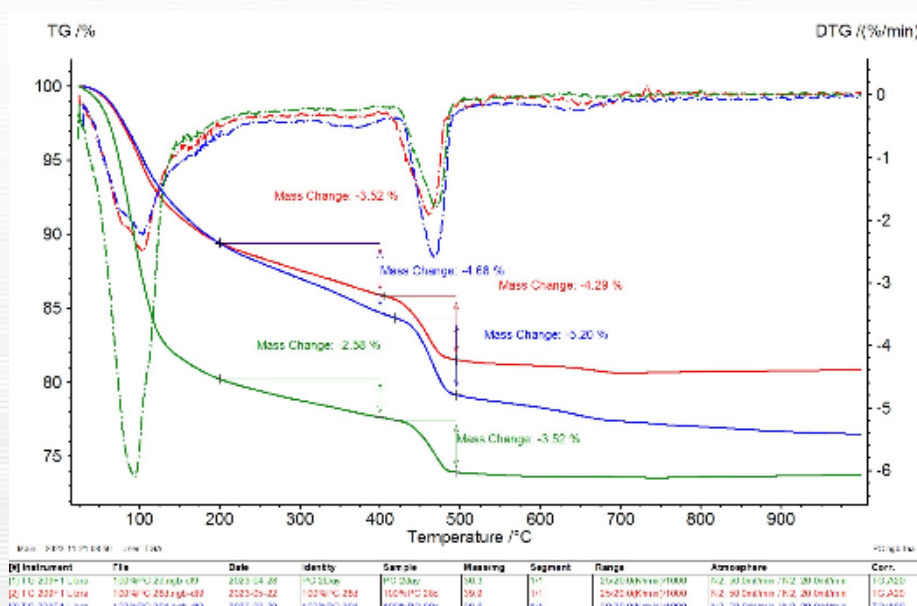


Figure 6-26 TGA of Portland cement samples at 2, 28 and 90 days hydration

Results indicate that hydrates predominately form in the samples that contain PC. The addition of SSA to PC seems to indicate that some hydrates form due to the presence of SSA. Hydrates also form in blends that are free from PC (e.g. SSA/Lime blend), indicating some pozzolanic activity.

As expected, CH values increase during the hydration of PC. However, when SSA is added, the CH values are significantly reduced and even decrease as hydration continues. This indicates that CH is being utilised in the PC/SSA blends. XRD results indicate this is due to the formation of ettringite and AFm phases. The reduction of calcium hydroxide in the SSA/lime blend indicates that calcium based minerals are being formed. Again, XRD indicates that this is due to the formation of ettringite and AFm phases.

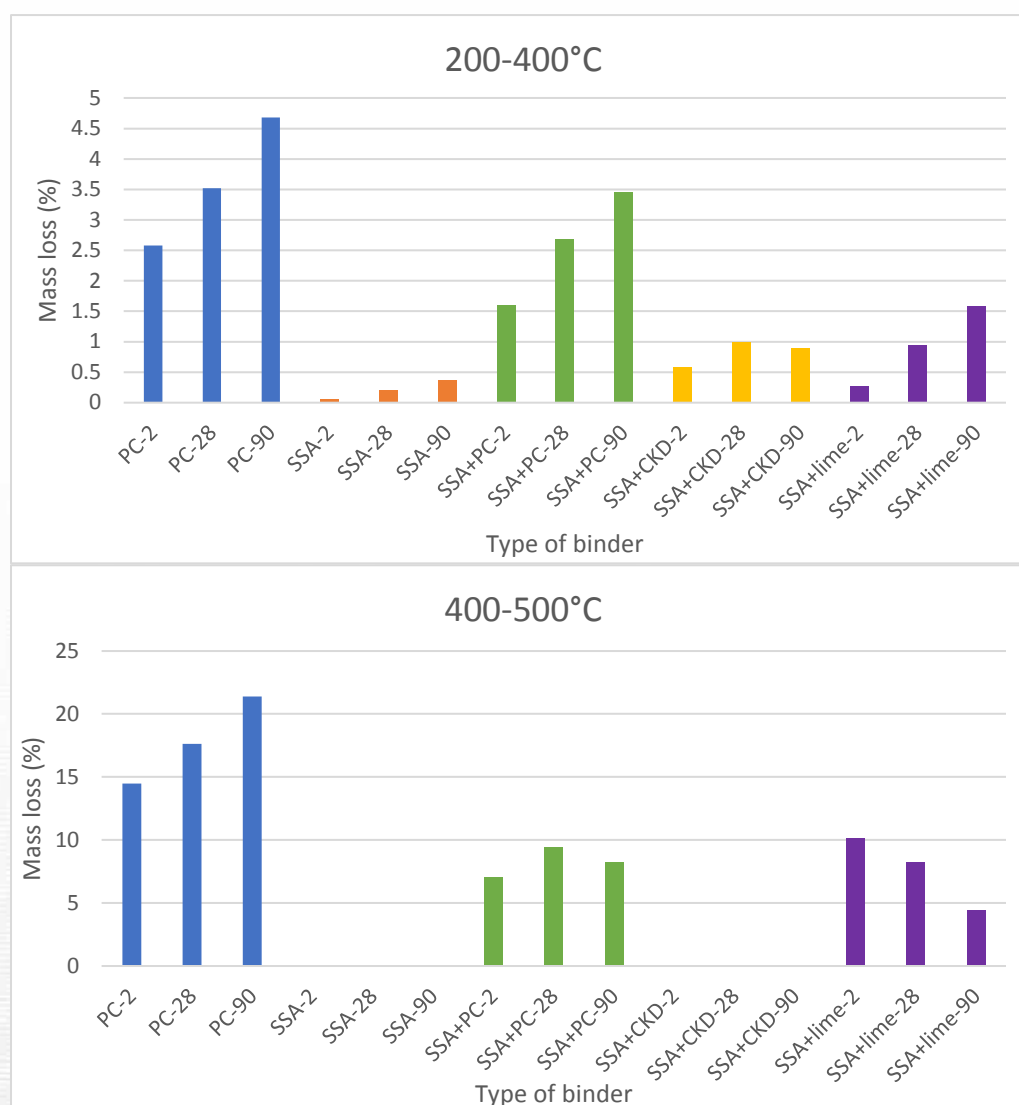


Figure 6-27 Analysis of TGA results for all the samples at 2, 28 and 90 days hydration. (a) mass loss between 200-400 degrees, typically representing CSH in PC mixes and (b) mass loss 400-500 degrees, typically representing CH in PC mixes.

6.2.5 Scanning Electron Microscopy (SEM)

The study of cement microstructure and the hydration of various cement compounds are greatly assisted by the scanning electron microscope (SEM) technique.

In this investigation, secondary electron (SE) images were taken under high vacuum using the Quanta 250 FEG Environmental SEM, Figure 6-28, with Oxford X-ACT Detector, secondary electron detector.

The SEM used in this study was equipped with an EDX attachment, which permits elemental analysis of minerals. The sample under investigation was bombarded with high energy electrons. A spectrum was generated that contains peaks, the positions of which indicate the presence of a particular element. It should be noted that the area being targeted for EDX is very finite (micrometers) and the electron beam will also release secondary electrons from near areas as well as from beyond the surface. For example, if a smaller particle is sitting on top of a larger particle, it is highly likely the electron beam will also target the underlying larger particle.

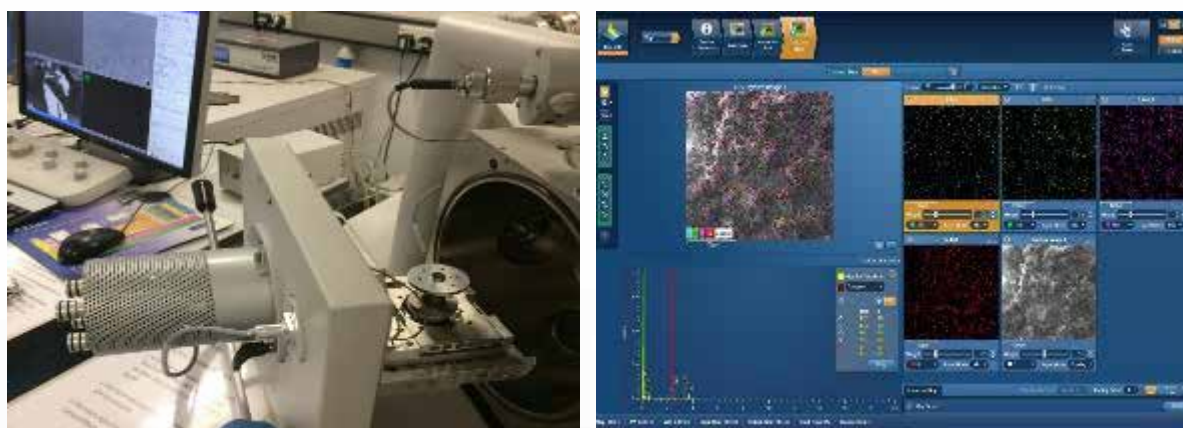


Figure 6-28 Quanta 250 FEG Environmental SEM (left) and output of EDX attachment providing elemental compositions (right)

High resolution SEM images were obtained to validate the mineral findings. Where possible, an elemental analysis was conducted (EDX) on a mineral of interest. This will help to determine the composition of the mineral and in some cases identification of the mineral if morphological details allow.

SSA hydration

The main minerals evident from the SEM on hydrated SSA sample are calcium phosphates with Fe, Si, Mg or Al inclusions. Figure 6-29 shows a large Phosphate mineral in the centre of the image (highlighted in blue/teal), with smooth surface texture. This mineral also has other smaller particles attached to its surface; they are also Phosphate minerals of different composition. The elemental composition of the blue/teal highlighted area is given in Figure 6-30, which also includes the composition of the smaller surface particles found in the blue/teal highlighted area. Results confirm the findings from the XRD analysis of raw SSA.

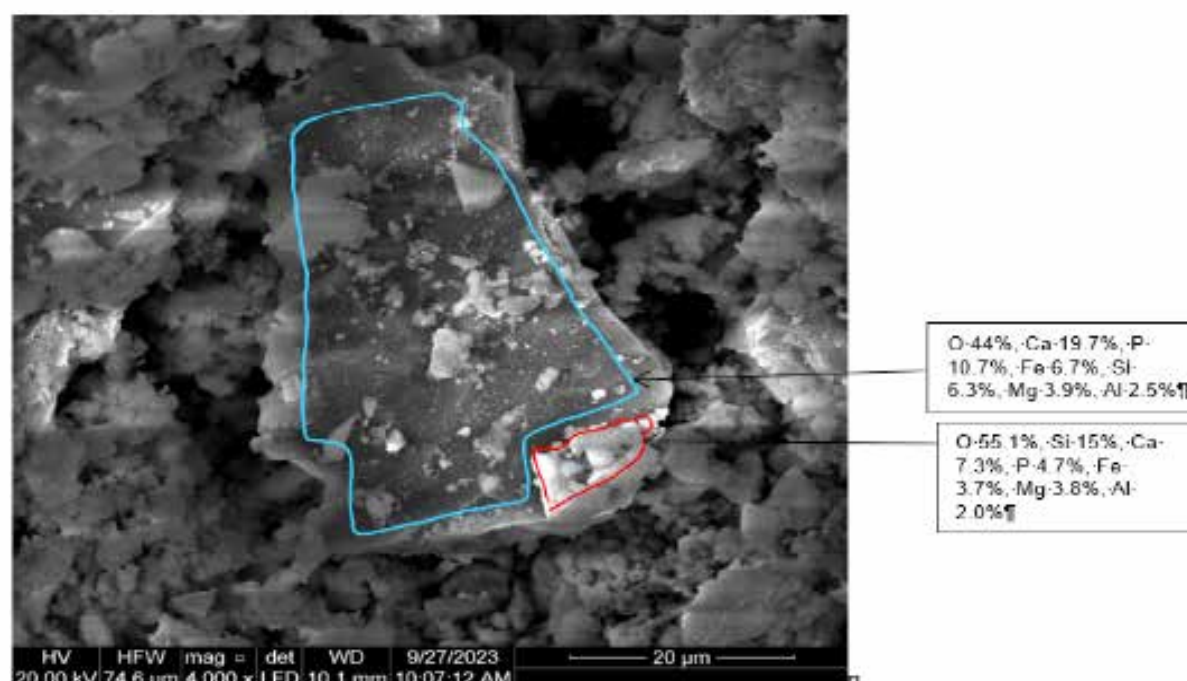


Figure 6-29 SEM image of a 90 days hydrated SSA sample. SEM. Elemental analysis performed on highlighted areas

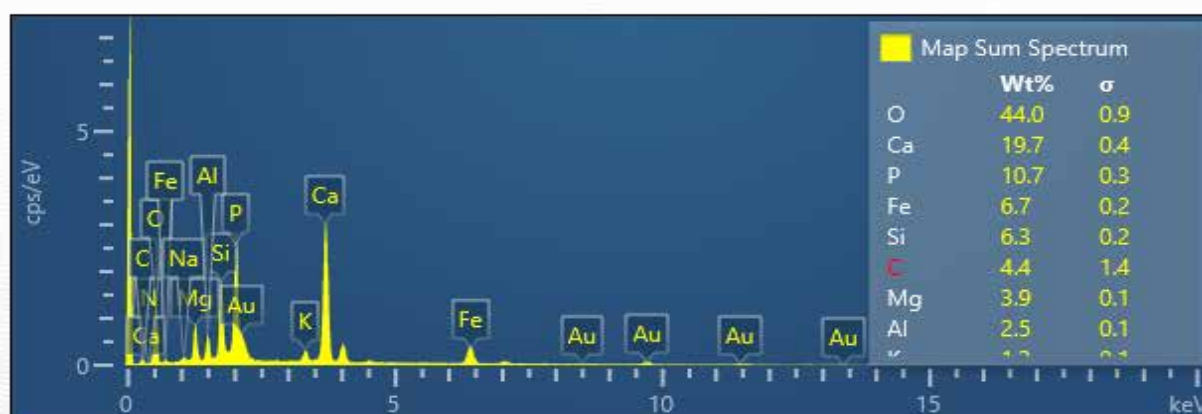


Figure 6-30 EDX elemental analysis of the large particle shown in Figure 14 from 90 days hydrated SSA sample

SSA (80%) and CH (20%) hydration :

The main minerals noted from SSA + CH sample are calcium hydroxide, ettringite and phosphate minerals. The elemental composition of the area in Figure 6-31, presented in Figure 6-32, shows Calcium, Silicon, Iron, Potassium, Phosphorous and Aluminium as the main elements. In Figure 6-31, the needle like ettringite crystals and plate like Calcium hydroxide are spread throughout. XRD results showed that ettringite disappeared between 28 to 90 days of hydration. But they are visible in Figure 6-31, despite the sample being 90 days of age. It is likely that these minerals are transforming into

monosulphates and the quantity of the remaining ettringites are low compared to monosulphates. The background (visible above the highlighted area) is likely to be a combination of monosulphate and other calcium phosphate mineral.

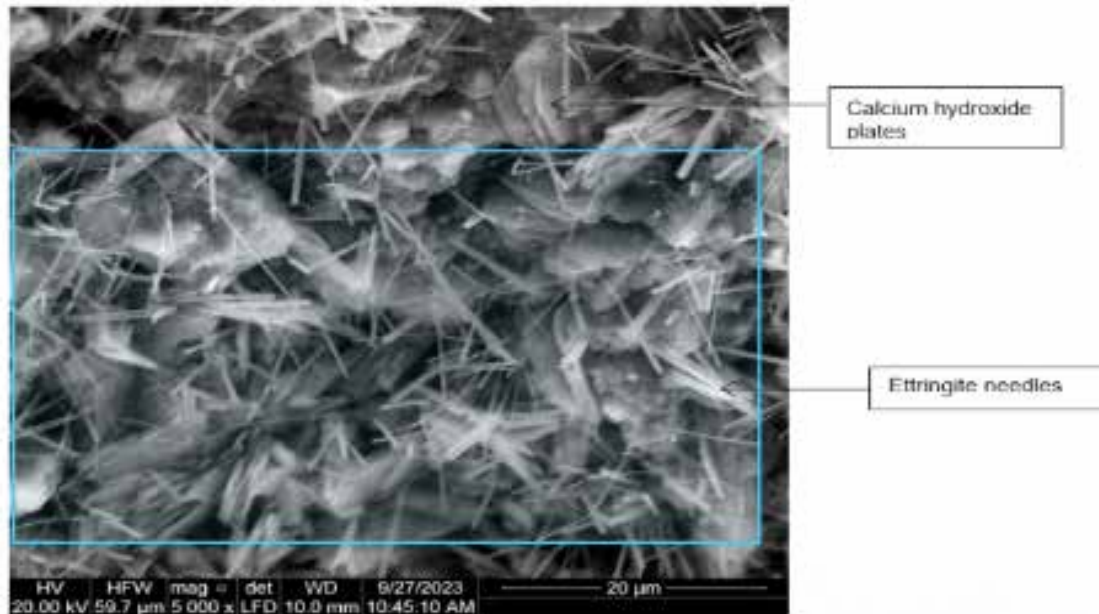


Figure 6-31 SEM image of a 90 days hydrated SSA + CH sample. SEM. Elemental analysis performed on highlighted area

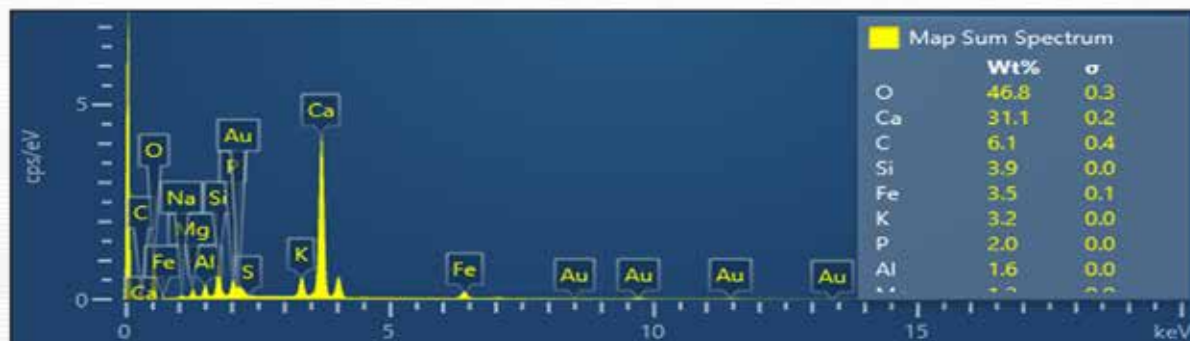


Figure 6-32 EDX elemental analysis of the large area highlighted in Figure 6-31 from 90 days hydrated SSA + CH sample

SSA (50%) and PC (50%) hydration:

Ettringite needles are visible in Figure 6-33. They are seen to be emanating from or fusing into other cementitious minerals, possibly CSH or monosulphate. The plate like substance highlighted in red contour is monosulphate. The SSA contributed to the calcium phosphate mineral background, as labelled in Figure 6-33. The elemental composition of blue/teal highlighted area is shown in Figure 6-34. This information confirms the mineral phases from XRD results.

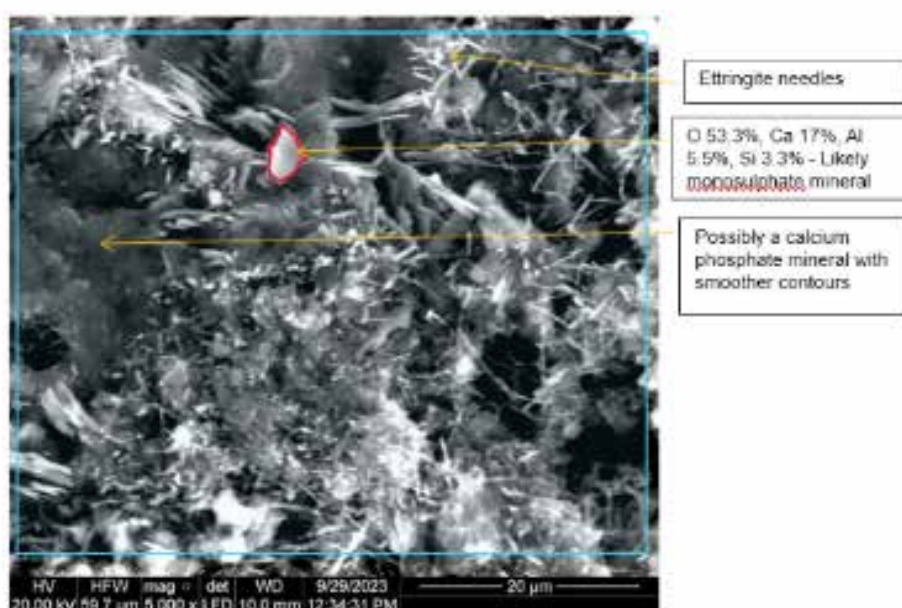
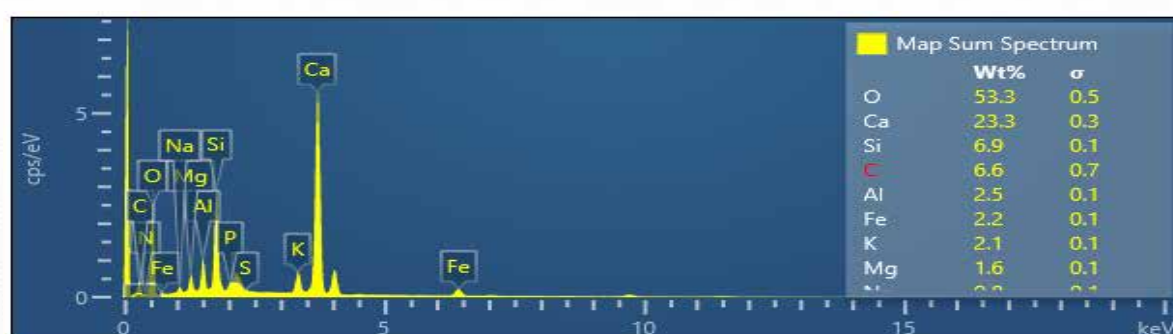


Figure 6-33 SEM image of a 90 days hydrated SSA + Portland sample. SEM. Elemental analysis performed on highlighted areas



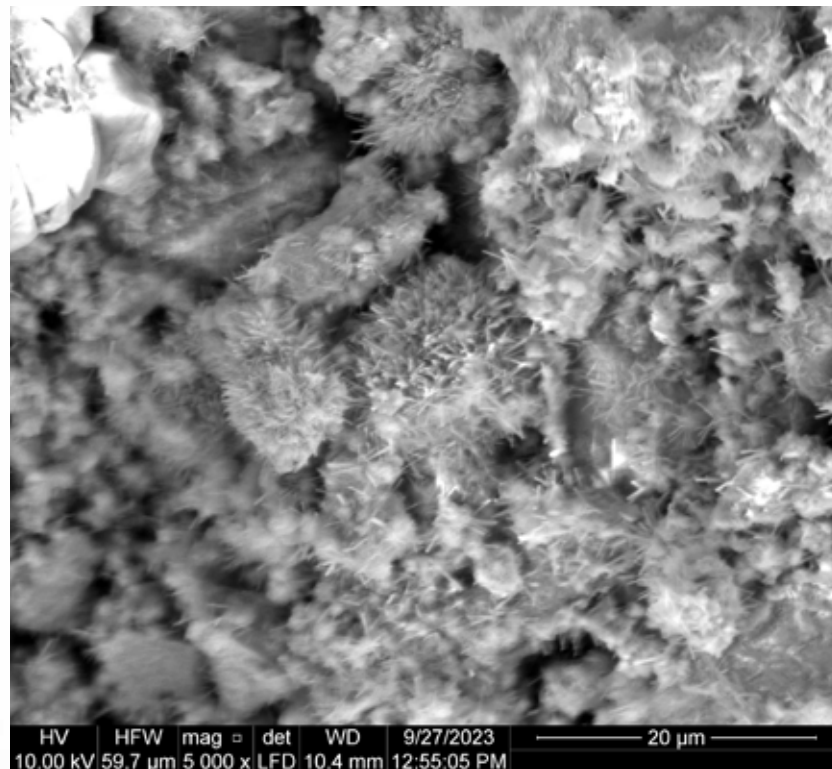


Figure 6-35 SEM image of a 90 days hydrated SSA + CKD sample. SEM. Elemental analysis performed on highlighted areas

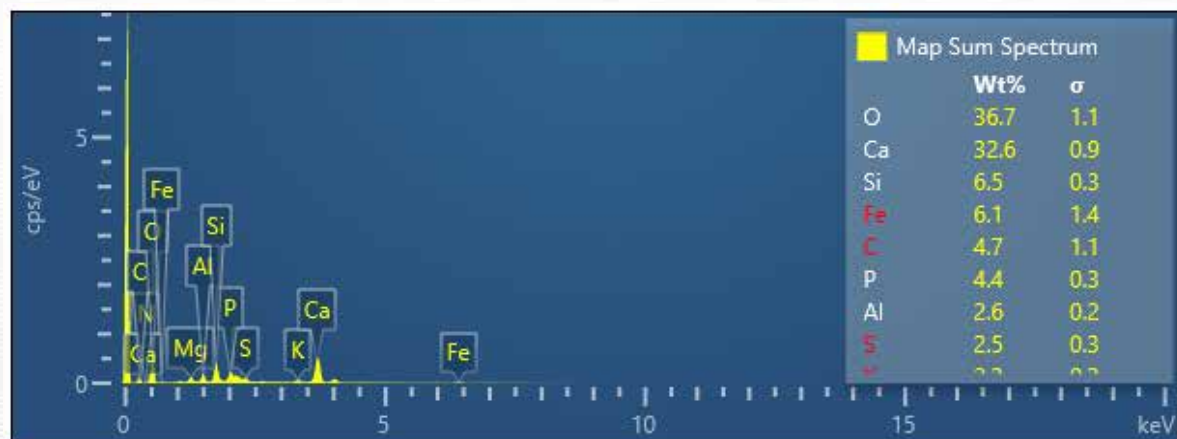


Figure 6-36 EDX elemental analysis of the large area highlighted in Figure 19 from 90 days hydrated SSA + CKD sample

6.3 Summary

The performance and durability of SSA concrete mixtures was assessed to produce low-strength concrete and compared with conventional concrete. The SSA mixtures exhibited similar consistency values to the PC, whereas higher values were observed for the SSA activated with lime and CKD. SSA increased the setting time of concrete, 3 times higher than PC concrete, mainly due to the increased content of phosphate that reacts with calcium and generates the insoluble calcium phosphate, limiting the access of water to the particles and hindering the hydration reaction. SSA had marginal effect on the density and workability of fresh concrete, compared to PC concrete. SSA possessed very low compressive strength values, up to 90 days of age. Replacing 50% and 75% of the PC with SSA resulted in 28-day compressive strength values of 27 MPa and 20 MPa, respectively, lower by 46% and 27% when compared to the 100% PC control mortar.

Drying shrinkage of concrete is the result of the loss of internal moisture to achieve equilibrium with the relative humidity (RH) of the external environment. Mortar mixtures incorporated SSA exhibited lower shrinkage values than conventional PC mortar. The 25SSA+75PC, 50SSA+50PC and 90%SSA+10CKD exhibited shrinkage values in the range of 0.44% to 0.65%, approximately 25% of the value achieved by the control 100% PC mixture. Immersion in hot water and expansion testing showed lowest values for the SSA and SSA-CKD mixtures, whereas the highest expansion values were for the SSA-Lime and PC mixtures. The durability of SSA low-strength concrete products was assessed from strength retention after immersion in water. The results indicate that immersion in hot water has no detrimental effects on the strength development and durability of controlled low-strength concrete mixtures. The SSA-PC mixtures exhibited strength gain after immersion in water and indicating more hydration and strength development in water.

Microstructural analysis indicated that SSA did not exhibit any normal hydration behaviours and no change was noted between 2 to 90 days. There may be some indication of limited pozzolanic reactivity in SSA, based on the formation of hydrates in the SSA blends with CKD, PC, and hydrated lime. There is clear indication of reactive alumina and a sulphate source in SSA, which resulted in various blends reacting with a calcium source (in PC, CKD, hydrated lime) to produce ettringite and monosulphates (AFm). The presence of AFm phases indicate that if more calcium sulphate (e.g. gypsum) was present, increased ettringite formation would likely occur.

The above findings would indicate that SSA only blends will not normally gain strength when hydrated with water, it would require calcium source to utilise the reactive alumina to form new minerals. The percentage of calcium and sulphate can be controlled to have maximum utilisation of alumina that is present in SSA, this will create a viable construction material albeit of low strength. It is likely that the ettringites will result in reduced drying shrinkage for such blends. However, further durability testing will be required, including shrinkage/expansion, reactivity to sulphates and long-term stability/expansion in moist environments.

7 Site Trials

Full-scale production of concrete blocks and foam concrete are presented in this chapter to demonstrate how the SSA could be used as green cement in practice. The concrete blocks and foam concrete was produced in collaboration with representative from the construction industry. The performance of SSA products was assessed in comparison with conventional products made with 100% PC. The new construction products were also assessed for compliance with the Qatar Construction Specifications (QCS 2014).

7.1 Concrete Blocks

Concrete blocks are one of the low-strength products selected for the application of green cement, made with incinerated sewage sludge ash (SSA). The SSA is used to partially replace Portland cement (PC) in the full-scale production of concrete blocks. The performance of SSA blocks was compared to that of conventional concrete blocks made with 100% PC.

Concrete block is one of the main precast concrete products with estimated annual production of 500 million blocks. The QCS 2014 allows the use of recycled aggregate, to replace primary aggregates, in the production of concrete blocks. However, there is no provision for the use of cement replacement and other solid waste materials to replace PC. This section covers the use of SSA green cement in the production of concrete blocks and compliance with the requirements of the QCS 2014.

7.1.1 Production of the blocks

The production of concrete blocks took place in summer, on Saturday 15th July, in the factory of Fahad Bin Abdulla at the Industrial Area of Doha. Three mixtures were used for the production of concrete blocks, with the mix composition given in Table 7-1.

Table 7-1 Mix composition of the concrete blocks (kg)

Mix	Control-100% PC	SSA-10%	SSA-20%
PC	300	270	240
SSA	-	30	60
Washed sand – 5mm	450	450	450
Dune sand – 3mm	450	450	450
CDW – 10mm	1200	1200	1200
Wadi gravel – 10mm	650	650	650
Water	150	150	150
Superplasticiser	5	5	5
Total	3206	3206	3206

The control mix was made of 100% PC, with the mix composition of the weight ratio of 1 part of binder to 3 parts of fine aggregate (sand, 5mm) to 6 parts of coarse aggregate (10mm) to 0.5 part of water. The water/binder ratio was 0.5 for all mixtures, and a fixed dosage of superplasticiser (SP) of 5 kg per cubic metre was used for all mixtures. The SP used was based on polycarboxylic polymers and supplied by Don Construction Qatar. The SSA mixtures were made by replacing 10% and 20% by weight of PC with SSA and were given the codes of "SSA-10%" and "SSA-20%", respectively. Hollow blocks were made from the three mixtures given of Table 7-1, 160 blocks from each mix of the dimensions of 200 x 200 x 400 mm.



Figure 7-1. Mixing of the concrete block materials

The coarse aggregate used to produce concrete blocks was 100% recycled and alternative materials. The construction and demolition waste (CDW) aggregates were supplied by Al-Awalia (Qatar Primary Materials Company) and was produced from the crushing and screening of construction and demolition waste. The Wadi gravel is a by-product from the washing of concrete sand in sand washing plants and was supplied from the Qatar Sand Treatment Plant (QSTP). The washed sand (fine aggregate) was also supplied by QSTP. The production of concrete blocks was made by blending the concrete ingredients as shown in Figure 7-2 and described hereafter.

The aggregate materials were initially weighed and loaded automatically into a mixer with the capacity of 0.5 tonnes. The aggregate materials were mixed dried first for 20 second before adding half of the mixing water. SSA was then added manually whereas the PC was added automatically to maintain a total binder content of 300 kg per cubic metre of blocks. The remaining mixing water was then added and followed by the SP. Samples were collected manually from the mixed and assessed visually for consistency. The total mixing process took approximately 60 seconds. Table 7-2 shows the various stages of aggregate loading and mixing of the materials.



Figure 7-2 Production of concrete blocks, pressure machine (left), curing and final products (right)

Once the concrete has thoroughly mixed it is fed into a vibrated pressure machine and moulded into the required shape and dimensions under a hydraulic pressure of 165 bars for 5 seconds. Hollow blocks of 400x200x200mm were produced as shown in Table 7-2. No difference in the production process was observed due to the use of SSA, unless the manual addition to the mixer. The freshly compacted blocks are moved onto a flat pallet using a conveyor and transferred into curing room maintained at $40\pm 2^{\circ}\text{C}$ and $65\pm 5\%$ relative humidity for 1 day. Table 7-2 also shows the transfer of the concrete blocks to the curing room (top right). After curing, the blocks are rolled out of the curing room and are aligned into pallets of 108 blocks each and stored outdoors. Table 7-3 shows the concrete blocks storage after 1 day of curing at controlled environment conditions.



Figure 7-3 Concrete blocks were stored outdoor until testing

7.1.2 *Testing, results, and compliance*

The concrete blocks were transported from the block factory (Fahad Bin Abdulla) to the Doha Technical Laboratory for testing at the age of 28 days. For each mixture, six blocks were tested for compressive strength as per BS EN 772-1 (2011) and dimensions determination to BS EN 772-16 (2011). Additional three blocks were tested for water absorption as per CML-9 (Qatar Standards, 1997).

The CML water absorption test method is based on drying the blocks in an oven for 72 hours at 105°C , to remove the free water, followed by immersing in water for 30 min. The QCS 2014 specifies the determination of average compressive strength and water absorption values, based on the testing of minimum 3 individual blocks for each test. In this investigation, six blocks were tested for compressive strength whereas three were used for water absorption. The compressive strength and water absorption results are given in Table 7-2.

Hollow blocks are generally used for the construction of non-load bearing walls. The Qatar Construction Specification (QCS, 2014) specifies a minimum average compressive strength of 7.0 MPa, with the lowest individual block ≥ 5.6 MPa for external non-load bearing walls. For internal non-load bearing walls, the minimum average compressive strength requirement is 4.0 MPa, with the lowest individual block ≥ 3.6 MPa. The QCS also specifies a maximum average water absorption of 7.0 %, and no individual block shall have a water absorption greater than 7.5% as per the CML Method 9-97 (1997). The water absorption requirements are identical for the external and internal non-load bearing walls.

Table 7-2 and Figure 7-4 present the compressive strength results of the concrete blocks made with PC and SSA binders. The Control 100% PC and the 10% SSA concrete blocks exceeded the minimum compressive strength requirement for external non-load bearing walls, with average strength values of 8.8 MPa and 8.0 MPa, respectively. The lowest individual block strength was also greater than the minimum requirement of 5.6 MPa. The 20% SSA achieved a lower average compressive strength of 6.1 MPa with the lowest individual block strength greater than 3.6 MPa, suitable for use in internal non-load bearing walls.

Table 7-2 Properties of concrete mixtures for blocks

	Block No.	Control-100% PC	SSA-10%	SSA-20%
Compressive Strength (MPa)	1	9.0	6.9	6.1
	2	9.7	10.3	6.3
	3	7.9	6.7	5.8
	4	8.2	8.3	6.6
	5	8.8	7.6	6.2
	6	9.1	7.9	5.7
	Average Strength	8.8	8.0	6.1
Water Absorption (%)	7	5.6	4.6	4.9
	8	4.3	4.6	5.1
	9	3.8	5.1	4.8
	Average Absorption	4.6	4.8	4.9

Figure 7-4 shows that the addition of SSA reduces the strength of the concrete blocks and the reduction is proportional to the SSA. The use of 10% SSA reduced the average compressive strength from 8.8 MPa to 8.0 MPa, approximately 10% reduction in strength compared to the Control 100% PC blocks. Similarly, the use of 20% SSA reduced the average compressive strength from 8.8 MPa to 6.1 MPa, a reduction of approximately 30% compared to the Control 100% PC blocks. The results clearly encourage the use of 10% SSA for concrete blocks that comply with the QCS 2014 strength requirement for external non-load bearing walls.

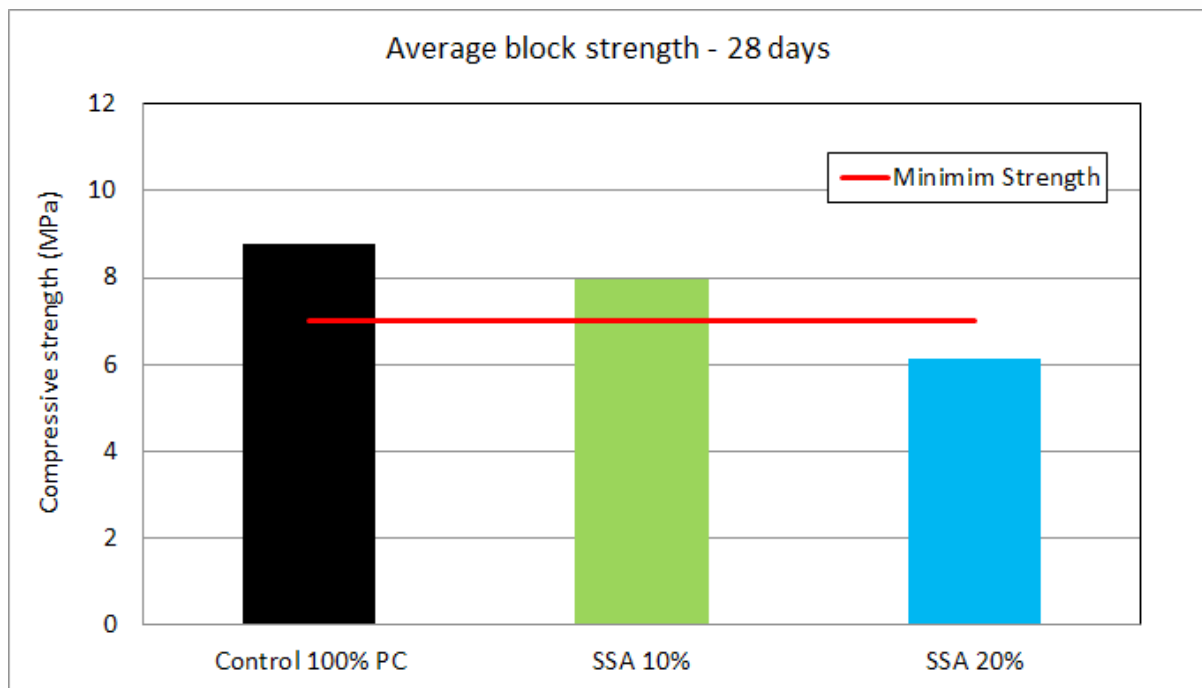


Figure 7-4 Compressive strength of SSA and PC concrete blocks

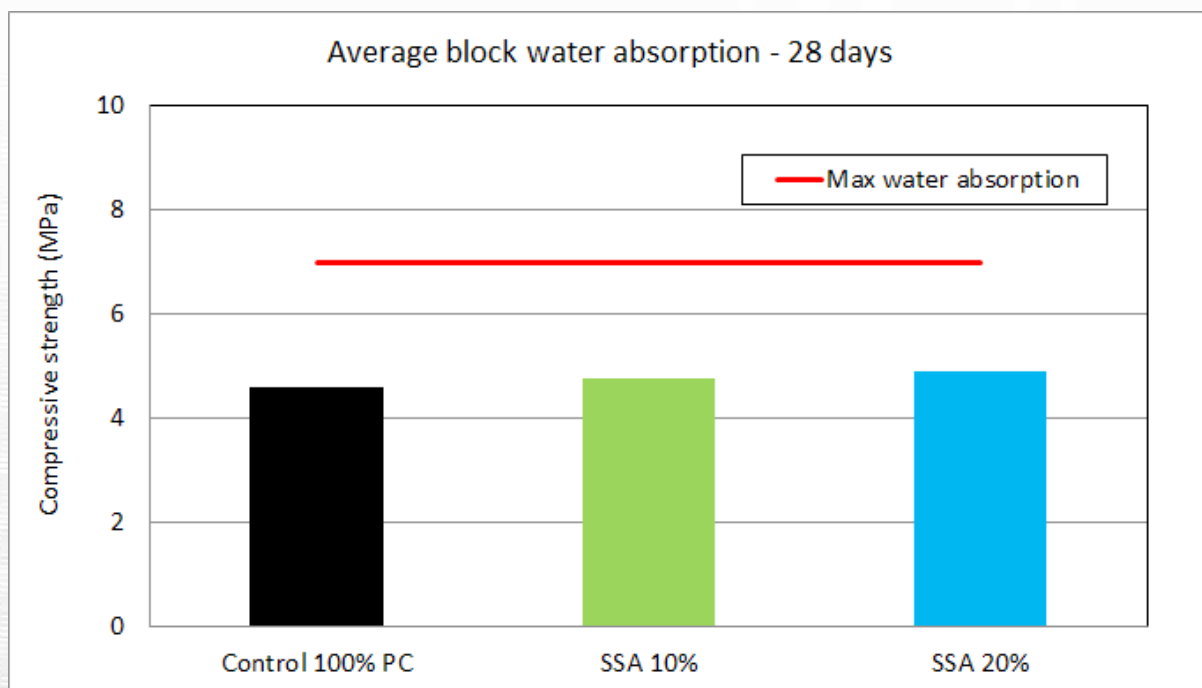


Figure 7-5 Water absorption of SSA and PC concrete blocks

Table 7-2 and Figure 7-5 present the water absorption results of the concrete blocks made with PC and SSA binders. The average water absorption values of the three mixtures ranged between 4.6% and 4.9%, lower than the maximum specified limit of 7% in the QCS 2014. The lowest average absorption

value was found for the Control 100% PC mixture, whereas the highest was for the 20% SSA mixtures. For the individual concrete blocks, the highest value was 5.6% for the Control 100% PC that is lower than the maximum specified limit of 7.5%.

The results indicate that SSA can be successfully used to replace 10% of PC with full compliance with the QCS 2014 requirements for use in external load-bearing walls. The 10% SSA blocks reduced the compressive strength by 10% and increased the water absorption by 4%, when compared to the Control 100% PC blocks. The properties of 10% SSA complied fully with the QCS 2014 requirements for use in external non-load bearing walls.

The 20% SSA exhibited lower compressive strength, approximately 30% reduction and increased the water absorption by 6% when compared to the Control 100% PC blocks. The 20% SSA blocks are not suitable for use in external but in internal non-load bearing walls.

7.2 Foam Concrete

Foam concrete (FC) is widely used as a backfill material in Qatar, with estimated 0.5 million cubic metres of materials consumed last year. FC is a cementitious mortar in which air-voids are entrapped in the mortar by a suitable foaming agent. FC has many advantages compared to conventional concrete in terms of high flowability, lightweight, controlled low strength, minimal consumption of aggregate, and good thermal insulation properties. This section covers the site trials for the implementation of FC in the reinstatement of road settlements around manhole covers. Two mixtures of FCs were used to include a Control PC and SSA. The production and performance characteristics of both foam concrete mixtures are presented in the section together with their compliance with national specifications.

7.2.1 Road reinstatement – Al-Thummama

The site selected for the site trial was part of the Ashghal Road Operations and Maintenance Department (ROMD) projects for road reinstatements. ROMD is responsible for the operation and maintenance of the road network in Qatar. As part of ROMD activities, Al-Thummama Road Reinstalment Project (Qatar North Section, Contract ZF_024) is a development scheme to reinstate the pavement depressions around manhole covers in local roads. Various depressions and patches were observed on Umm Al-Hawaya St, within Al-Thummama area, as shown in Figure 7-6. Visual inspection of the site indicated severe pavement depressions, up to 100mm in depth, around manhole covers. In some locations, the depressions were associated with cracking and disintegration of the pavement layers, Figure 7-6.

Depression around manhole covers is a common pavement defect due to the difficulty of compacting around the round manhole covers. Rolling compaction equipment are not permitted to pass near to the manhole frame and cover, as they may damage them. Backfilling with unbound materials will result in inferior compaction and will be subject to depression under traffic loadings. Best practice

includes placing the materials around the manhole cover and use a manual vibrating equipment to compact around the manhole cover, without touching the frame or cover. However, many contractors they do not perform good compaction and therefore the problem is noticed in many roads in Qatar.

The ROMD developed a procedure for the reinstalment around manhole covers, as given in the Amendment to the Code of Practice and Specification for Road Openings in the Highway (Ashghal, 2014). The procedure does not permit the use of unbound materials for the backfill of trenches up to 1.5m depth from surface. The following concrete materials are permitted for backfilling:

- Controlled Low Strength Material (CLSM) with a 28-day unconfined compressive strength of between 0.3 MPa and 2.5 MPa when tested in accordance with ASTM D4832 (2016);
- Foamed concrete with a characteristic 28-day compressive strength of 5 MPa;
- Fluidised Thermal Backfill (FTB) with a characteristic 28-day compressive strength of 5 MPa;
- SRC 20 concrete, which shall only be used for shallow utility trenches which require a concrete surround.



Figure 7-6 Depressions around manhole covers – Umm Al-Hawaya St

The current practice in Qatar is to use SRC 20 concrete, sulfate-resistant concrete with a 28-day strength of 20 MPa. The site trials included replacing the SRC 20 concrete with foamed concrete. Two types of foamed concrete were investigated to include a Control foam concrete made with 100% PC as the main binder, whereas the second type of foamed concrete was made of 40% SSA and 60% PC. Foam concrete offers many advantages over conventional SRC 20 concretes in terms of high flowability, lightweight, controlled low strength, minimal consumption of aggregate, and good thermal insulation properties. Foam concrete is also considered to be excavatable by hand tools and conventional machinery such as backhoe excavators, and therefore are ideal for reinstatement works.

7.2.2 *Site preparation and foam concrete*

Two manhole covers were selected for the site trials with pavement depressions around the covers. The pavement was excavated around the manhole cover to remove all depressed pavement areas. The area of excavation around the manhole was approximately 3.8m x 3.8m, with a depth of approximately 0.6m. Figure 7-7 shows the excavation around the manhole cover, using an excavator drill to break the asphalt layers followed by excavator crawler. The excavated materials were removed from around the manhole cover, and the bottom of the excavation was compacted using a vibrating hammer to produce a stable subgrade material. The completed excavation around manhole covers is shown in Figure 7-8, ready for the application of foam concrete.



Figure 7-7 Excavation around manhole cover



Figure 7-8 Completed excavation around manhole cover



Figure 7-9 Application of PC foamed concrete around manhole cover

The application of foam concrete was conducted on Thursday, 24th August 2023, where the average air temperature was 42 °C and 70% relative humidity. The excavated surfaces were sprayed by water to improve the bond with the foam concrete. ReadyMix Qatar supplied the foam concrete for the Control PC and SSA mixtures, in ready mix trucks. No difference was reported by ReadyMix Qatar in the production of SSA foam concrete compared to the production of PC foam concrete.

Approximately five cubic meters of each foam concrete mixture were delivered and poured into the excavated area as shown in Figure 7-9 for the PC foam concrete and Figure 7-10 for the SSA foam concrete. The foam concrete was self-levelling, so no compaction was required on site. In fact, the foam concrete was fluid but homogeneous with no segregation or bleeding associated with the high workability. The foam concrete was poured to the required level and then left to cure in normal exposure environment without the use of water or curing agents. Plastic barriers were placed around the freshly poured foam concrete until the concrete is set.



Figure 7-10 Application of SSA foamed concrete around manhole cover

Once the foam concrete hardened, the plastic barriers are removed, and the surface of foam concrete was temporarily covered with reclaimed asphalt pavement (RAP) to be levelled with the existing road. Figure 7-11 shows the RAP material placed on the top of foam concrete. The RAP material is used temporarily till all the depressed areas are reinstated before milling and replacing the asphalt wearing course for the whole project, as shown in Figure 7-12.



Figure 7-11 Covering of foam concrete with RAP



Figure 7-12 Placing the new asphalt wearing course on top of foam concrete

7.2.3 *Properties of foam concrete*

Two foam concrete mixtures were considered in this investigation, with the mix compositions given in Table 7-3. PC was used to produce the control FC mixture with a Portland cement content of 260 kg/m^3 . A blended SSA (40%) and PC (60%) binder was used for the production of the SSA foam concrete. The sand content and mixing water were fixed for both mixtures at 1530 kg/m^3 and 244 kg , respectively. The w/c was 0.94 for both foam concrete mixtures. A high-performance superplasticiser (SP), based on polycarboxylic polymers, was supplied by Don Construction Products Qatar and used to enhance the workability of foam concrete at a dosage of 6.0 litres/m^3 . A synthetic foam was used, based on sodium laureth sulfate and supplied by CHRYSO Gulf LLC. The amount of foam used is 2.5 kg/m^3 , which is used for the generation of stabilized air-entrainment during the production of foam concrete.

Table 7-3 Mix proportions of foamed concrete (kg/m^3)

Mix	Binder		Sand	Water	SP (l/m^3)	Foam
	PC	SSA				
Control-PC	260	-	1530	244	6.0	2.5
40SSA-60PC	156	104	1530	244	6.0	2.5

Samples of the foam concretes were taken from the two mixtures for testing and assessment of fresh and hardened properties.

7.2.3.1 Fresh properties

The fresh foam concrete mixtures were tested for wet density, as per BS EN 12350-6 (2019), air content to BS EN 12350-7 (2019), flow table to BS EN 12350-5 (2019), and setting times to ASTM C403 (2008). The results are summarised in Table 7-4, whereas **Error! Reference source not found.** shows the testing of fresh foam concrete mixtures on site.

Table 7-4 Properties of the fresh FC mixtures

Mix	Wet density (kg/m ³)	Air content (%)	Flow table (mm)	Setting time (minutes)	
				Initial	Final
Control-PC	1,583	27	680	1,507	2,129
40SSA-60PC	1,560	25	670	3,653	5,681

Foam concrete mixture is a highly workable free flowing concrete that levels under its own weight without compaction. The results in Table 7-4 show that both foam concrete mixtures achieved wet density values just below 1600 kg/m³, and could be classified as a lightweight concrete. The low density is mainly due to the elimination of coarse aggregates and the use of a foaming agent. The control PC foam concrete gave a wet density of 1583 kg/m³, compared to 1560 kg/m³ for the SSA foam concrete.

The air content results were similar for both mixtures, with 27% for the PC foam concrete and a slightly lower value of 25% for the SSA foam concrete. Both values of air contents are relatively high as reflected in the low density of the produced foam concretes. The flow table results showed high flowability concrete and similar values for the PC and SSA foam concretes. The flow table of the PC and SSA foam concretes were 680 mm and 670 mm, respectively. The results indicate that both foam concrete mixtures are highly flowable with low density and high air content. Visually, both mixtures looked homogeneous and with high stability. Despite the high air content and workability, no evidence of segregation or bleeding was observed.



Figure 7-13 Site testing of fresh FC of workability, density, and air content

Concrete cubes of 150mm were made from the foam concrete and used for the measurement of setting time as described in ASTM C403 (2008). The results in Table 7-4 show that the initial and final setting times of the foam concrete mixtures. The FC foam concrete exhibited setting time values of 1,507 minutes (approx. 25 hours) for the initial setting time and 2,129 minutes (35 hours) for the final setting times. These values are considerably high compared to conventional PC concrete, reflecting the effect of foam on delaying the setting time of concrete. The use of SSA resulted in further delay of the setting time to achieve initial and final setting times of 3,653 minutes (60 hours) and 5,681 minutes (95 hours), respectively. The SSA delayed the initial setting by 2.4 times and the final setting by 2.7 times of the control 100% PC foam concrete.

7.2.3.2 Hardened properties

Concrete cubes, 150mm sides, were prepared and used for testing the hardened properties of foam concrete as shown in Figure 7-14. The concrete cubes were cured in sealed plastic pages at room

temperature of $20 \pm 2^\circ\text{C}$ and tested at the ages of 7, 14 and 28 days for density and compressive strength. The density was determined from the weights in air and water before the cubes were crushed for compressive strength. Additional cubes were prepared for assessing the durability after immersion in water. After 14 days of curing in sealed plastic bags, the cubes were immersed in water at the same curing temperature of $20 \pm 2^\circ\text{C}$ for another 14 days and tested at the age of 28 days for retained strength. The retained strength is determined from the ratio of the average compressive strength after immersion in water to the average strength after curing in sealed plastic bags at the same age of 28 days. Three cubes were used for each test at a specific age and the average values are reported in Table 7-5.



Figure 7-14 Concrete cubes for density and strength measurement

Table 7-5 Properties of hardened foam concrete

Property	Control-PC	40SSA-60PC
Density (kg/m^3) – 7 days	1528	1541
Density (kg/m^3) – 14 days	1520	1538
Density (kg/m^3) – 28 days	1549	1552
Compressive strength (MPa) – 7 days	4.1	2.4
Compressive strength (MPa) – 14 days	4.3	3.3
Compressive strength (MPa) – 28 days	5.2	3.6
Retained strength MPa (%) – 28 days	4.1 (80%)	2.9 (81%)
Core strength MPa – 28 days	3.5	4.1



Figure 7-15 Coring of foam concrete around manhole covers

Cores were also taken from the laid foam concrete mixtures and tested for compressive strength at the age of 28 days, as shown in Figure 7-15. The cores were taken to verify the results of the laboratory-cured cubes. The core strength results are also given in.

The density results, as given in Table 7-5, gave values between 1520 and 1552 kg/m³ for both foam mixtures at all tested ages. The results indicate a lightweight foam concrete with density below 1600 kg/m³, with a small variation between the PC and SSA foam concrete mixtures.

The average compressive strength results for the PC and SSA foam concretes are given in Table 7-5, and also presented in Figure 7-16. The PC foam concrete exhibited compressive strength values of 4.1 MPa at 7 days and 5.2 MPa at 28 days. The SSA foam concrete gave lower strength values of 2.4 MPa at 7 days and 3.6 MPa at 28 days. The core strength results gave a different trend at the age of 28 days, as the SSA cores exhibited an average compressive strength of 4.1 MPa, compared to 3.5 MPa for the PC foam concrete. For the cube strength, the SSA foam concrete, made with replacing 40% of the PC with SSA, achieved 69% of the 100% PC foam concrete at the age of 28 days. However, for the core strength the SSA foam was 14% higher than the strength of the control PC foam concrete.

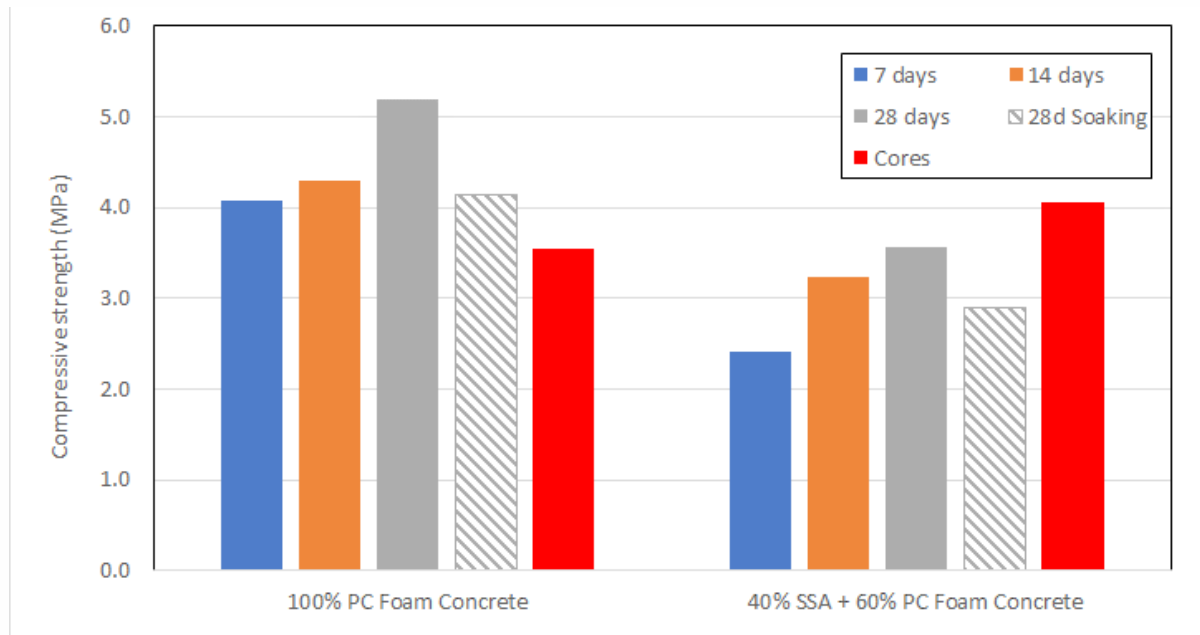


Figure 7-16 Compressive strength of foam concrete mixtures

The PC and SSA foam concrete gave retained strength values of at least 80% of the control cube strength, indicating good resistance to water immersion and enhanced durability.

Verification of results

Verification testing was conducted on the foam concrete by taking fresh concrete samples and prepare additional cubes, 150mm sides, at one of the approved testing laboratories by Ashghal. The concrete cubes were demoulded after 2 days of age and tested for compressive strength at the ages of 2, 7, and 28 days. The results are graphically presented in Figure 7-17. The effect of delayed setting time is reflected in both foam concrete mixtures at the age of 2 days, with values of 1.7 MPa and 0.80 MPa for the PC and SSA foam concrete, respectively.

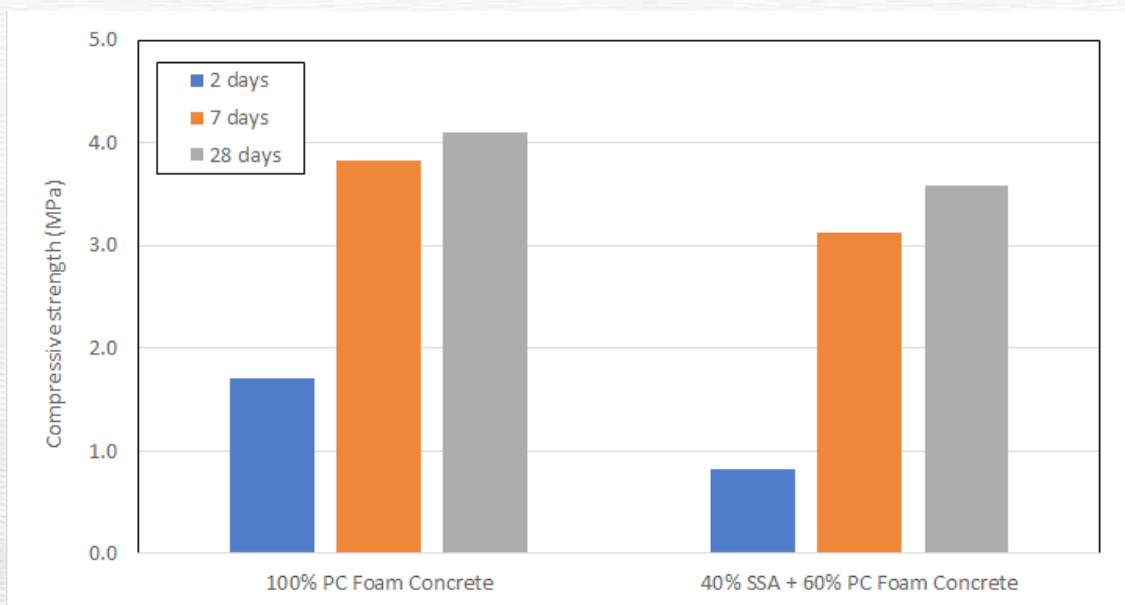


Figure 7-17 Verification of compressive strength results

The main strength developed was achieved at the age of 7 days with the PC concrete reaching 3.8 MPa compared to 3.1 for the SSA foam concrete. At the age of 28 days, the SSA foam concrete achieved an average strength value of 3.6 MPa identical to that achieved from the site cubes. However, the verification testing for the PC shows an average 28-day strength of 4.1 MPa, lower than the value obtained for the site cubes. The ratio of the SSA strength to the PC strength at 28 days is 87%.

In general, the strength and durability results show that SSA could be used effectively for the production of foam concrete with compressive strength values exceeding the values specified in the Ashghal CoP (Ashghal, 2014) for controlled low strength material, but slightly lower strength than specified for foam concrete of 28 MPa. Replacing 40% by weight of PC with SSA reduced the compressive strength of foam concrete by approximately 13% without impairing the durability of concrete. The high retained strength indicates the good durability provided by the SSA foam concrete, similar to that of PC foam concrete, after immersion in water.

7.3 Summary

The QCS 2014 allows the use of recycled aggregate, but no provision is provided for the use of alternative binders. SSA was used as a green cement to replace 10% and 20% by weight of PC in the production of concrete blocks.

The 10% SSA concrete blocks exhibited similar performance to the Control 100% PC concrete blocks, with full compliance with the QCS 2014 for use in external non-load bearing walls. The 10% SSA gave average compressive strength of 8.0 MPa and average water absorption of 4.8%, compared to 8.8 MPa and 4.6% for the Control 100% PC blocks. The 10% SSA showed marginal reduction in the compressive strength, 10%, and in the water absorption, 4%, when compared to the Control 100% PC concrete.

The 20% SSA exhibited inferior properties of 6.1 MPa and 4.9% water absorption, satisfying the QCS 2014 requirements for use in interior non-load bearing walls. The strength reduction was approximately 30% and the increment of water absorption was 6%, when compared to the Control 100% PC blocks.

SSA was used to replace 40% by weight of PC in the production of foam concrete (FC) for use as a backfill material for the road reinstatement around manhole covers. The PC and SSA foam concrete mixtures exhibited lightweight properties with density values of less than 1800 kg/m³ and air content exceeding 25%. Both FC mixtures are highly flowable that are self-levelling without the need of compaction. Despite the lightweight and high air content, the FC mixtures were homogenous and showed no evidence of bleeding or segregation during pouring and curing.

The initial and final setting time of the PC foam concrete were 25 hours and 35 hours, respectively. These values are considerable high compared to approximately 2 and 4 hours for normal PC concrete, and mainly because of the foaming agent. The use of SSA resulted in further delay of setting time by 2.4 – 2.7 times of the control 100% PC foam concrete.

The 28-day cube compressive strength values of the PC and SSA 5.2 MPa and 3.6 MPa, respectively. However, the core compressive strength gave a different trend of 3.5 MPa for the PC and 4.1 MPa SSA foam concretes. Verification testing at an independent testing house indicated average 28-day strength values of 4.1 MPa for the PC and 3.6 MPa for the SSA mixtures. Both mixtures exhibited high retained strength, after immersion in water, and indicating good durability for underground applications.

8 Environmental and Economic Benefits

The newly developed SSA concrete products are associated with cost and environmental benefits as discussed in this chapter. The variability of chemical compositions of SSA was assessed for the reliable production of green cement. Heavy metals within the sludge are generally encapsulating within the new green cement and SSA concrete products to minimise their leaching to the environment. A carbon footprint assessment is conducted on the production of SSA and SSA concrete products and compared to that of conventional PC and PC concretes. Finally, the cost associated with the processing of SSA and production of SSA concrete are calculated and compared to conventional products.

8.1 Variability of SSA Composition

SSA is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. While the composition of sewage sludge could vary widely, mainly the organic matters, limited information are available on the composition of inorganic materials. This section covers the variability of incinerated SSA, as obtained from the DNWWTP in Qatar. Samples of sludge pellets were collected monthly, over a period of six months, and tested for chemical composition to assess potential use in the production of green cement.

8.1.1 Chemical composition

Table 8-1 gives the chemical composition of SSA produced at the DNWWTP and tested monthly between May 2022 and October 2022, as determined using X-ray fluorescence technique (XRF).

Table 8-1 Variation of SSA composition from DNWWTP

Type	Apr-20	Aug-21	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Mean	CV%
SiO ₂ 19.1 20.9			18.3	19.4	19.3	21.8	19.3	17.7	19.5	6.4%
Al ₂ O ₃	5.1	6.9	5.7	5.9	5.6	6.2	5.6	5.2	5.8	9.2%
Fe ₂ O ₃	8.2	10.7	9.7	12.9	8.4	12.7	9.3	11.0	10.4	16.1%
CaO	28.3	22.2	22.1	22.4	21.8	22.1	22.3	21.0	22.8	9.3%
MgO	8.0	8.3	8.6	8.4	8.7	8.3	8.6	7.7	8.3	3.7%
SO ₃	0.5	1.2	0.8	0.4	0.4	2.1	0.6	0.5	0.8	65.5%
Na ₂ O	0.9	1.0	1.0	0.9	0.9	1.1	1.0	1.2	1.0	8.6%
K ₂ O	1.4	2.2	3.0	2.5	2.8	1.7	2.1	1.8	2.2	23.5%
TiO ₂	0.6	0.7	0.6	0.6	0.6	0.7	0.6	0.6	0.6	5.7%
Mn ₃ O ₄	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	12.8%
P ₂ O ₅	14.2	21.0	25.0	23.6	22.8	19.7	20.2	19.3	20.7	15.0%

The oxide compositions of additional samples tested in April 2020 and August 2021 from the same DNWWTP are also included in Table 8-1 and Figure 8-1. The mean value of the different oxides as well as the coefficient of variation (CV%) are also presented in Table 8-1. The results show that the main oxides found in SSA include silicon oxide (SiO_2), aluminium oxide (Al_2O_3), calcium oxide (CaO), iron oxide (Fe_2O_3), magnesium oxide (MgO) and phosphorus oxide (P_2O_5) as shown in Figure 8-1.

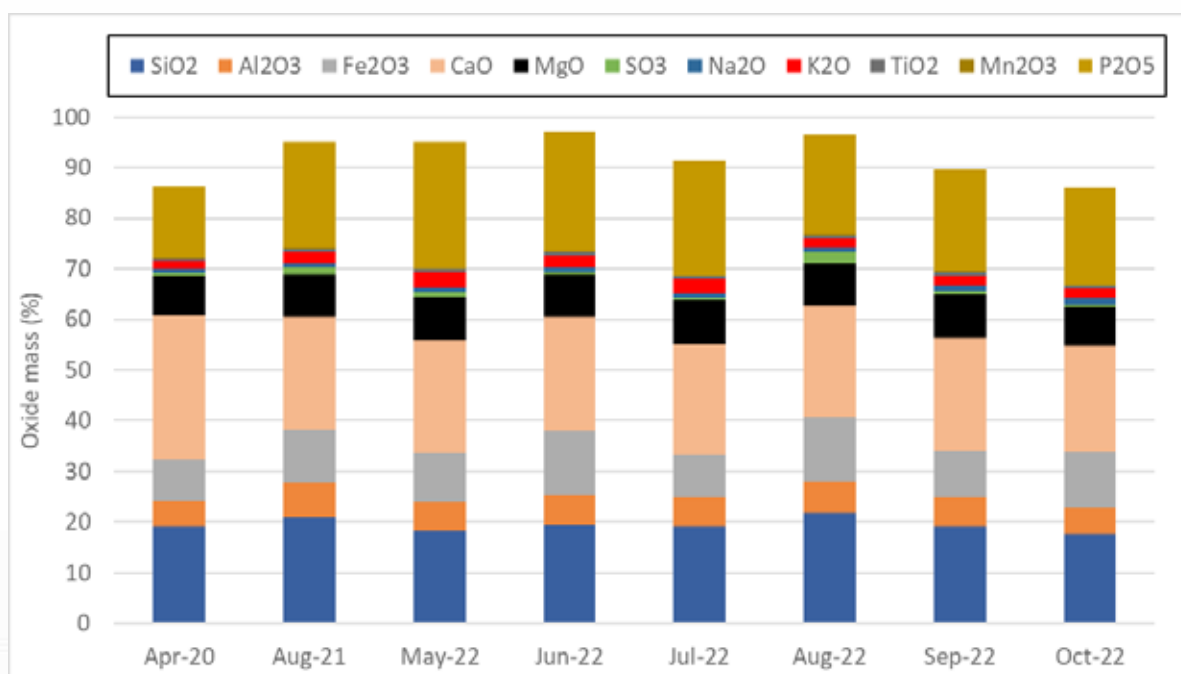


Figure 8-1 Main oxides of SSA from DNWWTP

The main oxides that may contribute to cement hydration are SiO_2 , Al_2O_3 , CaO , and Fe_2O_3 , which have approximately 60% of the total SSA content. There is also a considerable amount of P_2O_5 , approximately 20%, that could be recovered and utilised in agriculture.

The results in Table 8-1 indicate a range of variation of the oxides within the same treatment plant of DNWWTP. The main oxides of SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , MgO and P_2O_5 represent 80-90% of the SSA. The variation of these main oxides is ranging from 3.7% for the MgO to 16.1% for the Fe_2O_3 . Considering the high variability of the sewage sludge, the variability of SSA composition over the studies period is relatively low.

SiO_2 , Al_2O_3 , CaO and Fe_2O_3 are the main oxides available in cement and other cementitious materials and their variation within the Qatari SSA is between 6.4 and 16.1%. The highest variation of the SSA composition was found for the sulfur trioxide (SO_3), with a CV of 65.5%. However, the SO_3 is available in a small quantity within the ash (0.4 to 2.1%), and within the maximum level of 3.5% specified in BS EN 197-1 (2011).

A similar exercise was conducted to compare the mean oxides of SSA produced at DNWWTP, as obtained from Table 8-1, with other values of SSA compositions obtained from the literature for different countries. The results are presented in Table 8-2 and Figure 8-2.

The chemical composition of SSA produced from the same country is likely to exhibit less variation than those in different countries. The results show a wide variation in the composition of SSA from Qatar compared to other countries. The Qatar SSA has a relatively low content of aluminium oxide (Al_2O_3) and high contents of magnesium oxide (MgO) and phosphorus oxide (P_2O_5), compared to other countries included in Table 8-2.

The main oxides that could potentially contribute to the cementitious reactions, SiO_2 , Al_2O_3 , CaO and Fe_2O_3 , are again available in large quantities regardless on country. There is however a high variability of the phosphorous contents in different countries.

Table 8-2 Comparison of Qatar SSA composition to other countries

Type	Qatar	USA (FHWA, 2016)	UK (Halliday et al., 2015)	France (Mejdi et al., 2020)	Spain (Garcés et al., 2008)	Croatia (Vouk et al., 2017)
SiO_2	19.5	27.0	28.7	28.6	19.2	34.0
Al_2O_3	5.8	14.4	15.4	17.6	8.9	12.8
Fe_2O_3	10.4	8.2	18.3	4.4	10.0	11.4
CaO	22.8	21.0	10.6	20.1	30.6	15.8
MgO	8.3	3.2	2.6	2.3	2.7	2.1
SO_3	0.8	0.9	1.0	2.0	11.1	nd
Na_2O	1.0	0.5	1.0	0.6	0.8	0.7
K_2O	2.2	0.6	1.4	1.9	1.4	nd
TiO_2	0.6	nd	1.3	1.5	1.0	0.7
Mn_3O_4	0.1	nd	nd	0.0	nd	nd
P_2O_5	20.7	20.2	15.4	19.5	12.3	10.8

nd= not determined

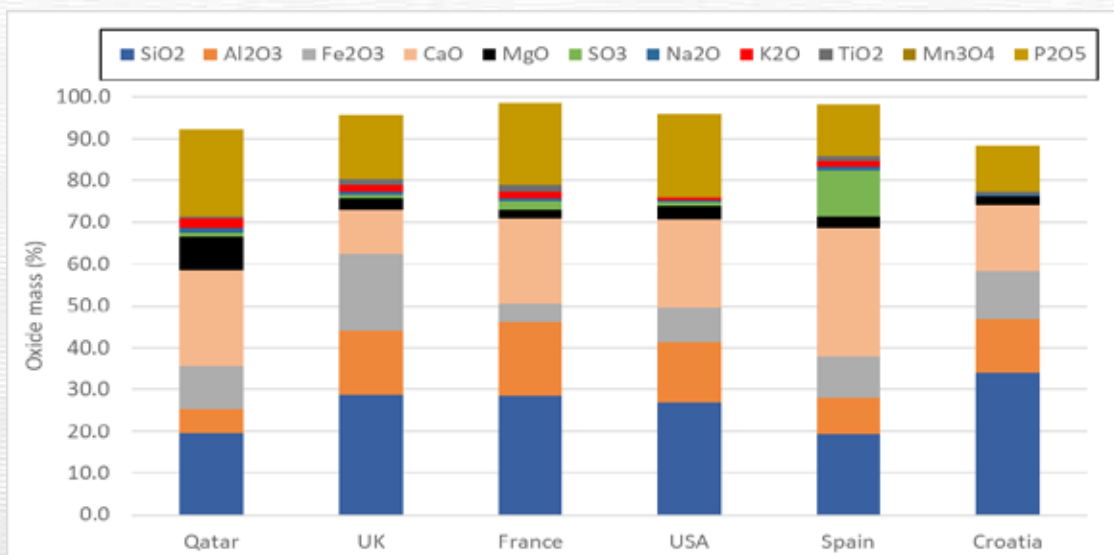


Figure 8-2 Main oxides of SSA from Qatar and internationally

There is an increasing interest worldwide for the recovery of phosphorous from incinerated sewage sludge ash, with some countries enforcing the process. For example, phosphorus (P) recovery is obligatory for all sewage sludges with more than 20 g P/kg dry matter (DM) from 2029 in Germany (Roskosch and Heidecke, 2019). Phosphorous is a key component of fertilisers, detergents and food additives, but is a limited resource. The primary source of phosphorus is from phosphate rock, which is a non-renewable resource and depleting worldwide. On average, the Qatar SSA contains more than 20% of phosphorus oxide (P_2O_5), which could be recovered and recycled towards sustainable development and more circular economy.

8.2 Heavy metals in sewage sludge

Heavy metals are part of the contaminants available within the sewage sludge, from municipal wastewater treatment plants. Most of these heavy metals are attributed to the contact of sewer with the surfaces of man-made urban elements during the sewer collection process (Wiechmann et al., 2015). Sustainable use of SSA as a construction material must ensure that potentially harmful environmental impacts arising from its heavy metals fraction are avoided. When sludge is applied to land, heavy metals can make their way to humans via the consumption of the edible parts of crops (Western Cape EADP, 2021). National and international standards set requirements for the final use of disposal of sewage sludge (SS) that are generated from the treatment of domestic sewage in a treatment works.

This section assesses the level of heavy metals within the sewage sludge pellets, after thermal drying, and after incineration for the production of SSA. The results are compared with the requirements of the Qatar Construction Specification (QCS, 2014) and US standards (EPA, 2019a) for use in landscaping. The immobilisation of heavy metals through the different green cement systems, made with SSA, is also investigated and reported in this section.

8.2.1 Sludge pellets and SSA

Samples of sewage sludge pellets produced at the DNWWTP are tested monthly for the leaching of heavy metals test as per USEPA 3050B (EPA, 1996). The test involves crushing the samples into powder, passing a 125 sieve, then drying in air. A representative sample of 0.5 g was taken and digested using a microwave according to USEPA method 3051A (EPA, 2007). The digestion was performed by using nitric acid (HNO_3) and hydrochloric acid (HCl). The digestion solution was tested for heavy metal by using Perkin Elmer Avio 220 Max ICP-OES according to USEPA method 6010D (EPA, 2018).

Table 8-3 shows the average monthly concentrations, mg/kg of dry weight, of heavy metals of sewage sludge pellets produced at the DNWWSTP for the 12 months of 2023, together with the maximum permissible values specified in the QCS (2014) and the USEPA standard (EPA, 2019). Table 8-3 also provides the heavy metal concentrations of SSA, which was utilised in this project to produce green cement. The results show that the sludge pellets fully comply with the concentration requirements

of the QCS 2014, and the EPA ceiling values for landscaping works. The QCS 2014 specify more stringent requirements than the USEPA ceiling values for heavy metals in sludge. The strictness of Qatar Specifications and potential ban of sludge landfill are the main drivers for effective waste management. The main heavy metals in SSA are zinc (Zn), copper (Cu), followed by chromium (Cr), nickel (Ni), lead (Pb), selenium (Se), arsenic (As) and traces of cadmium (Cd) and mercury (Hg). For the sludge pellets, zinc and copper had the highest concentrations of 699 and 283 mg/kg, respectively. The content of these elements is related to their dominance in municipal wastewater treatment plants but could be immobilised in concrete to be environmentally safe comparable to regular construction materials (Haustein et al., 2022).

Table 8-3 Contamination concentration (mg/kg) of SS produced at DNSTW

Element	Sludge pellets	SSA	QCS Specs	EPA ceiling conc.
Arsenic (As)	< 20	< 6.2	10	75
Cadmium (Cd)	< 0.5	< 1.0	20	85
Chromium (Cr)	68.7	183.4	300	3000
Copper (Cu)	450.3	1123	1000	4300
Lead (Pb)	32.5	21.3	300	840
Mercury (Hg)	< 0.1	< 0.2	10	57
Nickel (Ni)	35.9	106	200	420
Selenium (Se)	< 20	< 0.4	50	100
Zinc (Zn)	899.3	1643	2500	7500

The results of SSA are also presented in Table 8-3. In comparison to the sludge pellets, SSA exhibited substantially higher concentrations in most of the heavy metals, particularly Ni, Cr, Cu, and Zn. The increased concentration of SSA is attributed to the reduced weight and size of incinerated ash, compared to the sludge cake of pellets, and hence increased concentrations of heavy metals in SSA. This is not unexpected as the sludge pellets contain approximately 67% as loss on ignition on incineration at 800-900 °C, to produce only 33% SSA.

Waste incineration is considered as the best disposal of sewage sludge (Swierczek et al., 2021), as it significantly reduces the size and ensures complete decomposition of organic matters and harmful substances. However, incineration also increases the concentration of heavy metals as shown in Table 8-3. Apart from the initial concentration in sludge and the temperature of the incineration, the concentration of heavy metals in SSA is influenced by the volatility of heavy metals (Vogel and Adam, 2017). Werther and Ogada (1999) showed that approximately 78–98% of heavy metals, such as Cd, Cr, Cu, Ni, Pb and Zn, are retained in SSA after incineration.

Zinc and copper exhibited the highest concentrations in the sludge pellets and in the incinerated SSA. The concentration of Cr increased from 68.7 to 183.4 mg/kg, approximately 3 times of its original value. Incineration has also increased the concentration of Cu, Ni, and Zn by factors of 2.5, 2.9, and 1.8, respectively than its original concentrations in the sludge pellets.

The heavy metals in SSA satisfy the stringent requirements of the QCS 2014, except for Cu which exhibited a value of 1123 mg/kg greater than the maximum specified limit of 1000 mg/kg. However, the SSA fully complied with the EPA ceiling values for use in landscaping.

8.2.2 Immobilisation of heavy metals in concrete

The use of SSA as green cement reduces the demand for cement and contributes to sustainable construction by utilising waste materials that would have been landfilled. In addition, SSA green cement has potential for encapsulating heavy metals in the matrix of hydrated products, thereby reducing the leaching of heavy metals to the environment (Li et al., 2017). Heavy metal immobilisation is the process of mixing waste containing heavy metals with a binder (e.g. cement or geopolymer) to immobilise and reduce the bioavailability of the heavy metals (Chen et al., 2009). Developing a cementitious binder from SSA involves chemical reactions that stabilises heavy metals within the construction products, i.e. converting a toxic waste to produce a less toxic or less mobile form.

SSA produced from DNWWTP was used in this project for the development of green cement and innovative concrete products. The SSA was grinded into powder, similar to PC sizes, and activated with lime-based materials, such as PC, cement kiln dust (CKD) and hydrated lime. Innovative controlled low-strength concrete products were successfully made of SSA green cement, with varying content of SSA in the cementitious binder up to 90% by weight of binder.

Table 8-4 Heavy metal concentrations of SSA and concrete-containing SSA (mg/kg)

Element	SSA	25% SSA + 75% PC	50% SSA + 50% PC	90% SSA + 10% CKD	80% SSA + 20% Lime
Arsenic (As)	< 6.2	<6.2	<6.2	<6.2	<6.2
Cadmium (Cd)	< 1.0	<1.0	<1.0	<1.0	<1.0
Chromium (Cr)	183.4	46.41	55.7	60.3	53.15
Copper (Cu)	1123	144.6	256.1	394.7	314.6
Lead (Pb)	21.3	6.60	7.262	9.95	7.44
Mercury (Hg)	< 0.2	<0.2	<0.2	<0.2	<0.2
Nickel (Ni)	106	20.49	29.31	39.7	32.02
Selenium (Se)	< 0.4	<0.4	<0.4	<0.4	<0.4
Zinc (Zn)	1643	298.5	439.2	601	485.7

Table 8-4 gives the heavy metal concentrations of the SSA (incinerated sewage sludge ash) and for the green cement, incorporating SSA blended with lime-based activators. The results show substantial reduction in the concentration of heavy metals in the SSA green cements. The average concentration reduction of Cu, Cr, Pb, Ni and Zn heavy metals ranged between 65% to 75% for the different SSA binder systems. The other heavy metals were lower than the testing detection limits.

Blending SSA with PC significantly reduced the leachability of heavy metals compared to SSA. The greatest reduction of 87% was for copper (Cu), with values of 1123 mg/kg for SSA and 144.6 mg/kg for 25% SSA + 75% PC. In fact, blending SSA with PC reduced the Cu concentration to lower values than the maximum specified in the QCS 2014 of 1000 mg/kg, making it more environmental-friendly resource. Great reductions were also achieved in the concentration of Cr, Pb, Ni, and Zn heavy metals.

SSA-lime blend was also found efficient in immobilising heavy metals. Again, the greatest reduction of heavy metal leaching was found for the Cu between 1123 mg/kg for SSA and 256.1 mg/kg for the blend of 80% SS + 20% Lime, a reduction of 67% to fully comply with the QCS 2014 requirements. Similarly, the SSA-CKD blend converted the SSA into a fully compliant material with the QCS requirements.

While the SSA-PC blends exhibited the lowest heavy metal leaching values, these blends contain lower contents of SSA compared to other mixes made with SSA-lime and SSA-CKD. The green cement made with SSA-lime and SSA-CKD contained 80% and 90% of SSA, respectively, by weight of binder. The green cement products developed in this project showed significant reductions in the leachability of heavy metals to fully comply with the stringent QCS requirements for use in environmental-friendly concrete products.

Review of previous work has also confirmed the reduction of heavy metals from the SSA when used in the production of concrete. Heavy metals are encapsulated within the hydration products of cement, mortar, and concrete, resulting in reduction of their leaching for green construction products. Cenni et al. (2001) analysed the leaching of heavy metals such as Cd, Cu, Cr, Ni, Pb and Zn from ash derived from coal and sewage sludge co-firing and concluded that the concentration of these metals in the extracts was below the detection limit. Based on heavy metal leaching tests, Chen et al., (2018) found that the leachability of heavy metals from SSA containing concrete was lower than that of coal fly ash containing concrete. SSA was also found to suppress the alkali-silica reaction of concrete containing recycled glass. Coutand et al. (2006) reported the leaching of heavy metals from SSA mortars was slightly higher than conventional mortar made with PC, but within the same order of magnitude. Their results showed that metal concentrations in the leachate (Ti, V, Cr, Ni, Cu, Zn, As, Cd, Sn, Sb and Pb) meet the requirements for drinking water quality presented by the World Health Organization.

8.3 Carbon footprints of SSA and concrete products

A detailed carbon footprint calculation that has been undertaken by the Queens University Belfast for sewage sludge ash (SSA) produced at Doha North Wastewater Treatment Plant in Qatar, together with concrete products made with SSA. The concrete products made with SSA were designed on the bases of similar performance to the conventional products made with Portland cement (PC).

Greenhouse gases (GHG) emissions produced during the production stage of both the SSA and concrete products are considered in this assessment, and hence GHG emissions from the construction on site, site operations and end-of-life stages were excluded. The carbon footprint calculation was predominantly completed using primary data relating to inputs provided by the industry and secondary carbon factors. In circumstances where primary data was not available, secondary data from reliable literature sources was used.

8.3.1 Background

Concrete products, have a life cycle over which they operate. The life cycle of a concrete product is typically divided into four stages; production, construction on site, operation and end of life. During each of these stages, energy and resources are consumed and emissions to the environment and wastes are produced. The life cycle assessment (LCA) methodology, internationally standardised through ISO 14040 series (2006), may be used to quantify the environmental impacts of each of these stages.

Life cycle assessment can be used to evaluate a process, product or a service by:

- Compiling an inventory of relevant inputs (energy, materials) and outputs (waste, emissions).
- Evaluating the potential environmental impacts associated with identified inputs and releases.
- Interpreting the results to identify “hot-spots” of environmental impact and inform decision makers.

While life cycle assessment considers a range of impact categories, carbon footprint analysis considers only environmental impacts relating to GHG emissions. Under PAS 2050 (BSI, 2011), carbon footprinting of a product or service is carried out in four phases namely:

- Scoping
- Data collection
- Footprint calculations
- Interpretation

Details of the four stages of the carbon footprint analysis are provided by defining the overall scope of the assessment, detailing inventory information collected from cradle to gate for SSA, the other constituents of the concrete products and the energy required for manufacture of each product and calculating and interpreting GHG emissions.

These carbon footprint calculations have been undertaken in accordance with PAS 2050 (BSI, 2011), and consider impacts from cradle to gate only. In this case, cradle to gate includes all impacts from cradle to the end of the production process (i.e. the point when products leave the factory).

Cradle to gate assessment takes into account all life cycle stages from raw material extraction up to the point to the factory 'gate' i.e. the point in the life cycle where the respective concrete products have been produced and are ready to be transported and applied in construction projects in Qatar. In comparison, cradle to grave assessment takes into account all life cycle stages from raw material extraction right up to disposal at end of life (BSI, 2011), as shown in Figure 8-3.

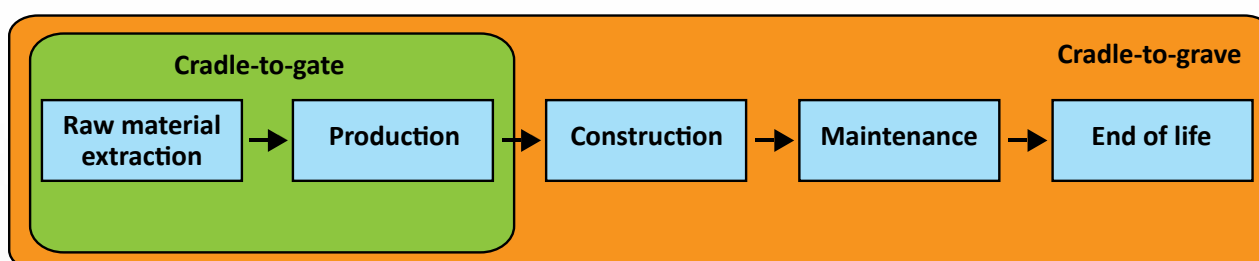


Figure 8-3 Cradle to gate and cradle to grave assessments

8.3.2 Scoping

The overall goal of this assessment is to 1) undertake a detailed carbon footprint calculation for the production of SAA in a Qatari context, 2) calculate the carbon footprint of three concrete products (concrete blocks, foamed concrete, and cement bound material) produced by replacing varying amounts of PC with SSA and 3) compare the SSA products with conventional products of similar performance made with 100% PC in a Qatari context. The carbon footprint calculations are conducted in accordance with PAS2050. The results will be used both internally by the project partners and externally with findings published in peer reviewed conference proceedings and journals.

8.3.2.1 Products to be assessed and functional unit

SSA and concrete products made with SSA are considered in this report for the carbon footprint calculations. Sewage sludge in Qatar is an output of the treatment municipal sewage. Between 52 to 70% of sewage sludge was landfilled between 2020-2022. However, a ban on landfilling of sewage sludge is expected to come into place in June 2024. Currently the remain sludge cake is thermally dried and a proportion of the dried pellets are distributed to landscape customers with the remainder being unused and therefore stockpiled until a future use can be found. It is proposed to incinerate these stockpiled pellets to create sewage sludge ash (SSA), which can then be utilised in concrete products.

This report includes an assessment of whether sewage sludge should be considered a waste for the purposes of this calculation, determines which treatment processes should be considered in a carbon footprint calculation for sewage sludge ash and calculates the carbon footprint of sewage sludge ash in Qatar.

GHG emissions arising from three concrete products were assessed and reported in this study. These concrete products are generally of low-strength characteristics and include:

- Concrete blocks
- Foamed concrete
- Cement bound material (CBM)

For each product, two alternatives were considered, a 100% PC mix and a concrete mix that substituted varying amounts of PC for SSA. Further details of the relevant mix designs are reported in the sections below. Selecting appropriate comparison products is an important part of carbon footprinting calculations. Directly substituting SSA for PC in a concrete mix is expected to alter strength characteristics and therefore in order for a fair comparison to be made between concrete products, it is important that the strength characteristics of both products are similar. Therefore, a brief discussion of the effect of substituting PC with SSA on strength characteristics is provided for each product.

As such the proposed functional unit for conducting this assessment is per m³ of the concrete mix designs, as given in the following sections.

8.3.2.2 System boundary and product life cycle

The system boundary that will be considered in both the carbon footprint calculation for the SSA and concrete products is cradle to gate. This will include the extraction and processing of sewage sludge from the point it becomes a waste and manufacturing of components up to the point that the product leaves the factory.

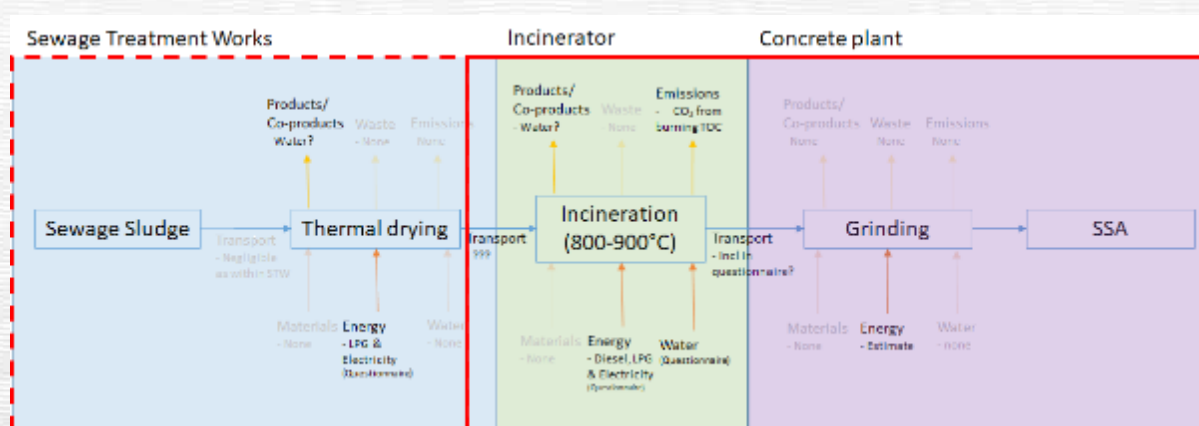


Figure 8-4 Flow diagram for sewage sludge ash production

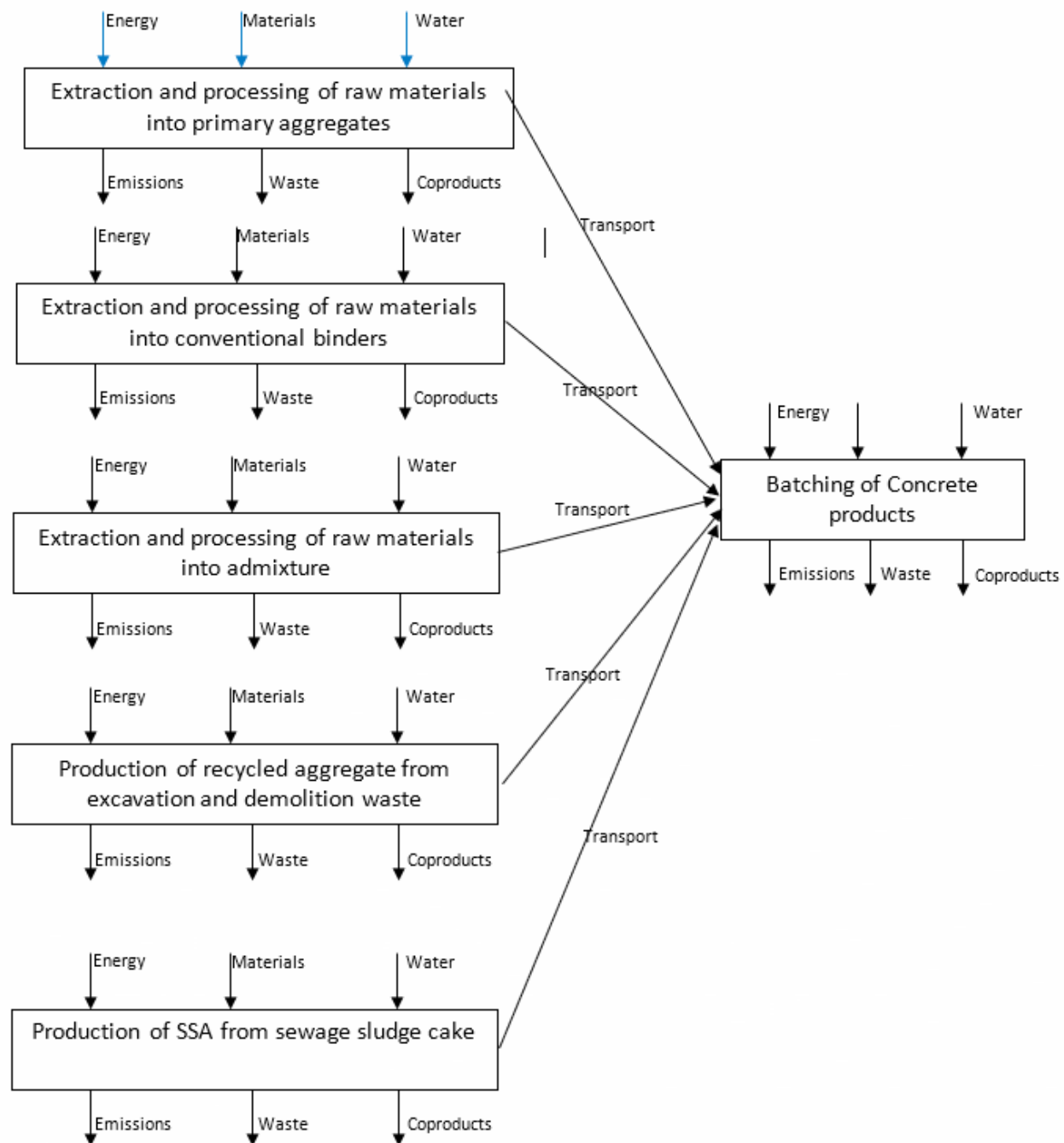


Figure 8-5 Flow diagram for production of concrete products

The process flow diagram for SSA is shown in Figure 8-4, while the process flow diagram for the concrete products is shown in Figure 8-5. A ban on landfilling of sewage sludge is expected to come into place in June 2024. After this date, thermal drying will be required to allow disposal of sewage sludge. Therefore, only processing that takes place within the solid red box in Figure 8-4, will be considered in carbon footprint of SSA.

8.3.2.3 Allocation procedures

The quantification of the environmental impacts of substances depends on whether they are formally designated as being a “waste” or a “by-product”. As discussed by Chen et al., (2010) the only environmental impact of producing a waste is in its disposal. However, when productive uses for waste materials have been discovered, their economic value increases and as a result they are no longer considered as waste materials and are instead considered as valuable by-products of the initial process. In this case, some of the environmental impacts of their production processes should be attributed to them (ISO 14040, 2006). Under the most recent Waste Framework Directive (Directive 2008/98/EC 2008), in Europe, a waste may be reclassified as a by-product if the following criteria are met:

- 1) there is certainty that the substance will be used.
- 2) the substance can be used without any further processing.
- 3) the substance is produced as integral part of the production process.
- 4) further use of the substance is lawful, without impact on the environment or human health as per Article 5 of Directive 2008/98/EC 2008.

Qatari legislation does not include a formal definition for waste or by-products, and as such materials cannot be formally designated as wastes or by-products in Qatar. For the purposes of this carbon footprint calculation, wastes and by-products will be defined using the EU legislation and impacts allocated in accordance with ISO 14044 (2006), as this will more reflect their true environmental impact.

Sewage sludge in Qatar and the subsequent production of sewage sludge ash will be described in the life cycle inventory section of this report and based on the Waste Framework Directive, sewage sludge pellets will be designated as either a waste or a by-product and appropriate allocation procedures discussed.

8.3.3 Data collection

The data collection stage in a carbon footprint calculation requires the quantification of all inputs and outputs producing GHG emissions for each life cycle stage of the concrete product. Working closely with project partners from industry, questionnaires were prepared and shared with the relevant stakeholders for the collection of primary data. In circumstances where primary data was unavailable, secondary data which was geographically appropriate and represented the technology and energy system in Qatar were used.

8.3.3.1 Sewage sludge ash

As discussed, sewage sludge in Qatar is an output of the treatment of municipal sewage, and the DNWWTP is equipped with thermal dryer for the production of pellets, with moisture content of less than 10%. The use of sewage sludge pellets in landscaping is declining and the majority of material is sent to landfill. Therefore, sewage sludge does not appear to have any economic or purposeful use in Qatar and as such will be designated as a waste in this carbon footprint calculation, meaning that only impacts associated with its processing and transportation to the concrete batching plant will be included in the calculation.

Table 8-5 shows the inputs and outputs required to produce SSA from sewage sludge cake from data obtained from the DNOMD at Ashghal considering the thermal drying, whereas the data for incineration was obtained from the incineration plant used in this investigation. Transportation of sewage sludge and pellets within the plant is assumed to be negligible.

Table 8-5 Energy and water requirements to process sewage sludge into SSA

Process	Input/Output	Amount	Unit
Thermal drying *	LPG	538.4 ^a	L/tonne dried sewage sludge pellets
Thermal drying *	Electricity	299.0 ^a	kWh/tonne dried sewage sludge pellets
Incineration	LPG	129.1645 ^b	L/tonne dried sewage sludge pellets
Incineration	Freshwater (input)	4.0770 ^b	m ³ /tonne dried sewage sludge pellets
Incineration	Recycled water (input)	3.2622 ^b	m ³ /tonne dried sewage sludge pellets
Incineration	Water (output)	0.1438 ^c	m ³ /tonne dried sewage sludge pellets
Grinding	Electricity	30 ^d	kWh/tonne SSA

1kg of sewage sludge cake produces 0.2 kg of dried sewage sludge pellets, and 1kg of dried sewage sludge pellets produces 0.33kg of SSA

- Energy requirements for thermal drying are not included in the carbon footprint calculation of SSA, and are included here to allow an assessment of the efficiency and optimisation of thermal drying operations
- a: LPG and electricity consumed by the thermal drying plant between 1 January 2021 and 30 October 2022, divided by total quantity of dried sludge produced. DNOM advised that thermal drying is not fully utilized (less than 50% of capacity is used) and therefore figures obtained have been divided by a factor of 2 to model the plant running at full capacity. In the future, we understand Ashghal is planning to use the waste heat from the incineration furnace to dry-out the sludge cakes before incineration, however this has not been modelled here.
- b: LPG and water consumed by the incinerator between from 2019 to 2nd quarter of 2022 and water consumed by the incinerator between from 2019 to 2021, divided by total quantity material incinerated materials in each period.
- c: 98% of water is recycled within the plant after wastewater treatment.
- d: Taken as the energy required to grind cement from Genç (2016) and Meng et al. (2021)

Typically, studies of the environmental impact of sewage sludge disposal include all of the emissions from treatment of sewage sludge within the assessment of the environmental impact of waste water treatment (Xiao et al. 2022; Abuşoğlu et al. 2017; Yang et al. 2023; Teoh and Li 2020; Zhou et al. 2022), while many studies considering the use of sewage sludge ash in construction products treat SSA as a waste and do not consider any of the environmental impacts from the treatment of sewage sludge within the impact of the construction materials (Ducoli et al. 2021; Nakic 2018).

After the ban on landfilling of sludge comes into place in June 2024, sewage sludge will require thermal drying prior to disposal, meaning that dried sewage sludge pellets are the output from the sludge management process. As it stands the current supply of dried sewage sludge pellets significantly exceeds demand, and this is expected to increase after the ban on landfilling sewage sludge is implemented in June 2024. Therefore, dried sewage sludge pellets do not appear have any economic or purposeful use in Qatar and as such will be designated as a waste in this carbon footprint calculation.

Therefore, impacts from thermal drying should be included in the carbon footprint of the wastewater treatment process and are excluded from the carbon footprint calculation of SSA. Only impacts associated with incineration of dried sewage sludge pellets and transportation of SSA to the concrete batching plant will be included in the calculation. However, to allow an assessment of the efficiency and optimisation of thermal drying operations, the carbon footprint of the thermal drying process is also reported separately in this report.

However, it should be noted that a recent review by Ding et al. (2021) found that treating the output of the sludge management process as a waste “has been criticized by some authors, who have begun to call the “zero burden assumption” into question”. Therefore, they conclude that, environmental risks, including the carbon footprint, of sludge management should be assigned between the production of clean water and any valuable by-products (Ding et al. 2021). Currently the use of SSA in concrete products in Qatar does not have an economic value and would not be considered a by-product, however it is likely that this will change as SSA is utilised in concrete products and derives an economic value.

SSA is produced in this project by burning sewage sludge pellets at temperatures of between 800 and 900 °C. Currently this is undertaken at pilot scale in an incinerator with no energy recovery. However, if the use of SSA in concrete is shown to be environmentally beneficial and widely implemented, it is hoped that large scale incineration of sewage sludge could be used to produce heat for the thermal drying process. However, as this is not currently the case. Data provided by the Ashghal DNOM department on thermal drying and data provided by the incineration plant do not consider any energy generation or heat reuse. After incineration, the resulting ash, i.e. SSA, is 6.4 % by weight of the original solid materials. The incinerated ash also requires grinding prior to use in concrete. In this project, grinding of SSA was carried out in a dry process using laboratory ball-mill grinders to produce powder, passing 120µm (microns), with homogeneous and consistent appearance.

8.3.3.2 Concrete constituents

The developed mix design for each product is given in Table 5-1 for the concrete blocks, Table 8-7 for the foam concrete, and Table 8-8 for the cement bound material along with the delivery vehicle used and transportation distances between the source and batching plant for each concrete product. These mixtures were developed and optimised by the project team and two of these mixtures were implemented in full-scale site trials. Transportation of chemical admixtures is assumed to be negligible, mainly due to the small quantity used for concrete production. For transportation of all other constituents, it was assumed that constituents were transported in lorries with a capacity of 33t, and that lorries returned to the source empty after delivery.

Values of energy use at the concrete batching plant per each cubic metre (m^3) of concrete are obtained from Hassan et al. (2022), which is published on the website of the Ministry of Environment and Climate Change in Qatar. Energy have been calculated per m^3 of concrete product produced at the mixing plant and does not reflect specific processes required for individual products on site. On this basis, for each m^3 of concrete products produced at the mixing plant, an average value of 5.761 kWh of electricity is used. In fact, the concrete blocks are fully produced at the patching plant, whereas the foam concrete and cement bound materials will require additional processing on site.

Table 8-6 Concrete blocks composition (kg/m^3), properties and transportation distance

Constituent	100% PC	SSA-10%	Distance to plant (km)	Vehicle
PC	300	270	66.5	artic >33t
SSA	-	30	43.8	artic >33t
Washed sand – 5mm	450	450	66.5	artic >33t
Dune sand – 3mm	450	450	45.1	artic >33t
CDW – 10mm	1200	1200	45.1	artic >33t
Wadi gravel – 10mm	650	650	66.5	artic >33t
Water	150	150	16	artic >33t
Superplasticiser	5	5	43.8	artic >33t
Average Strength (MPa)	8.8	8.0	-	-
Average absorption (%)	4.6	4.8	-	-

Table 8-7 Foam concrete composition (kg/m³), properties and transportation distance

Constituent	100% PC	SSA-40%	Distance to plant (km)	Vehicle
PC	260	156	66.5	artic >33t
SSA	-	104	43.8	artic >33t
Washed sand – 5mm	1530	1530	66.5	artic >33t
Water	244	244	16	artic >33t
Foam	2.5	2.5	43.8	artic >33t
Superplasticiser	6	6	43.8	artic >33t
Flow table (mm)	680	670	-	-
Cube strength (MPa)	5.2	3.6	-	-
Core strength (MPa)	3.5	4.1	-	-

Overall water usage and wastewater production at the site was also provided on a similar basis. As individual mix designs have different water requirements as part of each mix, it was not possible to directly attribute how much additional water was used for cleaning and other uses for each product. However, an estimate of this has been made on the basis of the overall amount of wastewater produced at the plant. Therefore, for each m³ of concrete products produced at the site, in addition to water required for concrete mixing, it has been calculated that on average 0.00138 m³ of water are used and the same quantity of wastewater is produced.

Table 8-8 CBM composition (kg/m³), properties and transportation distance

Constituent	100% PC	SSA-80%	Distance to plant (km)	Vehicle
PC	80	-	66.5	artic >33t
SSA	-	96	43.8	artic >33t
Hydrated lime	-	24	20	artic >33t
Washed sand – 5mm	690	690	66.5	artic >33t
Recycled aggregate	1500	1500	45.1	artic >33t
Water	120	180	16	artic >33t
Superplasticiser	1.4	2.0	43.8	artic >33t
7-day strength (MPa)	4.7	2.0	-	-
Retained strength (%)	97	87	-	-

Table 8-6, Table 8-7 and Table 8-8 also present the performance of SSA mixtures in comparison to the conventional PC mixtures. The mixtures were developed to have similar performance and to comply with the Qatar Construction Specification (QCS, 2014) for future implementation in construction projects. For the concrete blocks, the SSA mixture exhibited slightly lower strength (10% lower) and higher water absorption (4% higher), which are considered with the acceptable variation of compressive strength and water absorption testing. The SSA foam concrete exhibited lower cube compressive strength, but higher core strength compared to the conventional PC foam concrete. However, the strength attained by both foam concrete mixtures is satisfactory for backfill material with potential use in various applications.

Cement- or hydraulically-bound material is the only application made with no PC, where the SSA was activated with hydrated lime. Unlike most concrete projects, hydraulically bound material requires extended setting time to enable appropriate laying and compaction on site, especially in hot-climate weather, and also to provide a weak and consistent strength to support the overlaying pavement layers. Cement bound materials usually fail to comply with the consistent strength due to the low binder content, whereas increasing the cement content poses the risk of increased strength and reflection cracking. The strength attained by the SSA cement bound material is relatively low with excellent retained durability to use in road construction and rehabilitation projects.

8.3.4 Carbon footprint calculations

Trusted data sets were used such as the Inventory of Carbon and Energy (ICE) V3 (Jones and Hammond, 2019), UK HMRC reporting factors (UK Department for Energy Security and Net Zero, 2023) and EcolInvent V3 (Wernet et al., 2016) were used to obtain carbon factors for the calculation.

8.3.4.1 SSA

Table 8-9 shows the carbon factors found from literature for each input and output from the thermal treatment, incineration, and grinding of sewage sludge. A range of values were sought for each input with the carbon factor which was most geographically appropriate and represented the technology and energy system in Qatar being selected for use in the calculation. This value was used for the “most likely” calculation scenario. It had been hoped to obtain process specific, primary data for incineration emissions, however this was not possible and therefore the global value of 0.07711 kg CO₂e/kg for incineration of raw sewage was obtained from EcolInvent V3 and has been used instead for this scenario. Utilisation of recycled water was assumed to have no associated GHG emissions.

Table 8-9 Carbon factors contributing to carbon footprint of SSA

Material / Process	Carbon factor	Unit	Region	Source
Electricity	0.6677 kg	CO ₂ e/kWh	Middle East	https://www.iges.or.jp/en/pub/listgrid-emission-factor/en
Electricity	0.53 ^a	kg CO ₂ e/kWh	Qatar	EcolInvent V3: (Electricity medium voltage) Selected as is geographically specific
LPG	1.56	kg CO ₂ e/L	UK	UK HMRC reporting value
LPG	2.04 ^a	kg CO ₂ e/L	North America	EcolInvent V3: (LPG combusted in an industrial boiler) Selected as is more representative of LPG produced in Qatar (based on (North Sea Transition Authority 2023))
Water	0.177	kg CO ₂ e/m ³	UK	UK HMRC reporting value
Water	5.84	kg CO ₂ e/m ³	Global	EcolInvent V3: (Tap water production, seawater by reverse osmosis)
Water	4.08 ^a	kg CO ₂ e/m ³	Qatar	Meier et al. (2013): Selected as is more representative geographically and the technology is most appropriate
Wastewater	0.201 ^a	kg CO ₂ e/m ³	UK	UK HMRC reporting value
Incineration	0.02128	kg CO ₂ e/m ³	UK	UK HMRC reporting value for incineration of waste
Incineration	0.07711 ^a	kg CO ₂ e/m ³	Switzerland	EcolInvent V3 (Incineration of raw sewage): Selected as is more representative process

a: Values selected for “most likely” scenario

8.3.4.2 Concrete products

Where available, Qatari specific carbon factors for the constituents of each concrete mix were obtained from Hassan et al. (2022). Where Qatari specific values are not available, secondary carbon factors from literature have been determined, as set out in Table 8-10.

Table 8-10 Carbon factors for materials used in concrete products in this study

Material	Carbon factor	Source
Dune sand	0.0 kg CO ₂ e/t (0.0000 kg CO ₂ e/kg)	No processing of dune sand is required other than loading and unloading.
Washed sand	1.7 kg CO ₂ e/t (0.0017 kg CO ₂ e/kg)	Hassan et al. (2022)
Wadi gravel	7.3 kg CO ₂ e/t (0.0073 kg CO ₂ e/kg)	Hassan et al. (2022)
Imported aggregate	10.3 kg CO ₂ e/t (0.0103 kg CO ₂ e/kg)	Hassan et al. (2022)
Recycled Aggregate	3.0 kg CO ₂ e/t (0.0030 kg CO ₂ e/kg)	Hassan et al. (2022)
Hydrated lime	0.94 kg CO ₂ e/kg (0.00094 kg CO ₂ e/kg)	Laveglia et al. (2022), based on an EU analysis.
Portland cement (CEM I)	860 kg CO ₂ e/t (0.86 kg CO ₂ e/kg)	Mineral Products Association (2019), based on a UK analysis, but provides a similar value to Ahmed et al. (2021) (~850 kg CO ₂ e/t)
Admixtures (superplasticizer)	1880 kg CO ₂ e/t (1.88 kg CO ₂ e/kg)	European Federation of Concrete Admixtures Associations Ltd (EFCA) (2015). Based on a European value. Corroborated with the value in the Inventory of Carbon and Energy v3. Transportation considered to be negligible.
Admixtures (Foaming agent, air entrainer)	527 kg CO ₂ e/t (1.88 kg CO ₂ e/kg)	European Federation of Concrete Admixtures Associations Ltd (EFCA) (2015) Based on a European value. Corroborated with the value in the Inventory of Carbon and Energy v3. Transportation considered to be negligible.
Water	4.08 kg CO ₂ e/t (0.00408 kg CO ₂ e/kg)	Meier et al. (2013)
SSA	1.13 kgCO ₂ e/kg of ground SSA	Calculated in this study. "Most likely" scenario.

8.3.5 Interpreting footprint results

8.3.5.1 SSA

GHG emissions for each stage of production of SSA from sewage sludge cake are shown in Table 8-11 and Figure 8-6. Total GHG emissions for the “most likely” scenario are 1.13 kgCO₂e/kg of ground SSA. Of this the majority of GHG emissions (0.82 kgCO₂e/kg of ground SSA) are produced from combusting LPG during incineration, followed by 0.24 kgCO₂e/kg of ground SSA from emission from burning the organic material in the dried sewage sludge pellets. The carbon footprint of SSA is 31% higher than the value reported in Table 8-10 for PC (0.86 kgCO₂e/kg). This is mainly due to the high organic contents of SSA that combust during incineration, leaving a residual ash of 33% of the original pellet weight.

Table 8-11 GHG emissions for each stage of SSA production, for both the “most likely” and lower bound” scenarios

Process	“Most likely” scenario (kgCO ₂ e/kg of ground SSA)
Thermal drying – LPG	1.72
Thermal drying – Electricity	0.25
Incineration – LPG	0.82
Incineration – Fresh water	0.05
Incineration – Recycled water	0.00
Incineration – Waste water	0.00
Incinerator - Burning SS pellets	0.24
Grinding - Electricity	0.02
Total	3.10

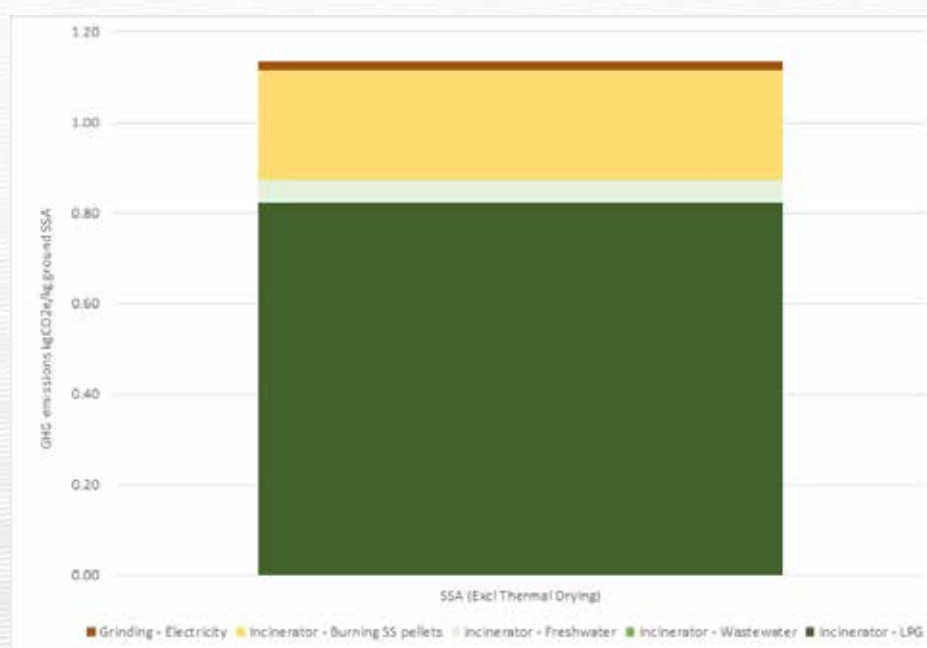


Figure 8-6 GHG emissions for each stage of production of ground sewage sludge ash produced from dried sewage sludge pellets

Table 8-12 GHG emissions reported recently in literature for processing and treatment of sewage sludge by thermal drying and incineration

Study	Location	Process	Stage	GHG emissions (kgCO _{2e} /kg dried SS)	
This study	Qatar	Pre-treatment (including thermal drying) and mono-incineration with natural gas	Thermal drying (combustion of LPG)	0.55	
			Thermal drying (electricity)	0.08	
			Incineration (combustion of LPG)	0.26	
			Incineration (combustion of organic matter)	0.02	
			Incineration (freshwater)	0.08	
			Grinding (electricity)	0.01	
			TOTAL (excluding thermal drying)	0.36	
			TOTAL (including thermal drying)	1.35	
Xiao et al. (2022)	China	Pre-treatment (including thermal drying) and mono-incineration with natural gas	Sludge pre-treatment (including thermal drying)	0.25	
			Incineration (combustion of natural gas)	0.37	
			Incineration (combustion of organic matter)	1.65	approx.
			Transportation processes and electricity consumption during exhaust gas treatment	0.05	approx.
			TOTAL (excluding thermal drying)	2.13	
			TOTAL (including thermal drying)	2.37	
Yang et al. (2023) thermal-drying and incineration technology has gained popularity, however, it may lead to significant greenhouse gas (GHG)	China	Indirect thermal-drying and self-sustain combustion	Indirect thermal-drying and self-sustain combustion	0.35	
		Direct thermal-drying combined with coal co-incineration	Direct thermal-drying combined with coal co-incineration	1.13	
Zhou et al. (2022)	China	Dewatered and incineration with energy recovery	Dewatered and incineration with energy recovery	-0.21	*
Bridle and Skrypski-mantle (2000) cited in Yoshida et al. (2013)	-	Incineration and landfill	Incineration with energy recovery and landfill	-0.78	
Houillon and Jolliet (2005) cited in Yoshida et al. (2013)	-	Incineration and landfill	Incineration with energy recovery and landfill	-0.055	
Hong et al. (2009) cited in Yoshida et al. (2013)	-	Incineration and landfill	Incineration and landfill	0.669	

Typically, GHG emissions are reported for a functional unit of “per kg of dried sewage sludge” or “per kg of sewage sludge”. As the conversion factors to adjust these to “per kg of ground SSA” (the functional unit used in this study) are not described in the literature, they are reported here in a unit of “per kg dried sewage sludge”.

*** Assumed a reduction in mass on 80% during dewatering**

Thermal drying of sewage sludge generates 1.96 kgCO₂e/kg of ground SSA, demonstrating that GHG emissions from thermal drying significantly exceed emissions from incineration. This is not unexpected as 15.6kg of sewage sludge cake needs to be dried to produce 1kg of SSA. The thermal drying reduces the moisture content of sludge cake from almost 80% to less than 10% for the sludge pellets. As emissions due to thermal drying have been attributed to the wastewater treatment process, they have not been included in the carbon footprint calculation for SSA, however they are discussed here to allow the efficiency of the thermal drying process to be optimised. GHG emissions figures for thermal drying assume the thermal drying plant is utilised at 100% capacity, which is more efficient than the current process but is representative of what would be the case in full scale implementation.

Several studies have reported carbon footprint values for the treatment and processing of sewage sludge using thermal drying and incineration. These are reported in Table 8-12 alongside the relevant values from this study converted to a unit of /kg dried sewage sludge. Table 10 shows there is general agreement between the values found in this study and the study undertaken by Yang et al. (2023). However, more widely there is a range in values obtained depending on the exact details of the treatment processes and their efficiency and the underlying assumptions of the life cycle assessment. The greatest range in results (including negative numbers) are observed when energy recovery to heat and electricity is considered in the assessment. This range of results suggests there are potential carbon efficiency measures that could be put in place when full-scale incineration is put in place.

GHG emissions figures for thermal drying assume the thermal drying plant is utilised at 100% capacity, which is more efficient than the current process but is representative of what would be the case in full scale implementation. Discussion with the DNOMD indicated Ashghal is planning to use the waste heat from the incineration furnace to dry-out the sludge cakes before incineration. If this was successfully implemented, there is the potential that a significant proportion of emissions from thermal drying could be eliminated. In addition, given the hot climate in Qatar, there is also potential for natural drying of the sewage sludge to be implemented to reduce emissions from thermal drying. However, to accurately reflect this, further work would be needed to model the full-scale incineration and drying processes.

8.3.6 Concrete products carbon footprint

The GHG emissions of the developed SSA concrete products are summarized in Table 8-13 and discussed in the following sections.

8.3.6.1 Concrete blocks

GHG emissions for each stage of production of both the 100% PC blocks and 90% PC/10% SSA blocks are shown in Figure 8-7 and Table 8-13. Total GHG emissions for the 100% PC blocks were 286.84 kgCO₂e/m³, while total GHG emissions were 294.91 kgCO₂e/m³ for the 90% PC/10% SSA blocks. In both products, the majority of these emissions are associated with the material stage.

As shown in Figure 8-8 the most significant contributing materials are PC for the 100% PC blocks and PC and SSA for the 90% PC/10% SSA blocks. The carbon footprint of the blocks containing SSA is only slightly (3%) larger than the carbon footprint of the 100% PC blocks. This is because a small amount of PC was replaced with SSA (10%).

It should be noted that the 10% SSA blocks have a 10% lower compressive strength than the 100% PC mix. If the carbon footprint is calculated on a $\text{kgCO}_2\text{e}/\text{m}^3/\text{MPa}$ basis the GHG emissions associated with 90% PC/10% SSA blocks will be 13% higher (per MPa compressive strength) than GHG emissions for 100% PC blocks.

8.3.6.2 Foam concrete

GHG emissions for each stage of production of both the 100% PC foamed concrete and 60% PC/40% SSA foamed concrete are shown in Figure 8-9 and Table 8-13. Total GHG emissions for the 100% PC foamed concrete and 60% OPC/40% SSA foamed concrete were $247.88 \text{ kgCO}_2\text{e}/\text{m}^3$ and $275.84 \text{ kgCO}_2\text{e}/\text{m}^3$, respectively. Again, in both cases the majority of these emissions are associated with the material stage.

As shown in Figure 8-10 the most significant contributing materials are PC for the 100% PC foamed concrete and PC and SSA for the 60% PC/40% foamed concrete. The carbon footprint of the foamed concrete containing SSA is somewhat (11%) larger than the carbon footprint of the 100% PC foamed concrete. This is because a larger amount of PC was replaced with SSA than for the concrete blocks.

The 40% SSA foamed concrete has an approximately 30% lower cube compressive strength and 17% higher core strength than the equivalent 100% PC mix. If the carbon footprint is calculated on a $\text{kgCO}_2\text{e}/\text{m}^3/\text{MPa}$ basis the GHG emissions associated with 40% SSA foamed concrete is 61% higher (per MPa cube compressive strength) and 5% lower (per MPa core compressive strength) than GHG emissions for 100% PC foamed concrete.

8.3.6.3 Cement bound material

GHG emissions for each stage of production of both the 100% PC cement bound material and 80% SSA/20% lime cement bound materials are shown in Figure 8-11 and Table 8-13. Total GHG emissions for the 100% PC cement bound material were $86.68 \text{ kgCO}_2\text{e}/\text{m}^3$ and $146.63 \text{ kgCO}_2\text{e}/\text{m}^3$ for 80% SSA/20% lime cement bound materials and in both cases the majority of these emissions are associated with the material stage.

As shown in Figure 8-12 the most significant contributing materials are PC for the 100% PC cement bound material and SSA and hydrated lime for the 80% SSA/20% lime cement bound material. The carbon footprint of the SSA cement bound material is about 70% larger than the carbon footprint of the 100% PC cement bound material. This is because the 50% higher binder content used for the 80% SSA/20% lime mixture.

Table 8-13 GHG emissions (kgCO₂e/m³) for each stage of SSA concrete products

	Blocks (100% PC)	Blocks (10SSA+90PC)	Foam (100% PC)	Foam (40SSA+60PC)	CBM (100% PC)	CBM (80SSA+20Lime)
Materials	0.00	0.00	0.00	0.00	0.00	0.00
Dune sand	0.765	0.765			1.173	1.173
Washed sand	0.765	0.765	2.601	2.601		
Wadi gravel	4.745	4.745				
Recycled aggregate	3.600	3.600			4.500	4.500
Hydrated lime						22.560
PC (CEM 1)	258.00	232.20	223.60	134.16	68.80	
Admixtures	9.40	9.40	15.98	15.98	3.76	3.76
Water	0.612	0.612	0.9955	0.9955	0.49	0.49
SSA		33.90		117.52		106.22
Processing						
Electricity	1.953	1.953	1.953	1.953	1.953	1.953
Water	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Wastewater	negligible	negligible	negligible	negligible	negligible	negligible
Transport						
Dune sand	1.00860	1.00860				
Washed sand	1.48718	1.48718	5.05642	5.05642	2.28035	2.28035
Wadi gravel	1.45687	1.45687				
Recycled aggregate	2.68960	2.68960			3.36200	3.36200
Hydrated lime						0.02385
PC (CEM 1)	0.99145	0.89231	0.85926	0.51556	0.26439	
Admixtures	0.01088	0.01088	0.01850	0.01850	0.00435	0.00435
Water	0.11927	0.11927	0.19402	0.19402	0.09542	0.09542
SSA		0.06530		0.22638		0.20461
Total	286.84	294.91	247.88	275.84	86.68	146.63

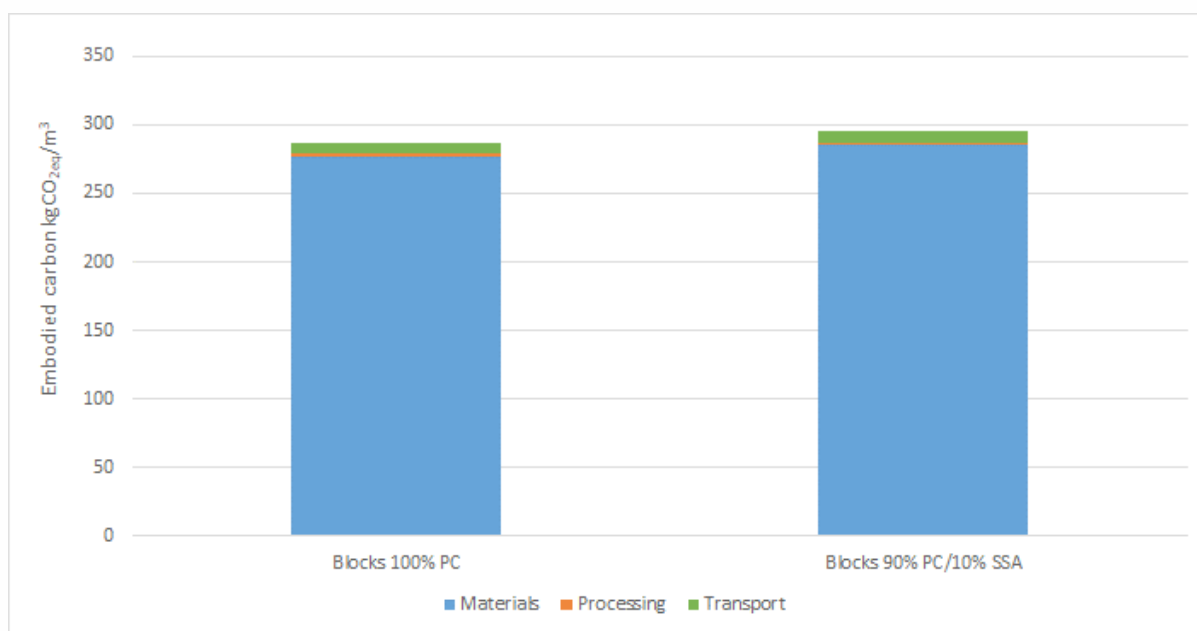


Figure 8-7 GHG emissions for each stage of production for both the 100% PC blocks and 90% PC/10% SSA blocks

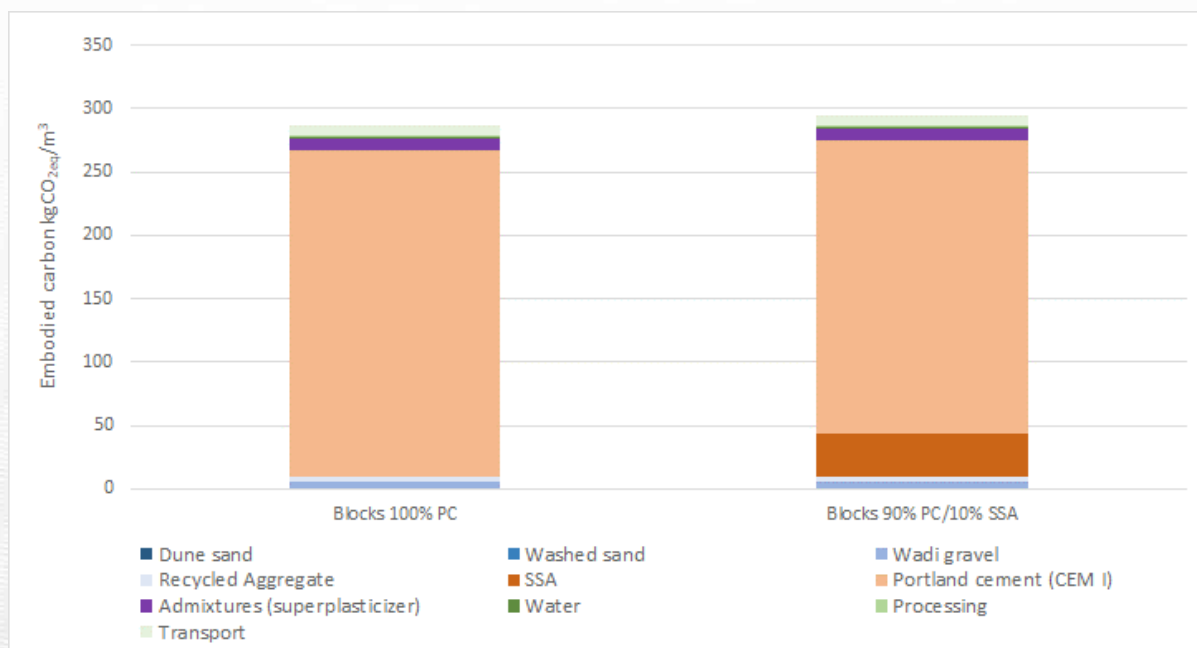


Figure 8-8 GHG emissions for each stage of production including materials breakdowns for both the 100% PC blocks and 90% PC/10% SSA blocks

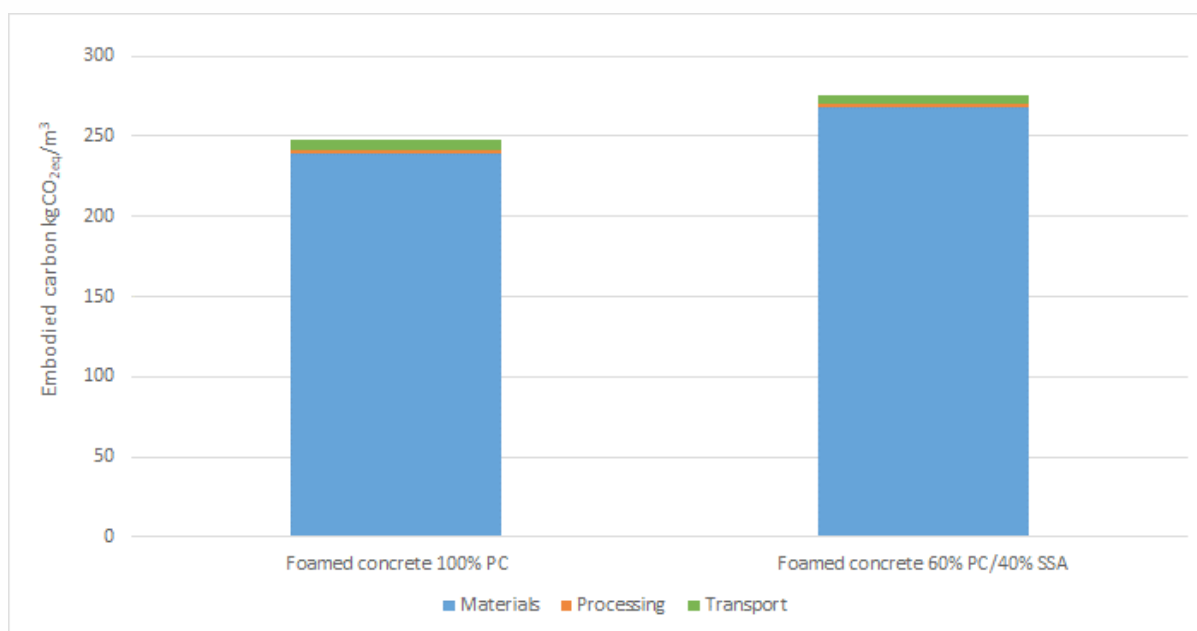


Figure 8-9 GHG emissions for each stage of production for both the 100% PC foamed concrete and 60% PC/40% SSA foamed concrete

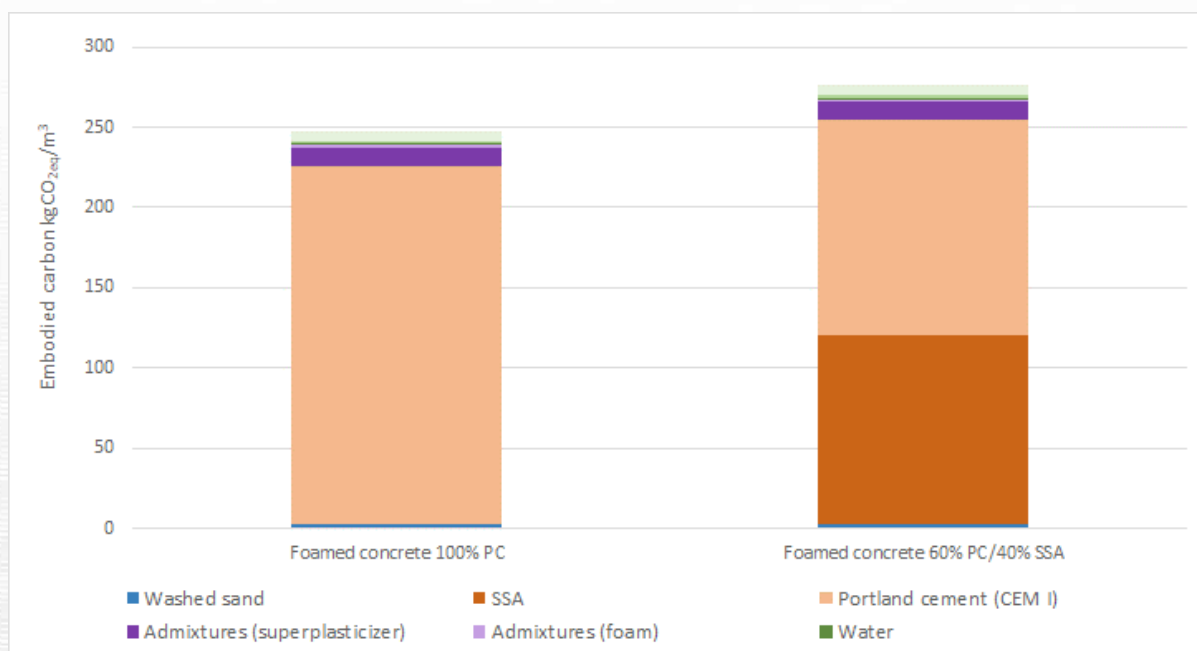


Figure 8-10 GHG emissions for each stage of production including materials breakdowns for both the 100% PC foamed concrete and 60% PC/40% SSA foamed concrete

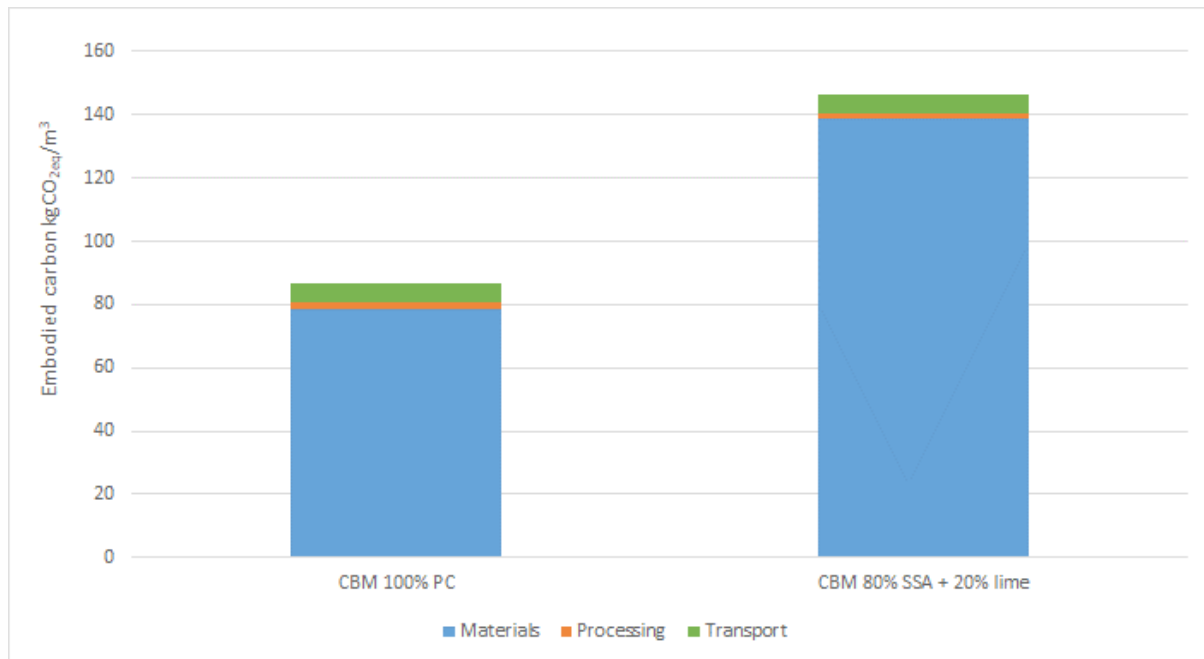


Figure 8-11 GHG emissions for each stage of production for both the 100% PC cement bound material and 20% hydrated lime/80% SSA cement bound materials

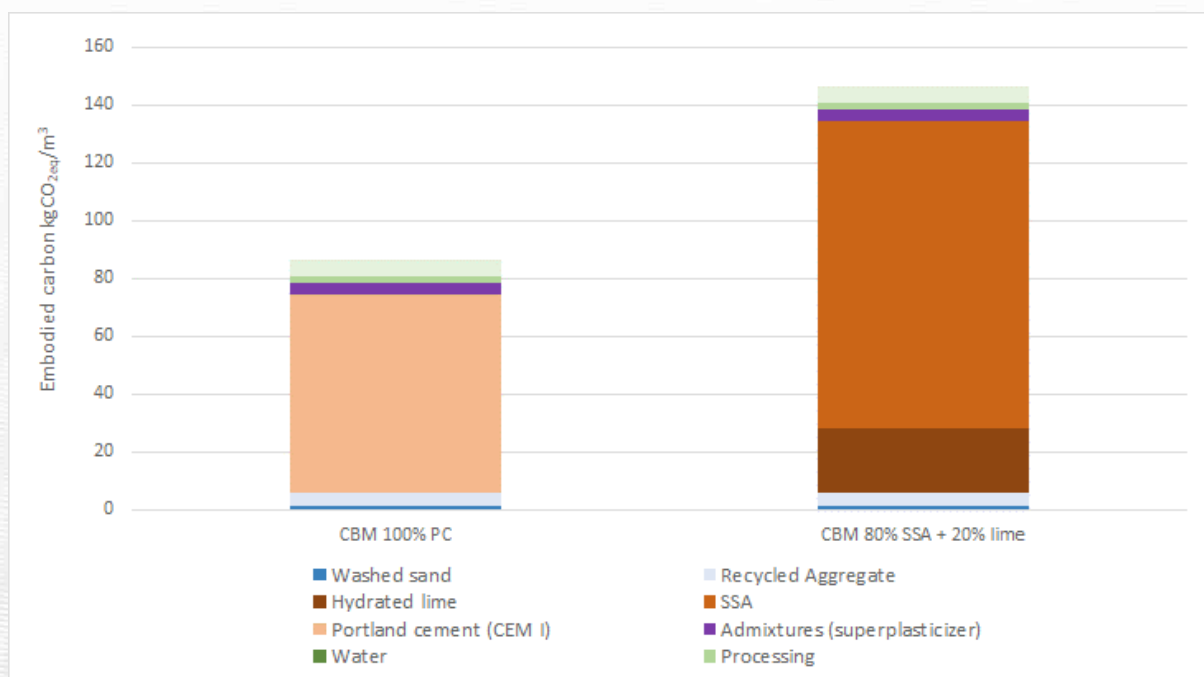


Figure 8-12 GHG emissions for each stage of production including materials breakdowns for both the 100% PC cement bound material and 80% SSA/20% lime cement bound materials

8.4 Economic Benefit

Financial studies are essential for the implementation of new products. Provided the SSA concrete products satisfy the end product requirements, as per the Qatar Construction Specifications and its use is justified environmentally, the cost will be a major factor in its implementation within the construction industry. This section covers the cost associated with SSA concrete products and compares to similar conventional production made with PC.

8.4.1 Processing cost of SSA

As indicated earlier, approximately 800 thousand cubic meters of municipal wastewater are collected daily in Qatar for treatment, accounting for 292 million cubic meters per year. The quantity of municipal wastewater is expected to increase with increased population in Qatar. The solid content of sewage sludge is 0.16 kg per cubic meter, accounting for 128 tonnes per day and 47,000 tonnes per year. Ashghal processes the sewage sludge into pellets and is currently the product has no commercial value and is available for use free of charge.

To produce the SSA from sludge pellets, the material needs to be incinerated at 800-900 °C and grinded into cement sizes, similar to the work conducted in this investigation. The sludge pellets contain usually less than 10% moisture, approximately 6%. Incineration evaporates any residual water in the pellets and combust organic materials, reducing the initial pellets weight to only 33% of incinerated ash (SSA). Previous trials on incineration showed that the LOI of sludge pellets is 67%.

SSA generation in Qatar is therefore expected to be 15 thousand tonnes per year. The quantity of SSA is relatively small compared to approximately 4-5 million tonnes of Portland cement produced annually in Qatar. The high cement production reflects the large market in the construction industry to consume all SSA produced in Qatar.

Consultation with one of the waste management companies in Qatar indicated that incineration and processing investment would require a capital investment (CAPEX) of QR 16 million with yearly operations of 10%, amounting for QR 1.6 million yearly (OPEX). For a 10-year investment payback period, the cost of SSA incineration and grinding will be approximately QR 240 per tonnes of SSA. This value is marginally lower than the value for PC of QR 243 per tonne. It can be said that the cost of SSA processing is expected to be the same price as PC. Further consultation is recommended for SSA incineration plants, as cost savings could be achieved through:

- Considering the high calorific value of sewage sludge.
- Waste heat from the incineration could be used to dry-out the sludge cakes.
- Natural drying of the sewage sludge could be implemented within the hot climate in Qatar.

8.4.2 Cost of SSA products

SSA was used for the production of controlled low-strength concrete products of concrete blocks, foam concrete and cement bound materials. These products are generally characterised with compressive strength values below 10 MPa, and widely used in Qatar for the construction of building and fences (concrete blocks), backfill applications (foam concrete) and road base and subbase applications (cement bound materials). Table 8-14 provides the calculated costs of SSA concrete products in comparison to the conventional PC products.

Table 8-14 Costs of SSA concrete products (QR/m³)

	Conc. Blocks 100% PC	Conc. Blocks 10% SSA	Foam Conc. 100% PC	Foam Conc. 40% SSA	CBM 100% PC	CBM 80%SSA
Dune sand	2.25	2.25	0	0	0	0
Washed sand	9.9	9.9	33.66	33.66	15.18	15.18
Wadi gravel	29.25	29.25	0	0	0	0
Imported aggregate	0	0	0	0	0	0
Recycled aggregate	33.6	33.6	0	0	42	42
SSA	0	7.2	0	24.96	0	23.04
Lime	0	0	0	0	0	9.6
CKD	0	0	0	0	0	0
PC	72.9	65.61	63.18	37.908	19.44	0
Superplasticizer	0.01	0.01	0.02	0.02	0.01	0.01
Foaming agent	0	0	0.01	0.01	0	0
Water	1.13	1.13	1.83	1.83	0.9	0.9
Total	149.04	148.95	98.69	98.38	77.53	90.73

The costs provided in Table 8-14 are based on the quantities of materials used in each concrete products (kg/m³) and the unit cost of each constituent in terms of Qatar Riyals per tonnes of material (QR/tonne). For concrete blocks, the total cost of materials required to produce one cubic metre is QR 149.04, with approximately half of the cost for the PC binder. Replacing 10% of the PC with SSA, marginally reduce the cost to QR 148.95. Similarly, the use of 40% SSA in foam concrete slightly reduce the cost from QR 98.69 for 100% PC to QR 98.38. A higher variation in cost is obtained for the CBM application. The cost of 80% SSA + 20% lime is QR 90.73, approximately 17% higher than the 100% PC CBM mixture (QR 77.53). This is mainly attributed to the increased binder content of the 80% SSA CBM, which is 50% higher than the binder content in 100% PC CBM, resulting in more consistent mix design and enhanced performance compared to the 100% PC mixture.

Aggregate is the cheapest ingredient of the developed concrete products, and occupies the greatest weight. Whilst Qatar uses imported gabbro aggregate in the production asphalt and concrete products, consideration was made in this project to maximising the use of local and recycled aggregate materials for the development of sustainable low-strength concrete mixtures.

In general, the cost of SSA concrete products is almost the same for the PC products, considering the marginal variation costs of SSA processing and market price of PC. However, there is an additional benefit for the resource recovery from SSA to avoid landfilling. In 2022, it was estimated that approximately 0.5 million cubic metre of foam concrete was used in Qatar for backfill applications, consumed approximately 130 thousand tonnes of PC. If foam concrete is to be made with SSA, the full production of SSA could be easily consumed in foam concrete.

8.5 Summary

Samples of the Qatari sewage sludge pellets were monthly collected from the DNWWTP and incinerated to assess the variability of SSA composition. The variation of main oxides that may contribute to the cement hydration, namely SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , is within 16% and is considered relatively low. The highest variation was found for the SO_3 , CV of 65.5%. However, the sulfur is available in a small quantity of 0.4 to 2.1%, and within the maximum level of 3.5% specified in BS EN 197-1 (2011).

The Qatar SSA contains a relatively high content of phosphorus oxide (P_2O_5), with a great potential for recovery and use in soil improvement. Phosphorus (P) recovery is obligatory for all sewage sludges with more than 20 g P/kg dry matter (DM) from 2029 in Germany, and a similar approach is recommended for Qatar to recover this valuable resource.

The main heavy metals found in SSA, produced at the DNWWTP, are zinc (Zn), copper (Cu), followed by chromium (Cr), nickel (Ni), lead (Pb), selenium (Se), arsenic (As) and traces of cadmium (Cd) and mercury (Hg). The concentrations of these heavy metals are lower the maximum permissible limits of the USEPA standard, and the more stringent requirements of the QCS 2014.

Incineration of sewage sludge reduces the weight and size of SSA, and hence increases the concentration of heavy metals by almost 2-3 times greater than the pellets. Incinerated SSA failed to satisfy the QCS 2014 leaching requirements, in particular the copper (Cu) concentration. SSA was blended with calcium-rich activators to produce green cement. The green cement products exhibited substantial reductions in heavy metal concentrations, to fully comply with the QCS 2014 and the USEPA requirements. The average concentration reduction of heavy metals Cu, Cr, Pb, Ni and Zn ranged between 65% to 75% for the different SSA binder systems. The greatest reduction was for the Cu, up to 87%, followed by Pb, Ni, and Zn heavy metals.

Total GHG emissions for SSA are 1.13 $\text{kgCO}_2\text{e/kg}$ of ground SSA. Of this the majority of GHG emissions (0.82 $\text{kgCO}_2\text{e/kg}$ of ground SSA) are produced from combusting LPG during incineration, followed by 0.24 $\text{kgCO}_2\text{e/kg}$ of ground SSA from emission from burning the organic material in the dried sewage sludge pellets. The carbon footprint of SSA is 31% higher than conventional PC, mainly due to the significant weight reduction of sewage sludge during incineration. GHG emissions for all concrete products containing SSA were greater than the equivalent 100%PC product.

The cost of processing the sewage sludge pellets was calculated for the production of SSA and found to exactly the same as the market price of PC in Qatar, approximately QR 240 per tonne. The processing includes incinerating the pellets at 800-900 °C and grinding into cement particle sizes. Based on the similar cost of SSA and PC, the SSA concrete products are expected to cost the same as the PC products.

9 Conclusions

Based on the project outcomes, the following conclusions can be offered:

Three solid waste materials were identified in the project for the development of green cement and includes sewage sludge ash (SSA) and municipal solid waste (MSW) of fly ash (FA) and incineration bottom ash (IBA).

The use of solid waste materials reduced the compressive strength of mortars, and the reduction was proportional to the replacement level. SSA exhibited the best performance in terms of compliance with BS EN 197-1, water demand, and compressive strength when compared to MSW-FA and MSW-IBA.

9.1 Development of SSA binder systems

Different binder systems were developed to include SSA activated with different proportions of Portland cement (PC), hydrated lime, cement kiln dust (CKD), and alkali solutions. SSA was found to mainly influence the setting time and strength development of the various binder systems.

SSA was used to replace 25%, 50%, and 75% by weight of PC in C40 concrete. The control 100% PC mortar gave a 28-day strength of 43.5 MPa, with a reduction of 19%, 49%, and 66% for increased SSA content.

At the same water to binder ratio, increasing the CH content improves the workability and strength of mortar. Increasing the CH content from 20% to 30% in the SSA binder system has marginal effect strength increment.

Increasing the CKD content in the SSA binder system has adversely affected the workability of mortar. The SSA-CKD system exhibited relatively high strength at 2 days, but the rate of strength development reduced with age. The best strength results were found for the SSA-10%CKD.

Chemical activators of sodium hydroxide (N) and sodium silicate (SS) were used to activate the SSA at different values of alkali content and silicate modulus. The best workability results were found at alkali content (N) of 6%. The compressive strength of the alkali-activated SSA systems were in the range of 1.9 MPa to 8.7 MPa, whereas a higher range of 12.7 MPa and 29.3 MPa for the SSA-GGBS system.

Microstructural analysis of the SSA-lime system showed a dense microstructure with the formation of calcium phosphates and calcium carbonate that contribute to concrete strength.

The alkali-activated SSA systems with high silicate modulus (M_s of 1.5) showed similar hydration products to that of the SSA-lime system, but with a porous microstructure and the presence of microcracks, especially at high alkali content.

9.2 Development of SSA concrete products

SSA products of concrete blocks, foam concrete and cement bound materials were successfully developed in the laboratory and compared to conventional products made with PC.

Replacing 25% of PC with SSA was effective to produce concrete block mixtures in the laboratory to satisfy the QCS requirements of compressive strength and water absorption.

The SSA-10CKD slightly exceeded the strength requirement, whereas the SSA-20Lime failed to achieve the required strength. Based on the results, the SSA-PC system was selected for the development of the concrete blocks.

SSA was used to replace 50% and 75% of PC in the production of foam concrete, with density values between 1500 and 1800 kg/m³ and air content of 20-25%. The SSA mixtures exhibited excellent fresh properties of workability and flowability with no segregation or bleeding. The 28-day compressive strength was at least 4.0 MPa for use as backfill and road construction.

Cement bound material (CBM) mixtures were made with SSA replacing 100% of PC. SSA was activated by 10% CKD or 20% hydrated lime to provide CBM mixtures with adequate strength and excellent durability performance for use in road construction.

9.3 Environmental and Cost Assessment

Incineration of sewage sludge significantly reduces the weight of SSA and increases the concentration of heavy metals. The SSA green cement exhibited substantial reductions in heavy metal concentrations of between 65% to 75% for the different SSA binder systems. The greatest reduction was for the Cu, up to 75%, followed by Pb, Ni, and Zn heavy metals.

A carbon footprint assessment was conducted on the SSA and concrete products. Total GHG emissions for SSA are 1.13 kgCO₂e/kg. The carbon footprint of SSA is 31% higher than conventional PC and could be reduced by considering the high calorific value of sludge.

GHG emissions for all concrete products containing SSA were greater than the equivalent 100%PC product, mainly due to the relatively high calculated carbon footprint of SSA.

Sewage sludge pellets have no current commercial value, and the cost of processing through incineration and grinding was found exactly the same as the market price of the PC in Qatar.

9.4 Site Trials

The 10% SSA concrete blocks exhibited similar performance to the Control 100% PC concrete blocks, with full compliance with the QCS 2014 for use in external non-load bearing walls.

Foam concrete, made of 40% SSA and 60% PC binder, was produced and used for the reinstatement of pavement depressions around manhole covers. The performance of SSA foam concrete was similar to that of 100% PC foam concrete.

Both concrete blocks and foam concrete are widely used in the construction industry in Qatar, with the ability to consume the full production of SSA in Qatar.

10 Recommendations

Approximately 50,000 tonnes of sewage sludge are generated in Qatar every year as by-product from the treatment of municipal wastewater. The sewage sludge contains a wide range of contaminants, such as heavy metals, pathogens, and organic pollutants, and its disposal presents significant challenges due to its potential impact on human health and the environment. Thermally dried sludge pellets are only permitted for use in landscaping and its utilisation is declining with time, with the majority is sent to landfill. The government is considering the ban of sewage sludge landfilling due to the potential risks of accumulated contaminants. This project provides an innovative solution for the conversion of sewage sludge into cementitious material for use in the construction industry.

Incineration significantly reduces the size of sewage sludge, destroys pathogens and toxic organic constituents, leaving behind residual sewage sludge ash (SSA) with potential use in construction. The project has developed innovative green cement binders through the activation of SSA with different conventional products of Portland cement, hydrated lime and cement kiln dust. The new SSA binder systems were successfully used for the production of low-strength concrete products, with the added benefits of resource recovery from sewage sludge waste, reduce reliance on energy-intensive PC, and support to green and sustainable construction in Qatar.

Public perception on the disposal of sewage sludge will favour its utilization in innovative concrete products for use in underground applications, such as foam concrete and cement bound materials, rather than above-ground applications. The ministry of Environment and Climate Change is the regulatory body for the protection of environment and Ashghal is the government authority entrusted with the management of wastewater, production of sewage sludge, as well as the construction and maintenance of the road network in Qatar. The following recommendations are for the effective implementation of SSA in construction:

- **Sludge incineration:** need to identify the most appropriate method for the incineration of sewage sludge, with considerations of the high calorific value of sludge; recovery of values resources of phosphorus and inorganic ashes; recovered heat for the pre-drying of sludge, and minimum energy consumption and carbon footprint for incineration to be much lower than that of PC.
- **Regulations:** proper regulation, monitoring, and management practices are essential to ensure that sewage sludge is handled safely and responsibly, minimising any adverse impacts on public health and the environment.
- **Implementation:** encourage the contractors on the use of SSA in specific concrete applications of foam concrete and cement bound materials in Ashghal projects. The full production of SSA could be easily consumed within the identified applications in Qatar.
- **Continuous improvement:** despite the encouraging results from the site trials, it is recommended to carry out long-term monitoring on the performance of SSA concrete products in service and conduct more trials for wider acceptance and implementation.

11 Implementation Plan

Recommendation for the implementation of project outcomes into practice.

11.1 Specifications and design guides

It will be necessary to update the Qatar Construction specification (QCS) and provide guidance to designers and contractors on how to use the green cement, particularly for use in concrete blocks and foam concrete.

The proper regulation, monitoring, and management practices are essential to ensure that sewage sludge is handled safely and responsibly, minimising any adverse impacts on public health and the environment. It will be important to make industry aware of the new development of green cement.

11.2 Infrastructure for green cement plant

It will be necessary to establish a central plant and infrastructure for a green cement plant to incinerate sewage sludge, with considerations of the high calorific value of sludge; recovery of values resources of phosphorus and inorganic ashes; recovered heat for the pre-drying of sludge, minimum emissions of GHG, and minimum energy consumption and carbon footprint for incineration to be much lower than that of PC.

Incineration significantly reduces the size of sewage sludge, destroys pathogens and toxic organic constituents, leaving behind residual sewage sludge ash (SSA) with potential use in construction. The project has developed innovative green cement binders through the activation of SSA with different conventional products of Portland cement, hydrated lime and cement kiln dust. The new SSA binder systems were successfully used to produce low-strength concrete products, with the added benefits of resource recovery from sewage sludge waste, reduce reliance on energy-intensive PC, and support to green and sustainable construction in Qatar.

11.3 Implementation

The Ministry of Environment and Climate Change (MECC) and Public Works Authority (Ashghal) should encourage the contractors on the use of sewage sludge ash (SSA) in specific concrete applications of foam concrete and cement bound materials in Ashghal projects. The full production of SSA could be easily consumed within the identified applications in Qatar.

The development of a local market for green cement provides an opportunity for reducing the cost of blocks and foam concrete with the added benefit of being green and sustainable.

11.4 Training, Development and dissemination

The use of green cement in construction, particularly in low strength concrete, will be a major change to current practice in Qatar and cannot be introduced overnight. A programme of training and dissemination of information to clients, designers and contractors will be required so that they can adapt to the new products as they become available.

Most people resist change and prefer established, safe ways of working rather than taking risks with new materials and technologies. It will be important to provide a sustained programme of awareness raising and training to help those involved make the transition, initially to make them aware of the possibilities then to provide detailed information on specific technical aspects when this is needed.

It is recommended that the above training programme, tailored to different audiences, is delivered on a regular basis to ensure continuous and wider implementation of green cement in construction projects. It is suggested that a certification system should be awarded at the end of the training course, and subject to the successful completion of an assessment exercise at the end of each training course. The certification system will motivate practicing engineers and help them to climb the professional ladder and encourage continuous education and development of the construction industry.

The Ministry of Environment and Climate Change (MECC) held a symposium to announce the outcomes of the “Green Cement” project. The Green Cement symposium was held on 23rd September 2024 and attended by the Minister of Environment and Climate Change, H.E. Dr Abdullah bin Abdulaziz bin Turki Al Subaie; the Minister of Municipality, H.E. Abdullah bin Hamad bin Abdullah Al Attiyah; the Minister of Education and Higher Education, H.E. Buthaina bint Ali Al Jabr Al Nuaimi and the symposium; senior management from the Public Works Authority (Ashghal) and key representatives from the construction industry.



Figure 11-1 Government Ministers with the project team in the Green Cement Symposium

The Minister of Environment and Climate Change highlighted the benefits achieved from the “Green Cement” project to preserve the health and safety of the society in Qatar by converting the sewage sludge waste into valuable construction products. The project enhances the nation’s environment, and supports the Qatar National Vision 2030, the 3rd National Development Strategy 2024-2030, and the Qatar Environment and Climate Change Strategy 2021. The Ministry praised the efforts made by the project team, Figure 11-1, who succeeded in processing the sewage waste and converting it into environmentally friendly green cement in line with the government strategy of waste management and circular economy.

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MECC announces green cement innovation

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The idea of this innovation was initiated by the Ministry’s scientific research team in cooperation with researchers from Qatar and Queen’s University Belfast. The project was submitted to 12th Qatar National Research Fund Competition for 2021, and was subjected to scientific and technical evaluation by international evaluators and experts in this field, where it obtained the highest evaluation grade (A) for three years.

According to the data, the amount of accumulated sewage waste is estimated at about 40,000 tonnes annually, which can be used to produce 40 million bricks or 150,000 cubic meters of foam concrete annually, which contributes to reducing production costs.

This innovation comes as a result of efforts by the MECC to enhance environmental sustainability and support the circular economy, which aims to reduce waste of materials, goods and energy and increase their sustainable use. This effort is in line with the fourth axis of Qatar’s



Minister of Environment and Climate Change H E Dr. Abdullah bin Abdulaziz bin Turki Al Subale (centre), Minister of Education and Higher Education H E Buthaina bint Ali Al Jabr Al Nuaimi (left) and Minister of Municipality H E Abdullah bin Hamad bin Abdullah Al Attiyah (right) during a symposium in Doha yesterday.

Environment and Climate Change Strategy, and is in line with the Third National Development Strategy (2024-2030),

which focuses on rationalising the use of natural resources, protecting ecosystems, reducing greenhouse gas emissions, and

enhancing capacity and resilience to confront future environmental threats, in support of QNV 2030.

Dr Al-Kuwari, Lead Principal Investigator of the project, presented the environment benefits of the scientifically proven-project to serve the environment, reduce reliance on Portland cement and its associated high carbon footprint, preserve the quality of the air, soil, and groundwater from pollutants through the safe disposal of the sewage sludge, and develop a new green cement for use in specialised concrete applications of roads and infrastructure projects.

Dr Hassan, Principal Investigator of the project, presented the processes involved in the production of green cement and green construction products of assessing the physical and chemical characterisation of the incinerated sludge; activating the powder waste using different techniques to produce green cement; developing quality construction products; applying the newly developed products in full-scale site trials, monitoring performance in service, and quantifying the environment and cost benefits of the new products.

MoECC launches eco-friendly 'Green Cement'

The Ministry of Environment and Climate Change (MoECC) has announced the introduction of "Green Cement", made from solid sewage waste, in line with environmental and sustainability standards and in support of the circular economy.

The announcement came at a seminar under the patronage and in the presence of HE the Minister of Environment and Climate Change Dr Abdullah bin Abdullatif bin Turki al-Sabae.

The seminar was attended by HE the Minister of Municipality Abdullah bin Hamad bin Abdullatif al-Attiyah and HE the Minister of Education and Higher Education Buthaina bint Ali al-Jabri al-Nuaimi.

The research team, which includes Dr Mohamed Saif al-Kuwari and Dr Khaled Hassan, in collaboration with Queen's University Belfast of the UK and several government, entities and private sector companies that contributed to the project, were honoured on the occasion.

The seminar featured a visual presentation of the project by the research team, with the attendance of consultants and experts in the fields of environmental sustainability, road construction, cement, and building materials.

The project was discussed from both technical and practical perspectives.

In his address, HE Dr al-Sabae, praised the efforts of the scientific research team in transforming solid sewage waste into environment-friendly green cement, aligning with Qatar National Vision 2030 Vision and sustainability.

He stressed Qatar's interest in supporting and promoting scientific research and innovation, under the wise leadership's directives.

The minister also highlighted the ministry's focus on applied scientific research that tackles the challenges in the fields of the environment, climate, wildlife, and sustainability, while encouraging researchers to conduct purposeful scientific studies.

Dr al-Kuwari, an environmental expert and engineering adviser at the Office of the Minister of Environment and Climate Change, stressed Qatar's commitment to protecting the environment and maintaining its natural balance to achieve comprehensive and sustainable development for all generations.

He specifically pointed out the priority areas, such as greenhouse gas emissions, air quality, biodiversity, water, the circular economy, waste management, and land sustainability.

This research promotes public-private sector partnerships to invest in natu-



Dr Mohamed Saif al-Kuwari speaking at the event.



HE the Minister of Environment and Climate Change Dr Abdullah bin Abdullatif bin Turki al-Sabae (centre) with HE the Minister of Education and Higher Education Buthaina bint Ali al-Jabri al-Nuaimi and HE the Minister of Municipality Abdullah bin Hamad bin Abdullatif al-Attiyah at the seminar yesterday.

ral green cement for use in construction projects and the manufacturing of engineering materials.

The production of "Green Cement" involves processing sludge from solid sewage waste through burning, grinding, and mixing it with stimulating materials.

It has been practically applied in the manufacturing of building blocks and foam concrete using recycled materials. This innovation contributes to reducing the carbon footprint and protecting air, soil, and groundwater quality from pollutants while minimising the environmental impact of sludge.

The idea for this innovation originated from the ministry's research team in collaboration with researchers from Qatar and Queen's University Belfast. The project was submitted to the Qatar

National Research Fund competition in its 12th cycle in 2021 and underwent scientific and technical evaluation by global reviewers and experts in the field, achieving the highest evaluation grade (A) for a period of three years.

According to the available data, the accumulated sewage waste amounts to approximately 40,000 tonnes annually, which can be used to produce 40mm blocks or 150,000cu m of foam concrete annually, contributing to reduced production costs.

The innovation is part of the MoECC's efforts to promote environmental sustainability and support the circular economy, which aims to reduce waste in materials, goods, and energy while maximising their sustainable use.

It also implements the fourth pillar of Qatar's Environment and Climate Change Strategy and is in harmony with the third National Development Strategy (2024-2030), which focuses on conserving natural resources, protecting ecosystems, reducing greenhouse gas emissions, and enhancing resilience to future environmental threats.

Green cement, an environment success story

The research project to make "Green Cement" from sewage sludge was undertaken by the Ministry of Environment and Climate Change (MoECC) in collaboration with Infrastructure Research & Development (IRD) at the Qatar Science & Technology Park (QSTP).

The project, titled "Green Cement: Scientific Innovation for a Better Environment and a Circular Economy", aligns with the Qatar National Environment and Climate Change Strategy 2030, which aims to develop a circular economy and implement efficient waste management practices.

The project addresses environmental challenges while implementing sustainable economic opportunities, in line with the Third National Development Strategy 2024-2030 and Qatar National Vision 2030.

On May 1, 2020, the Qatar National Research Fund

(QNRF), a division of the Qatar Research Development and Innovation Council (QRDI), awarded a \$500,000 grant to the MoECC scientific research team to produce green cement from solid sewage waste.

That project, titled "Development of a Novel Technology for Producing Green Cement and Advanced Construction Materials from Solid Waste", was developed by MoECC engineering consultant and environmental expert Dr Mohamed Saif al-Kuwari, IRD managing director Dr Khaled Hassan, scientists and researchers from Queen's University Belfast in the UK, and representatives from the Public Works Authority (Ashghal) and the construction industry.

The "Green Cement: Scientific Innovation for a Better Environment and a Circular Economy" project is set to serve the environment by reducing reliance on Portland cement and its high carbon footprint, preserving air, soil

and groundwater quality pollutants through the safe disposal of sewage sludge.

It also provides a sustainable option for specialised concrete applications in roads and infrastructure projects.

Sewage sludge is a sink for contaminants and its production increases every year due to population growth, leading to environmental challenges.

The World Bank report has estimated increased generation of global urban waste to reach 3.4bn tonnes by 2050.

Accumulation of such solid waste materials may cause environmental damage, destroy ecosystems, and create health risks for people, as well as its role in climate change and greenhouse gas emissions.

Hence, the urgent global need to develop waste management systems to reduce environmental damage and ease the rates of economic exploitation of this waste through recycling resources.

The project presents an excellent example on the collaboration between research team and industry to provide a practical solution to the efficient and effective use of solid waste materials in valuable construction applications. It provides an innovative solution for the conversion of sewage sludge waste from landfills into added-value construction products. The sludge processing destroys contaminants and combines heavy metals into hydrated cementitious products –Minimize impact on human health and environment. The newly developed "Green Cement" reduces reliance on Portland cement, an energy-intensive construction material, in low-strength concrete products –Sustainable construction. Finally, the project creates new business opportunities, and reduced cost of new sludge concrete products –Circular economy.

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